Rock Mechanics as a Multidisciplinary Science, Roegiers (ed.)
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Anisotropic stress influence on the permeability of weakly-cemented sandstones

M.S. Bruno, C.A. Bovberg & F.M. Nakagawa
Chevron Oil Field Research Co., La Habra, Calif.

ABSTRACT: The influence of anisotropic stress on the permeability of weakly-cemented sandstones is described. These materials are characterized by moderate to high porosity (15-25%) and relatively high permeability (200-1000 md). Laboratory measurements of permeability have been conducted on Kern River, Salt Wash, and Castlegate sandstones subjected to triaxial stress conditions up to 15 MPa.

Permeability sensitivity is shown to depend strongly on the direction of applied stress. For all samples tested, permeability reduction is relatively small when stress is applied parallel to flow, but is much more significant when the same stress magnitude is applied perpendicular to flow. Typical longitudinal permeability reduction due to radial stress applied onto cyclindrical samples ranged from 20 to 60%. Thin-section and SEM analyses of the mineralogy and pore structure for each lithology are also presented and discussed. Although the initial sample set is small, preliminary results indicate that permeability reduction is related to the amount and strength of cementation.

1 INTRODUCTION

Anisotropic stress states are common for many oil and gas reservoirs. This is especially true for those located within active tectonic regions, such as California, and in regions which have experienced extensive geologic deformation, such as the thrust belts within the Rocky Mountain Region. The non-hydrostatic state of stress can produce permeability anisotropy within some reservoirs, both parallel and perpendicular to bedding.

For most formations, differences in permeability between the horizontal and vertical directions are primarily controlled by stratigraphy and lithology. Permeability anisotropy in the horizontal plane (parallel to bedding), however, is often directly related to differences in horizontal in-situ stress magnitude. One practical implication is that the direction of maximum permeability within some reservoirs may be related to the direction of maximum compressive stress. While stress-induced permeability anisotropy is most pronounced within fractured reservoirs and very low-permeability formations, in-situ stresses can also influence the matrix permeability of many soft sediments.

This paper describes the influence of anisotropic stress on the permeability of weakly-cemented and underconsolidated sandstones. A brief review is first presented regarding some general influences of hydrostatic and non-hydrostatic stress on the permeability of well cemented and low-permeability rocks. Next, laboratory measurements of permeability of weakly-cemented sands subjected to triaxial stress are described. For these samples, stress-induced permeability reduction is demonstrated to depend strongly on the direction of applied stress, either parallel or perpendicular to flow direction. Finally, the possible influence of cementation on stress sensitivity for these samples is also discussed.

2 STRESS INFLUENCE ON PERMEABILITY

A number of researchers have described permeability reduction in sandstones due to increasing confining stress. Fatt and Davis (1952) presented some of the earliest data on moderately permeable consolidated sandstones, demonstrating reductions in permeability from 20 to 60% for samples subjected to pressures up to 100 MPa. Permeability reductions of more than an order of magnitude have been reported for very low permeability sandstones (less than 0.1 md) by Vairogs et. al., (1971). In general, permeability declines approximately exponentially with stress. Proportionately greater reduction occurs for low compared to high permeability sandstones, and also for less consolidated compared to well-cemented sandstones. For most sedimentary rocks, permeability perpendicular to bedding is initially lower and generally more stress sensitive than permeability parallel to bedding.

Several researchers have related permeability reduction to pore volume compressibility, including McLatchie et. al., (1958), Dobrynin (1962), and Wilhelmi and Somerton (1967). This would indicate that fabric and mineralogy influence the pressure sensitivity of sandstones. For example, many low-permeability sandstones contain high aspect ratio pores (length to thickness ratio > 100) whose flow capacity is proportionately more sensitive to stress than that of larger pores. Walls (1982) and Kilmer et. al., (1987), among others, have suggested that pressure sensitivity within low permeability sandstones is more strongly influenced by pore structure than by mineral composition. When porosity and permeability is relatively high (greater than about 50 md), however, mineralogy can also play an important role. Both increasing clay content and decreasing cementation tend to produce a sandstone which is more compressible and pressure-sensitive.

