MECHANICAL PROPERTIES ANALYSIS: THE KEY TO UNDERSTANDING PETROPHYSICAL PROPERTIES STRESS SENSITIVITY

R.A. Farquhar, B.D.G. Smart, B.R. Crawford, A.C. Todd & J.A. Tweedie
Department of Petroleum Engineering
Heriot-Watt University

ABSTRACT

This paper presents the results of an investigation into the stress sensitivity of the petrophysical and mechanical properties of low permeability gas bearing sandstones from the UK Southern North Sea. The stress sensitivity of both Young's modulus and permeability is found to be influenced by the deformation characteristics of different depositional facies. It is demonstrated that an appreciation of the mechanical property stress sensitivity can aid the interpretation and application of permeability stress sensitivity behaviour. From the literature it is known that a linear relationship between porosity and Young's modulus exists at reservoir stress levels which is thought to reflect their dependence on the *in situ* mineral framework. The work reported here confirms this observation but also shows that for the low confining pressure levels encountered in routine core analysis the relationship fails to develop. It is proposed that structural alteration associated with the formation of stress relaxation microcracks, during core recovery, is the most likely explanation for this behaviour. Evidence from SEM and thin sections supports this suggestion. Microstructural alteration related to strain relaxation effects could lead to inaccuracies in the interpretations attached to core data and its applications, particularly in low permeability/low porosity formations which are often very stress sensitive. However, the study indicates that the association of depositional facies with the petrophysical and mechanical stress sensitivity character of sandstones may be a key to reconciling the problem.

INTRODUCTION

To establish the stress sensitivity of a particular rock property, measurements are conducted on core plugs at increasing stress levels from zero or a few hundred psi confining pressure, up to effective stress levels though to exist in the reservoir. The principal aims of stress sensitivity characterisation are as follows:

1) provide a representative value of the property under evaluation at reservoir stress levels
2) determine a stress sensitivity factor which can be applied to "correct" routine core data for stress effects
3) establish a means of predicting further changes in the property due to future changes in the *in situ* stress state by extrapolating trends fitted to the data

The latter aim becomes increasingly more important as a field matures. The effective reservoir confining stresses will increase due to pore pressure reductions as a result of hydrocarbon production. In an attempt to optimise recovery at the end of a reservoir's economic life, near complete reservoir fluid pressure depletion or "blowdown" may be a valid option, but which will similarly increase the earth stresses acting on the rock. To implement stress sensitivity analysis requires an understanding of the physical behaviour of the rock and an appreciation of the influences which are being compensated for.

This paper presents several observations which became apparent from a recent examination of the petro-mechanical stress sensitivity of Rotliegendes sandstones. Permeability and conductivity stress sensitivity behaviour were observed to be related to depositional environment and diagenesis. Characterisation of Young's modulus stress sensitivity is shown to validate this observation. Consideration of the mechanical deformation of the rock has the potential to be a valuable aid in interpreting stress sensitivity behaviour and could assist in the practical application of permeability stress sensitivity analysis.

The development, with increasing confining stress, of the porosity-Young's modulus relationship is used to examine the changes which have occurred in the rock due to core recovery. The results support the hypothesis that structural alteration occurs due to microcrack genesis as a result of strain relaxation during coring. It is shown that the rock properties and stress sensitivity behaviour measured in the laboratory may not be representative of the *in situ* structure.

STRESS RELAXATION AND SANDSTONE STRESS SENSITIVITY BEHAVIOUR REPORTED IN THE LITERATURE

The effect of increasing stress on the petrophysical properties of sandstones has been extensively studied over many years and the industry is well acquainted with the standard response of permeability, porosity and electrical conductivity (figure 1). The effects of shale streaks[1], clay content[2], natural fractures[2, 3, 4], mineral cements[5] and compressibility[6] have all been seen to have some bearing on the petrophysical property stress sensitivity. However, in general such effects have been limited to a qualitative understanding.

Stress sensitivity behaviour has been modelled from both empirical and theoretical viewpoints. Wyble (1958) and Jones (1986) both claim good agreement between experimental data and empirical relationships based on the behaviour of a single exponential function. Theoretical models based on fluid flow through microcracks or high aspect ratio slot pores have also proved to be an attractive means of explaining petrophysical property stress sensitivity and have been quite successful in describing permeability stress sensitivity.[9-12] Fatt and Davis (1953) and Wyble (1958) were early advocates of microcracks being responsible for the form of the stress sensitivity observed in sandstones. Networks of high aspect ratio cracks or sheet pores have been identified as being important for fluid transport in several low permeability sandstones. In some cases these are the result of diagenesis and are features of the *in situ* pore structure[14], in other cases[15] there is evidence that the cracks are closed at reservoir stress levels and are a facet only of the pore structure which exists at low confining stresses. In addition to the visual evidence from pore casts and thin sections, the hypothesis of flow-controlling cracks or slot pores is supported by the experimental evidence of Jones and Owens (1980).

The development of microcracks in sandstones, other than those due to diagenesis, is associated with the changes in stress acting on the rock during coring. During coring operations the *in situ* stresses acting on reservoir rock are relaxed and as a result, strain energy, which has accumulated in the mineral grains and matrix due to burial, tectonic and thermal stresses, is released. It is generally accepted that the strain relaxation of a core is proportional to the magnitude and orientation of the *in situ* principal stresses. The strain relaxation process may be physically explained if it is considered to be a consequence of microcrack generation as a result of differential stress relaxation.[17] The density of the microcracks is assumed to be proportional to the magnitude of the *in situ* stresses. Teufel (1983) states that microcrack alignment will be controlled primarily by the directions of the principal stresses, with the greatest strain relaxation and hence greatest density of microcrack opening being in the direction of the maximum principal stress. Kulander et al (1990) discuss how stresses acting on the rock during coring change from compressive to tensile in certain circumstances. The tensile stresses induce fractures in the core often observed as core disking.