A few researchers have also investigated permeability reduction under triaxial stress conditions. Most of these studies have been conducted on very well-cemented sandstones, such as Berea, Bandera, and Boise (see for example, Gray et. al. (1963), Wilhelmi and Somerton (1967), and Morita et. al. (1984)). Zoback and Byerly (1976) studied the effects of high pressure deformation on the permeability of clean Ottawa Sand, and noted an accelerated loss in permeability above 60 MPa due to grain crushing and pore collapse. For a given confining pressure, both strain and permeability loss were greater under compression loading (increasing axial load) than under extension loading (decreasing axial load). Holt (1989) investigated permeability reduction induced by triaxial stress on a relatively weak North Sea sandstone. He found a rapid decrease in permeability when the differential stress exceeded the material yield strength (about 40 MPa), under both triaxial compression and triaxial extension load conditions.

3 EXPERIMENTAL METHOD

The goal of the present experiments is to compare the influence of stress applied parallel and perpendicular to flow direction on the horizontal permeability of several weakly-cemented rock lithologies. Cylindrical rock samples, 2.5 cm in diameter and 7.5 cm in length, are cut parallel to bedding (as best as can be discerned from visual inspection) and loaded into a standard triaxial cell.

Computer controlled hydraulic pumps are used to independently control and maintain radial and axial pressure loading on the rock samples. The core samples are surrounded by a heat-shrinkable teflon sleeve to separate the confining pressure from pore fluid pressure. A third computer controlled pump is used to flow a low viscosity oil through the samples at precise flow rates, ranging from 1.0 to 4.0 cc/min, with an accuracy of about 0.01 cc/min. A high-precision quartz transducer is used to measure the pressure drop along the length of the rock samples.

The samples are first loaded hydrostatically to a pressure of about 3 MPa, and an initial permeability is measured. To assess the influence of load applied parallel to flow direction, only the axial load is increased and permeability is measured at increments of about 3 MPa up to about 12 to 15 MPa. Permeability is also measured as the axial load is decreased back to the initial hydrostatic conditions. To assess the influence of load applied perpendicular to flow direction, the radial load is next increased. Permeability is measured at increments of about 3 MPa up to about 12 to 15 MPa, and again as the radial pressure is unloaded. The axial load was applied first for most tests because, as will be discussed later, there is much less irreversible permeability reduction associated with the axial load cycle compared to the radial load cycle. For comparison purposes, the order of loading was reversed for some samples and additional tests were conducted under simple hydrostatic loading conditions.

4 SAMPLE DESCRIPTION

Permeability measurements were conducted on samples from three distinct lithologies: Salt Wash Sandstone, Castlegate Sandstone, and Kern River Sands. A summary of the sample mineralogy is presented in Table 1. The Salt Wash material was cored from an outcrop member of the Morrison Formation in Central Utah. It is Late Jurassic in age and classified as a lithic arenite. Salt Wash Sandstone is friable, medium-grained, and well-sorted. The detrital grains are subangular to rounded, and are composed of quartz (35% of total volume), lithic fragments (22%), and potassium feldspar (5%). The grains are bonded with calcite cement (5%). Authigenic (6%) smectite and smaller amounts of kaolinite (2%) is common on the framework grain surfaces, causing some pore throat occlusion. Average sample porosity is about 25% and typical oil permeability is on the order of 700 md. An SEM photograph is presented in figure 1.

The Castlegate Sandstone samples were cored from a Late Cretaceous aged outcrop in Northwestern Colorado. The rock is very friable, very fine grained, well-sorted, and composed of angular to subrounded grains. It may be classified as a sublithic arenite. The framework grains are composed of quartz (56%), potassium feldspar (5%), and lithic fragments (8%). The primary bonding material is kaolinite (4%) and small amounts of illite (1%). Average sample porosity is about 27% and typical oil permeability is on the order of 900 md. An SEM photograph is presented in figure 2.

The Kern River samples were obtained from well core samples in the Southern San Joaquin Valley, California. The formation is Late Pliocene aged, relatively shallow (about 200 m), and weakly consolidated to unconsolidated. The material is medium-grained, poorly sorted, and composed of angular to subangular grains. It may be classified as a lithic arenite. The framework grains are composed of quartz (12%), potassium feldspar (18%), lithic fragments (30%), and small amounts of mica and heavy minerals. Authigenic smectite pervasively coats most detrital grains. Average sample porosity is about 30% and typical oil permeability is on the order of 400 md. An SEM photograph is presented in figure 3.