Strickland et al (1979) have identified three general categories of microcracks attributed to microstructural damage during core recovery: 1) coincident grain boundary, or intergranular cracks, 2) intragranular cracks, and 3) cracks in shale laminae. Grain boundary cracks were the most frequently observed often connecting otherwise isolated pore space. They concluded that these cracks were not *in situ* features since there was no evidence of secondary cementing mineral deposition nor crack healing. Brower and Morrow (1983) noted that in pore casts of low permeability sandstones, grain boundary cracks were significantly less numerous in cases where the sample was confined at simulated reservoir stress whilst the epoxy resin cured, compared to casts made at ambient conditions. This suggests that the majority of the cracks were not a feature of the *in situ* pore structure. Several authors have presented results of experimental studies which support the hypothesis that microcracks are a feature of strain relaxation and that they may influence the measurement of the petrophysical properties of sandstones in the laboratory.[17, 20, 21]

CHARACTERISATION OF THE STRESS SENSITIVITY OF ROTLIEGENDES SANDSTONES

Sample Suite

Sandstone samples were available from three facies associations reflecting the following depositional environments: 1) aeolian dune and interdune; 2) spasmodic and prolonged stream flow fluvial channel fill; and 3) lake margin sabkha interdune and sheetflood. The sandstones are classified as sublith- to lithic arenites and have a broadly similar detrital and authigenic mineralogy. Quartz is the dominant detrital grain mineral (45% to 65%) in addition to ubiquitous feldspars and lithic fragments. Detrital clay content averages 3% rising to 6%. Dolomite and quartz are the most widespread mineral cements. Authigenic clay minerals are mainly grain coating platy chlorite and grain coating fibrous illite. Illite also occurs in pore bridging habits. Pseudo-hexagonal kaolinite booklets are found as an extensive pore filling mineral in some low porosity/permeability fluvial samples.

Sample Preparation

A suite of core plugs were cut from preserved whole core with the cylindrical axis parallel to the horizontal direction using a diamond tipped core barrel, flushed with synthetic formation brine (SFB). Core ends were trimmed using a trim saw core holder to enable SFB to be flushed through the plug, removing fines from the cut face reducing a potential source of sample damage. The plugs were cleaned using a mild miscible solvent flushing technique followed by drying and storage in a relative humidity oven at 60°C and 40% relative humidity.

Experimental Equipment and Procedures

The samples were loaded using a pseudo-triaxial core holder which permitted independent axial and radial loading. Porosity, permeability and electrical conductivity were measured at discrete stress stations during cycles of increasing mean stress up to a maximum of 34.5 MPa according to either a hydrostatic, triaxial or biaxial stress state.

Porosity and permeability were determined on dry samples using a Boyle's law porosimeter and steady state Nitrogen permeameter respectively. Permeability measurements at specific stress levels were conducted over a range of mean flowing pressures to enable the Klinkenberg slip factor to be evaluated. Electrical conductivity was determined on samples saturated with SFB over a similar range of stress conditions. Measurements were made using platinum/platinum black combination electrodes at the core face and an electrical component analyser. Porosity change during the electrical properties tests was determined by measuring the volume of fluid expelled between stress stations.

The change in each property as a function of increasing confining pressure was quantified by fitting a dual exponential function to the experimental data of the general form:

$$f(\sigma) = C0 + C1\exp^{C2\sigma} + C3\exp^{C4\sigma} \quad .....(1)$$

where $f(\sigma)$ is the value of the property at a mean stress σ and C0, C1,..., C4 are empirical constants. The constants C2 and C4 determine the rate of change in property. This type of function has been found from experimentation with various forms to best capture the nuances of the stress sensitivity profile whilst satisfying the required boundary conditions.[22, 23] The stress sensitivity has also been quantified by the stress sensitivity ratio, which is the ratio of the property at 34.5 MPa relative to the value of the property at some base value.

Following the petrophysics tests the samples were reconditioned in a relative humidity oven for several months. A pore image analysis (PIA) study was conducted which compared matched core trims taken from representative samples "before" and "after" testing. It was concluded that little or no permanent structural alteration occurred as a result of the loading cycle. This supports the view that the deformation during stress sensitivity tests was predominantly elastic.

Measurement of the elastic deformation properties as a function of confining pressure were conducted by loading strain gauged samples in a Hoek triaxial cell using a servo-controlled stiff testing machine. Axial and radial strains were measured using diametrically opposed foil strain gauges arranged in a 90° rosette and a Wheatstone bridge arrangement.

Young's modulus was determined from analysis of the isotropic elasticity matrix over a range of confining pressures from 6.9 MPa to 34.5 MPa. In order to test the assumption of isotropy of the elastic properties, several samples which displayed distinctive mm to cm scale bedding features were the subject to transverse isotropic analysis. For the sample orientation (relative to the bedding) in this study transverse isotropic analysis results in a value of Young's modulus in the plane of the bedding and an aggregate value for directions parallel and perpendicular to the bedding.

STRESS SENSITIVITY BEHAVIOUR OF ROTLIEGENDES SANDSTONES

General Observations

Porosity, permeability and electrical conductivity all displayed classic stress sensitivity behaviour. Each property followed a rapid initial decrease from the base measurement (3.5 or 6.9 MPa) up to mean stresses of 10 MPa to 15 MPa followed by a gentle, asymptotic or near linear decrease until reservoir effective stress levels were reached (34.5 MPa). The greater part of the property reduction occurred during the initial rapid reduction and in many cases up to half of the ultimate reduction occurred in this interval. In general, stress sensitivity increased as the magnitude of the property measured at the base level decreased. Permeability was the most stress sensitivite property of the three and displayed the broadest range of stress sensitivity ratios. Porosity was the least stress sensitive.

Young's modulus and Poisson's ratio increased with increasing confining pressure. Young's modulus increased by a factor of just over 2 to nearly 3.5 between confining pressures of 6.9 MPa and 34.5 MPa. Variation in the magnitude of the elastic properties and their stress sensitivity was noted to be poorly related to lithology. This is consistent with the findings of Senseny (1983) for sedimentary rock from the Piceance Basin.

Facies Dependence

The Rotliegendes sandstones examined in this study displayed a very wide range of petrophysical property stress sensitivity (figure 2). In particular permeability reduced by a moderate 13% to over 90% in some cases. Permeability and electrical conductivity stress sensitivity were observed to be influenced by the depositional facies. When the samples were ordered according to stress sensitivity ratio, samples from the same facies were found to cluster together. This is shown for permeability stress sensitivity in figure 3. Both fluvial and lake margin sabkha sandstones can be seen to form groups of high stress sensitivity and low stress sensitivity. It is not possible to determine whether the two ranges of stress sensitivity represent separate groups with different stress sensitivity characteristics or a single group with a wide range of permeability stress sensitivity behaviour. This uncertainty could create problems in assigning the appropriate stress sensitivity ratios to a suite of routine core data for conversion to "reservoir" values.

Figure 4 shows a stress sensitivity plot for Young's modulus for samples from each group identified in figure 3. The first point to note is the separation based on facies association. Aeolian dune sandstones are the least stress sensitive overall and the lake margin sabkha sandstones the most, with the fluvial samples intermediate between the two. This confirms the influence of depositional facies on the stress sensitivity behaviour of these Rotliegendes sandstones.

The second point worth noting is the form of the stress sensitivity curves. Both lake margin sabkha samples and the low permeability stress sensitivity fluvial sample display a concave upwards trend of increasing Young's modulus with increasing confining pressure. This is the form of the Young's modulus stress sensitivity curve reported by Cleary (1959). The aeolian dune sample follows an essentially linear increase whilst the low permeability/low porosity fluvial samples trace a concave downwards path. These results indicate that most of the increase in stability of the lake margin sabkha and low permeability stress sensitivity fluvial rocks occurs at lower confining pressures whereas higher confining pressures are required to achieve a similar effect in the high permeability stress sensitivity fluvial sandstones. This suggests that a different deformation mechanism is active in that group compared to the other rocks. The departure from linearity at each successive point was found to be greater than that which could be attributed to the measurement error implying that the two types of curve are a real feature of Young's modulus stress sensitivity behaviour.

It is clear that the development of the deformation characteristics of the load-bearing framework with increasing confining pressure for both low and high stress sensitivity lake margin sabkha sandstones is identical in form and similar in magnitude. This suggests that as confining stress increases, the changes in the load-bearing structure which will influence the pore structure and hence permeability are also similar. Thus the difference in permeability stress sensitivity could be due to the relative magnitude of the permeability reduction attributable to the deformation behaviour compared to the initial permeability.

The low stress sensitivity samples are observed to consist of laminae of coarse grains with a fairly open pore structure and fine grained laminae containing detrital clays and more extensive authigenic, pore reducing mineralisation. The high stress sensitivity samples have similar characteristics to the fine grained laminae. The coarse grained laminae are responsible for the higher permeability of the low stress sensitivity samples and will retain significant permeability at elevated confining pressures compared to the permeability associated with the deformation of the load bearing structure. Therefore the appropriate stress sensitivity ratio could be attributed to the lake margin sabkha sandstones by employing a permeability and porosity restriction which would identify those samples with high permeability and porosity as the least stress sensitive.

The two groups of fluvial sandstones on the other hand are observed to posses different deformation behaviours. The permeability reduction which could be attributed to deformation of the load-bearing framework may therefore contribute to the observed permeability reduction in different ways. SEM photographs reveal the high stress sensitivity samples to posses a grain structure which has been significantly altered by authigenic mineralisation and a pore structure which is dominated by extensive pore filling kaolinite. The kaolinite does not occupy any load bearing positions. The less stress sensitive fluvial samples possess a more open grain structure and intergranular porosity reduced by pore lining chlorite and illite. It is expected that permeability changes due to deformation of the load-bearing structure would have a different impact on samples from the two groups. In this case it would be necessary to identify the samples by a more dependable means than a permeability or porosity criterion. For these samples the contrast between permeability and porosity of the two rock types is not as reliable as that for the lake margin sabkha sandstones.

EFFECT OF STRESS SENSITIVITY ON THE RELATIONSHIPS BETWEEN SANDSTONE PROPERTIES

It is well known that relationships often exist between certain rock properties such as porosity and formation factor, porosity and permeability and porosity and strength. These relationships are empirical in nature and arise due to a shared dependence on some facet of the grain or pore structure of the rock. The case for the existence and development of these relationships *in situ* can be argued to be due to the concomitant changes in each property due to depositional structure, compaction and diagenesis.

It has been shown that the load-bearing structures of sandstones deform according to different, in some cases facies dependent, forms. The value of the exponent C2 in expression 1, which describes the rate of property reduction with increasing stress, has also been observed to be related to depositional facies for both porosity and permeability. Interestingly, the rate of porosity reduction for aeolian dune sandstones is more rapid than that for fluvial sandstones whereas the reverse trend is found for permeability. Since it is obvious that a variety of deformation behaviours exist it is therefore important to determine whether such behaviour in any way changes the relationships between the properties which exist *in situ.*

Wyllie et al (1956 & 1958) presented an empirical relationship between porosity and the propagation of acoustic waves through rock. The velocity of the wave is determined by the elastic stiffness and density of the mineral framework. Therefore it is expected that a relationship should exist between porosity and Young's modulus. It has long been considered in a qualitative sense that because porosity represents the proportion of the rock which is does not contribute directly to the load-bearing structure that it should be related to the mechanical behaviour of the rock. Vernik and Nur (1992) found linear compressional and shear wave velocity-porosity relationships at near reservoir effective stresses in siliclastics which were primarily related to the diagenetic character of the rocks. These relationships transformed into linear trends of increasing dynamic Young's modulus with decreasing porosity.