Table 1. Sample Texture and Mineralogy

	Salt Wash	Castlegate	Kern River
Quartz Grains (%)	35	56	12
Feldspar Grains (%)	5	5	18
Lithic Fragments (%)	22	8	30
Authigenic Clays (%)	8	4	10
Silica Cement (%)	0	1	0
Calcite Cement (%)	5	0	0
Grain Size (microns)	250-500	65-125	250-500
Sorting Quality	very well	well	poor
Oil Permeability (md)	600-800	850-950	300-500
Porosity (%)	25	26	30

5 EXPERIMENTAL RESULTS

Some preliminary tests have been completed on several samples from each lithology described above. Additional measurements are continuing and will be more fully described in a future paper. The initial experimental results, however, are consistent. Figures 4, 5, and 6, present examples of the stress-induced permeability reduction for typical Salt Wash, Castlegate, and Kern River samples, respectively. In each figure the reduced permeability is expressed as a percentage of the initial permeability at the start of the loading cycle. The repeatability of experimental results for different samples from each lithology is about ± 5%.

As seen in figures 4, 5, and 6, the permeability of each sample is reduced only slightly when subjected to loading parallel to the flow direction. When loaded perpendicular to flow direction (radial load), the permeability of each sample is more significantly reduced. Typical permeability reduction under radial loading varies from 18 to 40 %, depending on lithology. The Salt Wash sample permeability is reduced a maximum of 18%, the Castlegate sample permeability is reduced a maximum of 25%, and the Kern River sample permeability is reduced a maximum of 40%. It is important to note that radial pressure induces both compressive radial and tangential stresses, while axial loading induces only axial compressive stresses. However, even at equivalent mean stress levels, the experimental data indicates that permeability is more significantly reduced by loading applied perpendicular to flow direction than by loading applied parallel to flow.

Note that a larger reduction in permeability is produced by the radial load cycle, even though some irreversible permeability damage remains from the initial axial load cycle. Figure 7 illustrates the typical permanent reduction in permeability for the Castlegate sample, showing the complete loading and unloading cycles for both axial and radial stress. Similar results are obtained if the order of loading is reversed. That is, under the radial load cycle significant permeability reduction occurs, while under the axial load cycle almost no further reduction takes place. These latter types of tests are less conclusive, however, since it can be argued that the initial radial cycle significantly and irreversibly compacts the samples.

It is important to recognize that the current tests in which radial stress is increased from an initially low hydrostatic level are fundamentally different from typical "triaxial extension" tests conducted by Zoback and Byerlee (1976) and Holt (1989), in which the axial stress is decreased from an initially high hydrostatic level. From triaxial compression and extension tests on Ottawa Sand Zoback and Byerlee (1976) conclude that if granular material is subject to sufficient deformation, "permeability in the direction of maximum compression (would be) significantly lower than permeability normal to that direction." Such a statement must be strongly qualified. The stress history and irreversible compaction behavior of weakly-cemented and unconsolidated sands must be taken into account. It may be true that for a given confining stress, increasing the axial load on a sample will reduce permeability more than decreasing the axial load. However, our tests indicate that for a given confining stress, increasing the radial load reduces permeability more than increasing the axial load. The implication is that for many formations, permeability will be <u>greater</u> in a direction <u>parallel</u> to the maximum compressive stress.

6 DISCUSSION AND CONCLUSIONS

Although this preliminary data set is quite small, it may also be worthwhile to comment on some possible influences of lithology on stress-induced permeability reduction. There is a general consensus that compression of microcracks and high aspect ratio pores dominates stress-induced permeability reduction in low permeability rocks (see for example, Walls (1982), Brower and Morrow (1985), and Kilmer et. al. (1987)). Fatt (1958a,1958b) described a similar mechanism to explain stress sensitivity in higher permeability sandstones as well. A few researchers, including Snow (1969) and Sayers (1990), attribute permeability anisotropy in fractured rock to preferential closing of cracks aligned perpendicular to the maximum stress direction.

While microcrack closure may play some role in controlling the influence of anisotropic stress on the permeability of the samples tested for this study, we do not believe that this is the primary mechanism for permeability reduction in weakly cemented sandstones. An examination of the SEM photographs presented in figures 1, 2, and 3, reveals that most pore throats and fluid channels for these sample lithologies are relatively large (compared to grain size). Although there are a number of high aspect ratio channels and microcracks, these probably do not dominate fluid flow. Furthermore, a certain amount of microcrack closure is often reversible. The significant permanent reduction in permeability demonstrated by figure 7 suggests that irreversible compaction and deformation plays a more dominant role than elastic microcrack compression within these material.