Young's modulus versus porosity was plotted as a function of increasing confining stress as can be seen in figure 5. Obviously Young's modulus changes considerably more than porosity; however, the most striking point in figure 5 is the non-existence of the expected relationship between porosity and Young's modulus at low confining pressures. This implies that porosity and Young's modulus cannot have been altered in a consistent manner as the stresses were relaxed. Further, any relationship between properties derived at low confining pressures may not be representative of *in situ* rock structure. It should also be noted that the quality of the relationship improves with increasing confining pressure which suggests that the behaviour is reversible. Unfortunately log data was not available to confirm whether the relationship formed at a confining pressure of 34.5 MPa is the similar to that which may exist *in situ.*

Figure 6 illustrates in more detail the porosity-Young's modulus relationship at a confining pressure of 34.5 MPa. This figure shows a separation between the fluvial facies on one side of the best fit line and the lake margin sabkha and aeolian dune sandstones. This may be indicative of the influence of depositional facies on the intimate relationship between sandstone properties.

EFFECT OF STRESS RELAXATION MECHANISM ON STRESS SENSITIVITY OBSERVED IN THE LABORATORY

Stress sensitivity measured in the laboratory actually reflects the changes which have occurred in the rock as a result of drilling, coring and handling. Whilst damaged induced by handling and preparation cannot be discounted, every effort was taken to minimise possible alteration.

The strain recovery mechanism associated with stress relaxation during drilling and coring is though to be one of microcrack genesis. A convincing case exists in the literature for microcrack generation and their effect on rock properties. Several pieces of evidence can be found for these Rotliegendes sandstones which suggests the observed stress sensitivity behaviour is influenced by stress relaxation microcracks:

1) The results of the transverse isotropic analysis indicate anisotropy with respect to Young's modulus in samples from the three different facies associations. Young's modulus measured in the direction of the vertical stress is lower than that in the horizontal direction at low confining stresses. Greater stress sensitivity is also observed in the direction normal to the bedding. The anisotropy is quite apparent as can be seen in figure 7. These observations are consistent

with the influences of an oriented network of microcracks.

Cracks in rocks can be shown to reduce Young's modulus.[21] According to the anelastic strain recovery mechanism discussed by Teufel (1983) a greater degree of crack opening would be expected in the direction of maximum stress relaxation. Since it can be assumed that the maximum principal stress in the reservoir would be coincident with the vertical direction, it would be expected that a greater density of cracks would be generated with maximum opening in the vertical stress direction. This would account for the lower Young's modulus and the different deformation behaviour in the two directions. The interface between grains perpendicular to the bedding is often considered to represent a plane of weakness in sandstones.[29] Grain-grain and grain-matrix contacts represent the weakest points in the load-bearing structure, which would facilitate the development of grain boundary cracks.

2) The point at which the dominance one exponential decay component in expression 1 switches to the other coincides with a transition from rapid property reduction to an asymptotic decay. This coincides approximately with the turning point in both types of Young's modulus stress sensitivity curves. This possibly indicates a transition in the deformation mechanism from one influenced by microcracks to one influenced by the *in situ* load-bearing structure.

3) Following the work of Klinkenberg it can be shown that the slip factor for a packing of spheres and a high aspect ratio slot pore is related to permeability by exponents of -0.5 and -0.33 respectively. A slip factor-Klinkenberg permeability plot was constructed for some low permeability/low porosity sandstones from the sample suite among which the influence microcracks would be expected to be more noticeable. At a confining pressure of 6.9 MPa an exponent of -0.37 results which is acceptably close that for a high aspect ratio slot or crack. However, at higher confining stresses above 27.6 MPa no relationship is found which suggests that the microcracks have closed as would be expected.

4) Direct observation of grain boundary cracks in SEM images is hampered by the need to break a fresh surface in order to create the image. It could be argued that this would create grain boundary separation which would then be mistaken for microcracks. In figure 8(a) and (b) several very obvious grain boundary cracks can be seen. In figure 8(a) several cracks can be seen in a sample which exhibited high permeability stress sensitivity. In this sample, which has undergone extensive diagenesis, the "clean" appearance of these features suggests that they are not *in situ* features. Figure 8(b) shows a parting between a detrital quartz grain and detrital clays. In many samples with grain coating clays, partings could be seen between the clay rims and the detrital grains. If these features are examples of grain boundary cracks, then it is clear that the separation occurs at the weakest point in the structure, between grain-matrix or grain-clay interfaces.

Figure 8(c) shows grain boundary cracks observed in thin section close to the transition from fine grained, muddy lamina to a coarser grained clean lamina. Note how the profile of the crack surface closely follows the outline of the grains and also that the outline of grain surfaces are displayed in relief by mineral cements on the opposing surface. This is a clear indicator that the crack formed after the rock was cored and is not a feature of the *in situ* structure. Numerous other smaller grain boundary cracks were observed in this sample, all oriented with maximum opening, normal to the bedding, which is assumed normal to the maximum principal stress acting in the vertical direction.

DISCUSSION

The validity of core data measured at low confining stresses in the laboratory is based on the assumption that the structure of the rock has either changed little or at least in a consistent manner compared to other samples from the same formation. The use of core data measured at elevated stresses assumes that upon applying stresses in the laboratory these deformations are reversed and that the trends can be extrapolated to predict the future behaviour of the rock structure which exists *in situ*. The results presented in this paper clearly contradict these assumptions.

If the strain relaxation mechanism in sandstones is considered to be related to microcrack genesis, their effect on the properties measured in the laboratory cannot be discounted. Not only will the properties posses some unquantifiable contribution due to the microcracks but the grain and pore structure will not be representative of that *in situ*. The stress sensitivity of different properties is quite different in form and extent and variable even for a single property in some cases. Due to the different deformation mechanisms the samples will not be altered by a consistent factor and thus the relative alteration in property will be different. Comparison between different samples will not represent the actual variation between the properties which exists in the reservoir. These suggestions are supported by the failure of the Young's modulus-porosity relationship to form at low confining pressures.

Several implications regarding the use of routine core data can be identified which will be influenced by the foregoing. Principally, the magnitude of the properties evaluated at low confining pressures will be in error; however, because the error due to microcracks is not a consistent factor, any comparison based on property contrasts will also be in error. For example permeability and porosity contrasts evaluated using routine core data may not accurately represent the contrasts in the reservoir since some samples will be altered to a greater or lesser degree than others. In addition to inaccuracies in reserves and recovery estimates, this type of problem is relevant to the delineation of reservoir zones and the location of perforations etc. The existence of grain boundary microcracks will also influence pore size distribution and saturation determinations. This could have a detrimental influence on the reliability of reservoir simulators due to errors transmitted via the data used to generate pseudo-functions. The influence of microcracks implies that the deformation mechanism which is manifest as the observed stress sensitivity behaviour in the laboratory is not representative of the deformation which would be expected of the *in situ* load-bearing structure.

The solution to some of the problems indicated by this study are not necessarily intractable. The observation that the permeability, conductivity and even Young's modulus stress sensitivity are related to depositional facies in these Rotliegendes sandstones presents a possible solution. If depositional facies influences the form of the *in situ* load bearing structure it might be expected that it would also influence the distribution of stresses through the structure and thus influence microcrack location. As a result the deformation behaviour including the effect of microcracks would still appear related to depositional facies. If a facies dependence can be identified within a suite of samples and characterised, it could be used to "correct" routine core data. An example of the application of this method for these sandstones[30] found good agreement between DST permeability and "stress corrected" core permeability averages for a number of wells. The use of dual component functions such as expression 1 or some other technique which permits a change from deformation behaviour influenced by strain recovery microcracks to deformation of the *in situ* load-bearing structure will enable the effect of increasing reservoir stresses accompanying "drawdown" to be extrapolated with greater certainty.

It is acknowledged that much more work is required to examine whether the behaviour observed in these Rotliegendes sandstones is an important feature of the stress sensitivity behaviour of other sandstones. The aim of this paper has not been to invalidate core analysis permeability data conducted at low confining stresses. It should be possible by considering the issues raised here objectively to improve the application and appreciation of core data.

CONCLUSIONS

The behaviour of the mechanical properties of low permeability Rotliegendes sandstones due to changing stress conditions has been evaluated and compared with the stress sensitivity behaviour of the petrophysical properties of the same rocks. The following main conclusions can be drawn:

1) The development of the load-bearing structure of low permeability Rotliegendes sandstones with increasing confining stress is observed to be related to depositional facies and diagenesis. This confirms the observed relationship between the same two factors and permeability and electrical conductivity stress sensitivity. Examination of the mechanical properties stress sensitivity has the potential to be a useful aid in the "correction" of routine core data for the effects of stress sensitivity.

2) Evidence has been found which indicates that structural alteration due to stress relaxation effects has occurred which could adversely affect the quality of routine core analysis data determined at low confining stresses. The magnitude of the data may be in error and it is observed that relationships between properties which are dependent on the load-bearing structure do not materialise at low confining stresses. This indicates that the structure of the rock at low confining pressures is not representative of the *in situ* structure.

3) The persistent relationship between depositional facies and stress sensitivity may provide the means in suitable cases of overcoming the problems implicit in conclusion 2) above.

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REFERENCES

1. Mc Latchie, A.S., Hemstock, R.A. and Young, J.W., "The Effective Compressibility of Reservoir Rock and its Effects on Permeability", Pet Trans AIME, Vol 213, 1958, pp 386-388

2. Vairogs, J., Hearn, C.L., Dareing, D.W. and Rhoades, V.W., "Effect of Rock Stress on Gas Production From Low - Permeability Reservoirs", J. Petroleum Technology, September 1971, pp 1161-1167

3. Thomas, R.D. and Ward, D.C, "Effect of Overburden Pressure and Water Saturation on Gas Permeability of Tight Sandstone Cores", J. petroleum Technology, February 1972, pp 120-124

4. Luffel, D.L., Howard, W.E. and Hunt, E.R., "Relationships of Permeability, Porosity, and Overburden Stress Derived From an Extensive Core Analysis Data Base in the Travis Peak Formation", SPE 19008, Proc. SPE Joint Rocky Mountain Regional / Low Permeability Reservoirs Symposium and Exhibition, Denver Colorado, March 6-8 1989, pp 729-740

5. Kilmer, M.H., Morrow, N.R. and Pitman, J.K., "Pressure Sensitivity of Low Permeability Sandstones", J. Petroleum Science and Engineering, 1, 1987, pp 65-81

6. Dobrynin, V.M., "Effect of Overburden Pressure on Some Properties of Sandstones", SPE Journal, December 1962, pp 360-366

7. Wyble, D.O., "Effect of Applied Pressure on the Conductivity, Porosity and Permeability of Sandstones", Pet Trans AIME, Vol 213, 1958, pp 430-432

8. Jones, S.C., "Two - Point Determinations of Permeability and P.V. Vs. Net Confining Stress", SPE 15380, 61st Annual Technical Conference and Exhibition of the SPE, New Orleans, October 5-8 1986

9. Ostensen, R.W., "Microcrack Permeability in Tight Gas Sandstone", SPE Journal, December 1983, pp 919-927

10. Gangi, A.F., "Variation of Whole and Fractured Porous Rock Permeability With Confining Pressure", Int. J. Rock Mech. Min. Sci and Geomech. Abstr., 15, 1978, pp 249-257