Figure 8 presents a comparison of the permeability reduction induced by radial loading for each of the sample lithologies. There appears to be a general trend towards increased stress sensitivity with decreasing amount and strength of cementation. Among the lithologies tested, the Salt Wash samples are most strongly cemented, with about 5% calcite. Next in cementation strength is the Castlegate samples, whose grains are more weakly bonded by pore bridging clay and trace amounts of silica cement. The Kern River samples, which are almost completely unconsolidated, are most sensitive to stress.

The observed trend is consistent with the understanding that inelastic deformation of many sandstones is most strongly dominated by intergranular cementation and bond strength, rather than by grain mineralogy, as described by Bruno and Nelson (1990). Independent measurements on strongly cemented sandstones which display significantly less stress-induced permeability reduction, such as on Berea Sandstone by Morita et. al. (1984), are also consistent with the present observations. Additional tests combining strain and strength measurements with permeability reduction are required to substantiate these preliminary conclusions.

In summary, the experimental results indicate that permeability reduction in weakly cemented sandstones is strongly influenced by the direction of the applied loading with respect to the direction of fluid flow. Axial loading alone on the cylindrical rock samples produces relatively little change in longitudinal permeability. Subsequent radial loading, however, reduces the permeability more significantly. These results suggest that horizontal permeability anisotropy in the field, even within some unfractured formations, may be strongly influenced by the direction of maximum compressive stress. The preliminary results also suggest that the magnitude of permeability reduction is related to the amount and strength of intergranular cementation.

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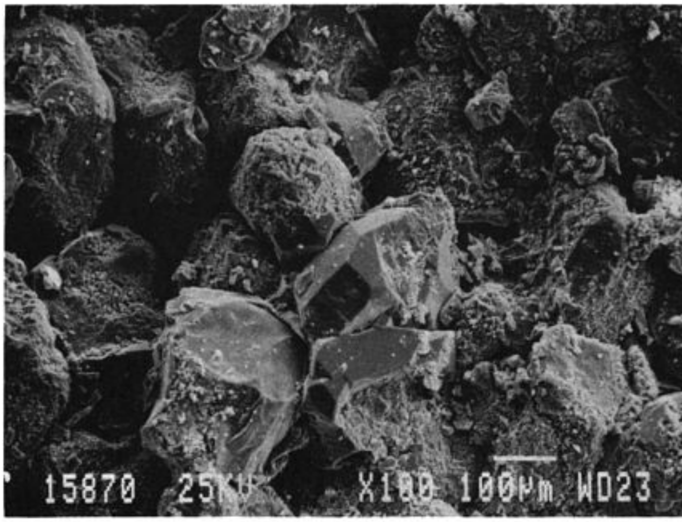
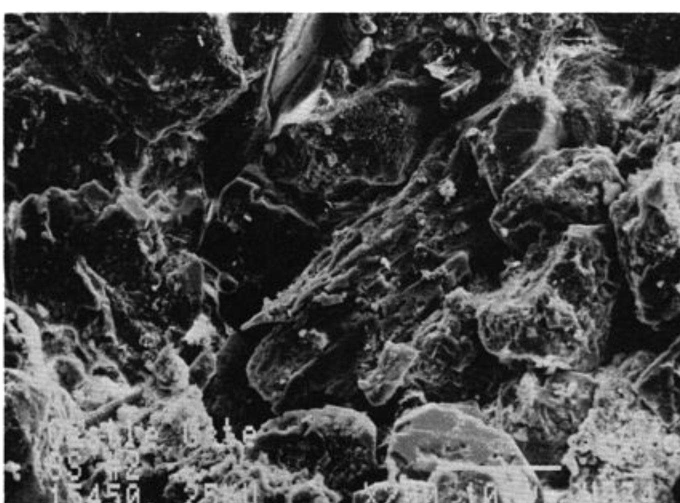