11. Jennings, J.B., Carroll, H.B. and Raible, C.J., "The Relationship of Permeability to Confining Pressure in Low Permeability Rock", SPE / DOE 9870, 1981 SPE / DOE Low Permeability Symposium, Denver Colorado, May 27-29 1981, pp 391-394

12. Walsh, J.B., "Effect of Pore Pressure and Confining Pressure on Fracture Permeability", Intl. J. Rock Mechanics and Mining Sciences and Geomechanical Abstracts, October 1981, V18, pp 429

13. Fatt, I. and Davis, D.H., "Reduction in Permeability With Overburden Pressure", Pet Trans AIME, Vol 195, 1952, 329 pp

14. Soeder, D.J. and Randolph, P.L., "Porosity, Permeability and Pore Structure of the Tight Mesaverde Sandstone, Piceance Basin, Colorado", SPE Formation Evaluation, June 1987, pp 129-136

15. Brower, K.R. and Morrow, N.R., "Fluid Flow in Cracks as Related to Low Permeability Gas Sands", SPE / DOE 11623, 1983 SPE / DOE Symposium on Low Permeability, Denver Colorado, March 14-16 1983, pp 201-208

16. Jones, F.O. and Owens, W.W., "A Laboratory Study of Low-Permeability Gas Sands", J. petroleum Technology, September 1980, pp 1631-1640

17. Teufel, L.W., "Determination of In-Situ Stress From Anelastic Strain Recovery Measurements of Oriented Core", SPE/DOE 11649, Proc. 1983 SPE/DOE Symposium on Low Permeability, Denver, Colorado, 14-16 March 1983, pp 421-427

18. Kulander, B.R., Dean, S.L., and Ward, B.J.,Jr., "Fractured Core Analysis: Interpretation, Logging, and Use of Natural and Induced Fractures in Core", AAPG Methods in Exploration Series, No. 8, AAPG, Tulsa, 1990, ISBN 0--89181-658-5

19. Strickland, F.G., Feves, M.L., and Sorrells, D., "Microstructural Damage in Cotton Valley Formation Cores", SPE 8303, Presented at the 54th Annual Fall Technical Conference and Exhibition of the SPE, Las Vegas, Nevada, September 23-26, 1979

20. Jaeger, J.C. and Cook, N.G., "Fundamentals of Rock Mechanics", 3rd Edition, Chapman Hall, London, 1979, ISBN 0-412-22010-5

21. Gregory. A.R., "Fluid Saturation Effects on Dynamic Elastic Properties of Sedimentary Rocks", Geophysics, V41(5), October 1976, pp 895-921

22. Farquhar, R.A., "The Petro-Mechanical Characterisation of the Rotliegendes Sandstones", Submitted for the Degree of Ph.D. at Heriot-Watt University, Edinburgh, Scotland, 1993

23. Farquhar, R.A., Smart, B.D.G., Todd, A.C., Tompkins, D.E. and Tweedie, J.A., "Stress Sensitivity of Low Permeability Sandstones From the Rotliegendes Formation", SPE 26501, Poster Paper presented at the 58th Annual Technical Conference & Exhibition of the SPE, Houston, TX, 3-6 October, 1993

24. Senseny, P.E., "Laboratory Measurements of Mechanical Properties of Sandstones and Shales", SPE/DOE 11762, 1983 SPE/DOE Symp. on Low Permeability, Denver, Colorado, 14-16 March 1983, pp 431-433

25. Cleary, J.M., "Hydraulic Fracture Theory; Part 111.-Elastic Properties of Sandstone", Illinois State Geological Survey Circular 281, 1959

26. Wyllie, M.R.J., Gregory, A.R. and Gardner, L.W., "Elastic Wave Velocities in Heterogeneous and Porous Media", Geophysics, 21, 1956, pp 41-70

27. Wyllie, M.R.J., Gregory, A.R. and Gardner, L.W., "An Experimental Investigation of Factors Affecting Elastic Wave Velocities in Porous Media", Geophysics, 23, 1958, pp 459-493

28. Vernik, L. and Nur, A., "Petrophysical Classification of Siliclastics for Lithology and Porosity Prediction From Seismic Velocities", AAPG Bull., 76(9), September 1992, pp 1295-1309

29. Fjær, E., Holt, R.M., Horsrud, P., Raaen, A.M. and Risnes, R., "Petroleum Related Rock Mechanics", Developments in Petroleum Science 33, Elsevier, Amsterdam, 1992, ISBN 0-444-88913-2

30. Farquhar, R.A. and Tompkins. D.E., "Poroperm Evaluation in Relation to Applied Stress States For a Gas Reservoir", in Advances in Core Evaluation , Proc. 1st SCA European Core Analysis Symposium, London, 21-23 May, 1990, pp 239-268

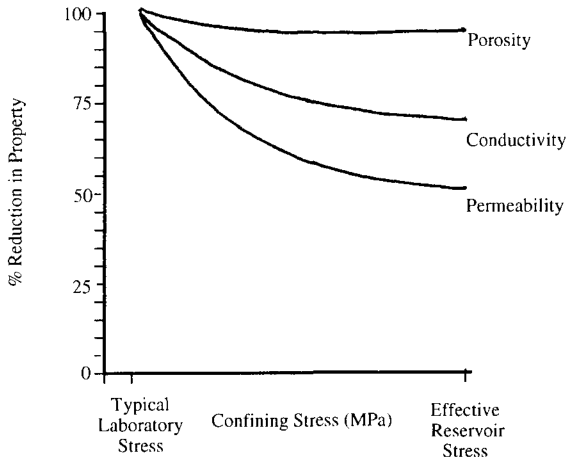

Figure 1 Classic stress sensitivity behaviour of porosity, electrical conductivity and permeability for sandstones between typical laboratory stress levels and reservoir stress levels

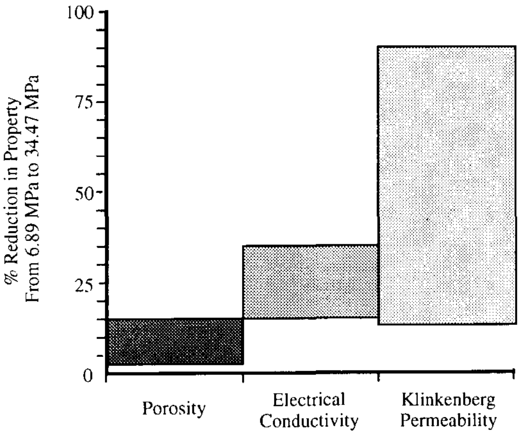

Figure 2 Range of stress sensitivity behaviour displayed by the Rotliegendes sandstones examined in this study

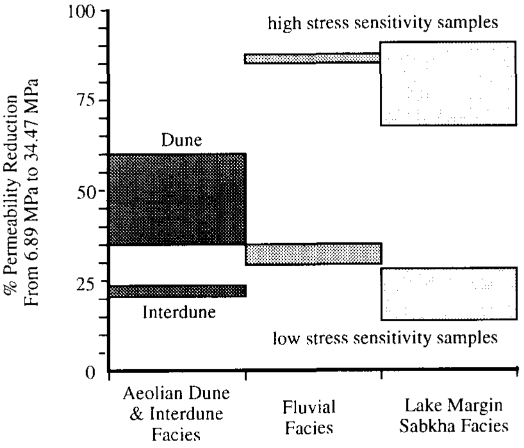

Figure 3 Facies dependent permeability stress sensitivity range for the Rotliegendes sandstones from this study showing high and low stress sensitivity groups. Note also that the stress sensitivity of the aeolian interdune sandstones is comparable with that for the lake margin sabkha sandstones deposited under identical conditions.

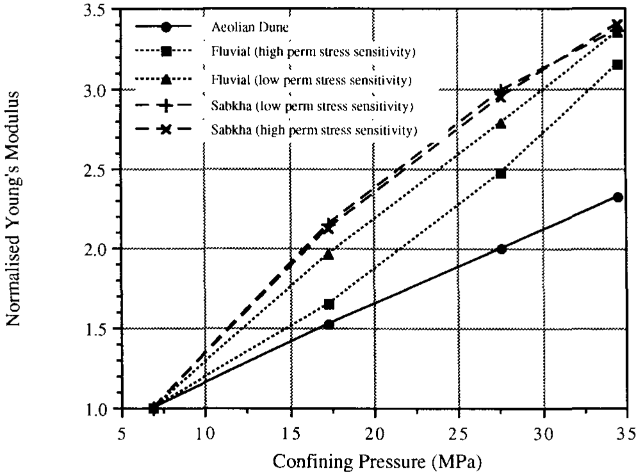

Figure 4 Young's modulus stress sensitivity between confining pressures 6.89 MPa and 34.47 MPa for the different permeability stress sensitivity/depositional facies groups

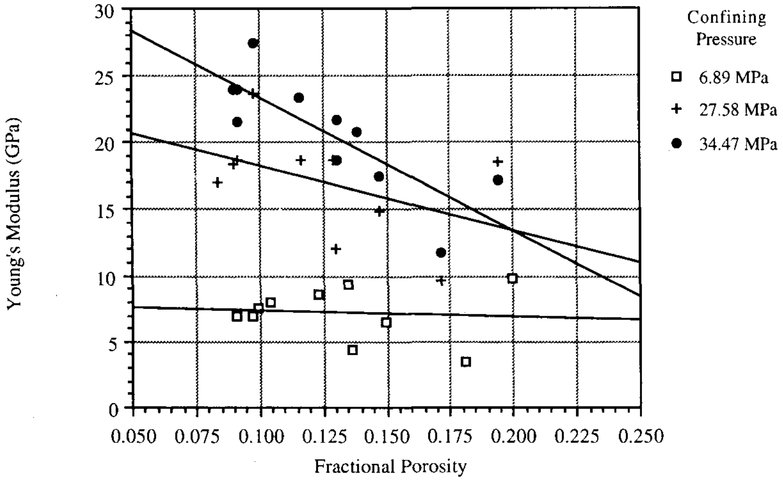

Figure 5 Development of porosity-Young's modulus relationship with increasing confining pressure. Note the failure of the properties to correlate at low confining pressure.

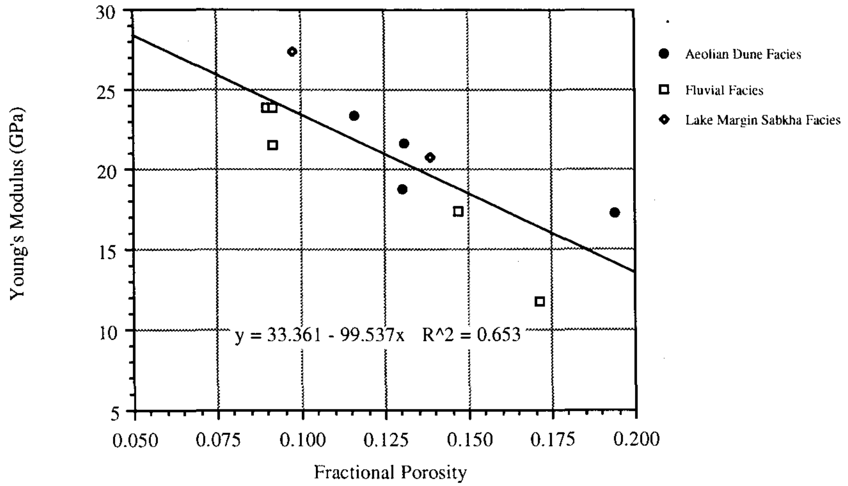

Figure 6 Facies distribution around the general porosity-Young's modulus relationship at a confining pressure of 34.47 MPa