100 μm

Figure 1

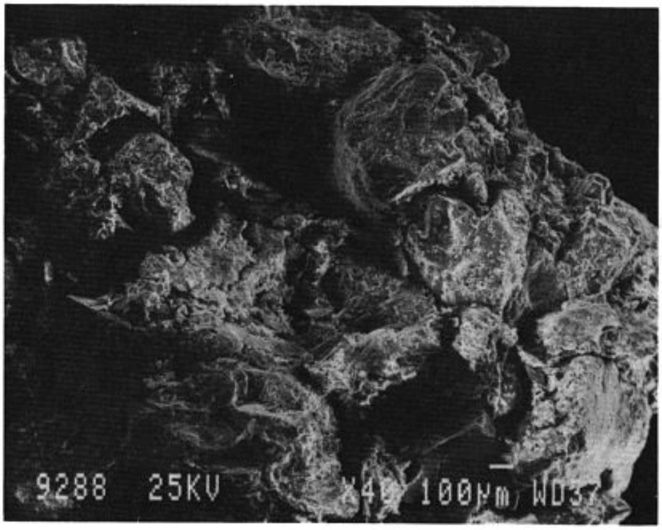
Salt Wash Sandstone SEM Image



100 μm

Figure 2

Castlegate Sandstone SEM Image



100 μm

Figure 3

Kern River Sample SEM Image

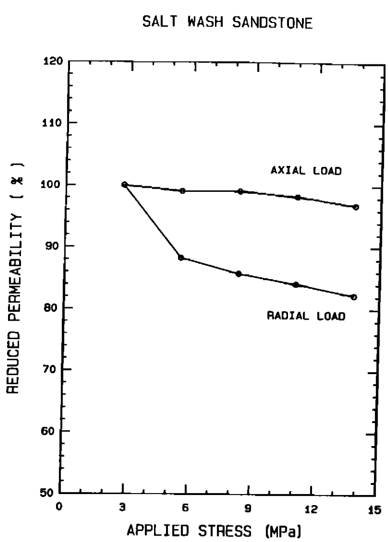


Figure 4

Stress-Induced Permeability Reduction, Salt Wash Sandstone

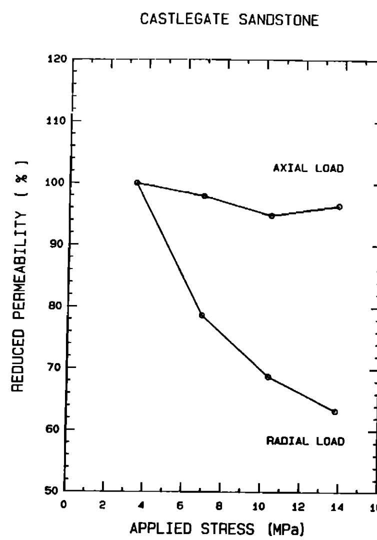


Figure 5

Stress-Induced Permeability Reduction, Castlegate Sandstone

KERN RIVER SANDS

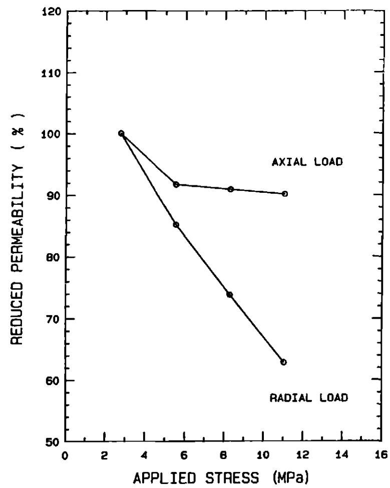


Figure 6

Stress-Induced Permeability Reduction, Kern River Sample

CASTLEGATE SANDSTONE

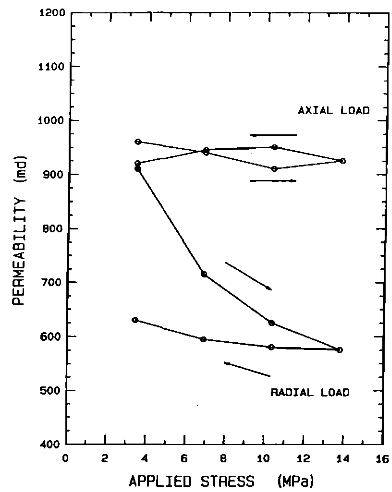


Figure 7

Castlegate Sandstone Permeability Versus Applied Stress

SAMPLE COMPARISON

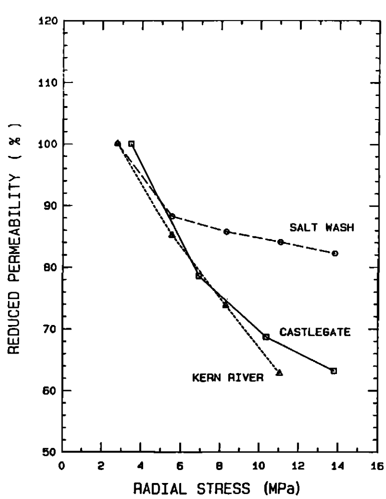


Figure 8

Comparison of Reduced Permeability due to Radial Stress