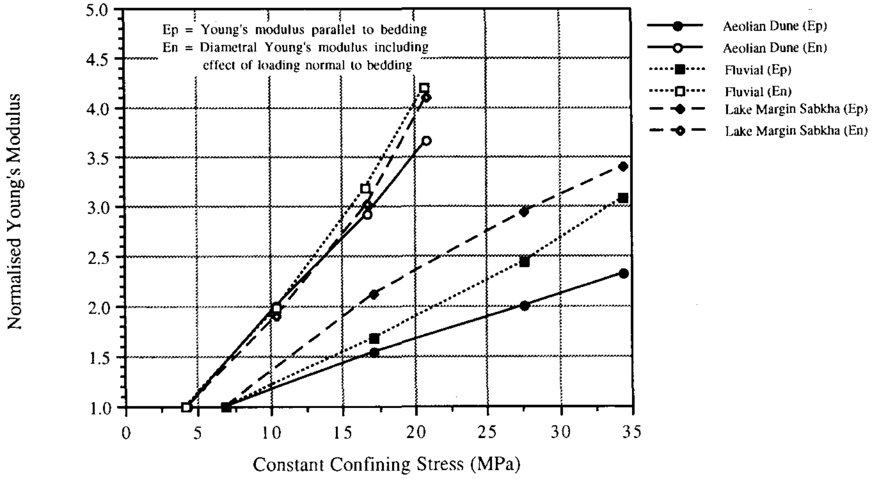

Figure 7 Transversely isotropic Young's modulus stress sensitivity. Note that although normalised with respect to different base conditions En is still more stress sensitive.

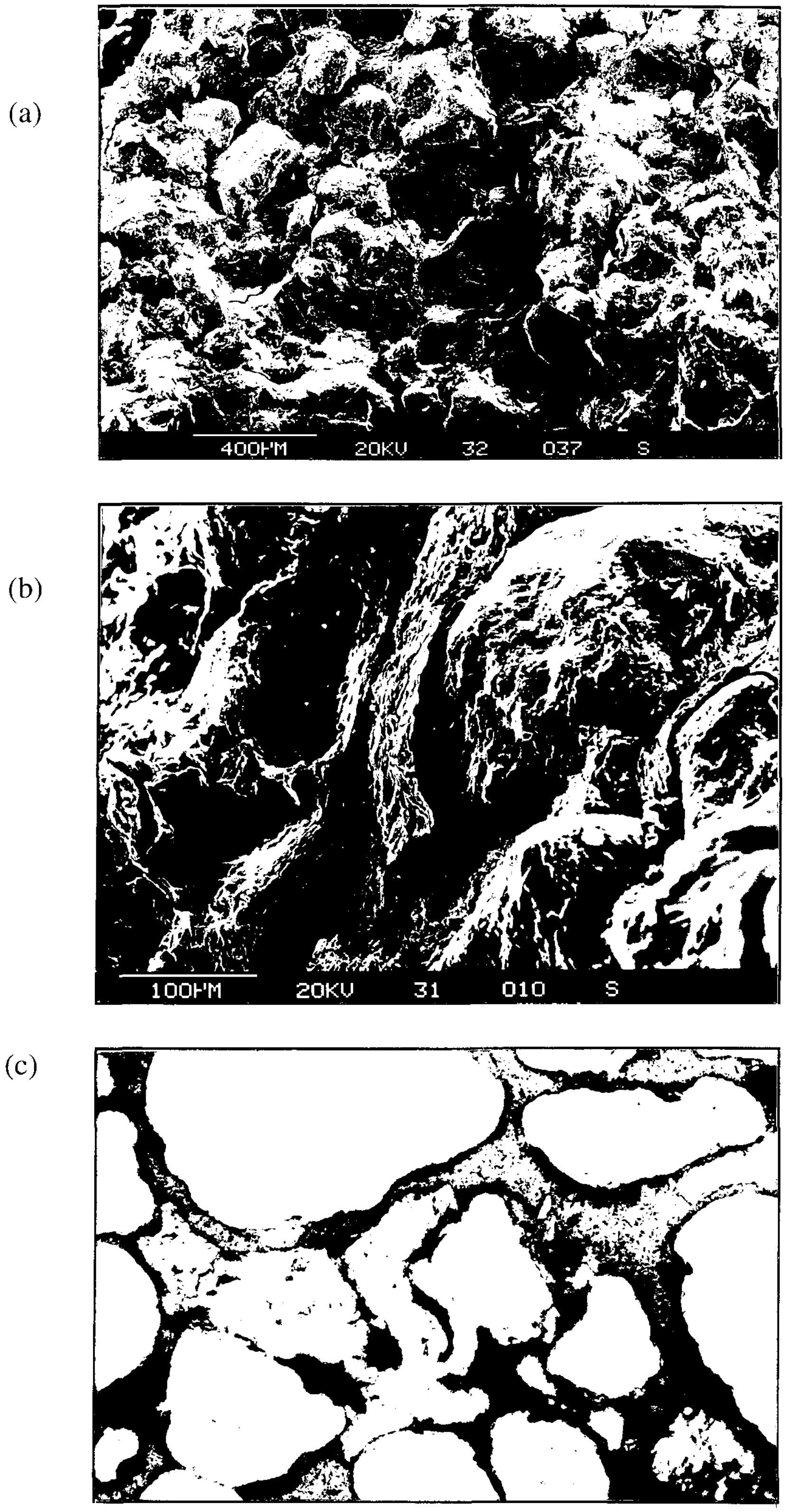

Figure 8 Microstructural deformation in the structure of Rotliegendes sandstone which are suspected of being related to microcrack genesis as a result strain relaxation: a) intergranular boundary cracks, b) parting between detrital quartz grains and detrital clay minerals & c) thin section which displays intergranular boundary cracks opening normal to the bedding