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# Effect of Reservoir Depletion and Pore Pressure Drawdown on In Situ Stress and Deformation in the Ekofisk Field, North Sea

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**ABSTRACT:** Knowledge of *in situ* stress and how stress changes with reservoir depletion and pore pressure drawdown is important in a multi-disciplinary approach to reservoir characterization, reservoir management, and enhanced oil recovery projects. Over 20 years of petroleum production from the Ekofisk field has resulted in a 21-24 MPa reduction in reservoir pore pressure. The effect of pore pressure drawdown on the minimum horizontal *in situ* stress in the Ekofisk field has been determined from shut-in pressure data of 32 hydraulic fractures. The effective stresses in the reservoir increase linearly with pore pressure drawdown, but at different rates. The ratio of the change in effective minimum horizontal stress to the change in effective vertical (overburden) stress is approximately 0.20. Laboratory experiments, which simulate the stress path followed by reservoir rock during the production history of the Ekofisk field, clearly indicate that shear failure has occurred during compaction of high porosity chalk as the shear stress increased with pore pressure drawdown. It is suggested that shear failure during primary production has increased fracture density and reduced matrix block dimensions, and has therefore maintained reservoir permeability, which may account for the continued good producibility of the Ekofisk field, in spite of compaction.

## 1 INTRODUCTION

*In situ* stress affects nearly all physical properties of rock and hence the measurement and interpretation of (1) geophysical data, (2) petrophysical properties, such as porosity and permeability, (3) rock strength and ductility, and (4) mechanisms of rock deformation and failure. In naturally fractured reservoirs the influence of stress on reservoir behavior is even more pronounced, particularly with respect to fluid flow through fractures. Accordingly, knowledge of *in situ* stress and how stress changes with reservoir depletion is important in a multi-disciplinary approach to reservoir characterization, reservoir management, and enhanced oil recovery projects.

A joint research program between Phillips Petroleum Company and Sandia National Laboratories is being conducted to study and understand the interrelationships between *in situ* stresses, natural fractures, and reservoir permeability in the Ekofisk field. The Ekofisk field is the largest of nine chalk reservoirs in the southern part of the Norwegian sector of the North Sea. Over 20 years of petroleum production has resulted in a 21-24 MPa reduction in reservoir pore pressure. The decline in pore pressure has led to an increase in the fraction of the overburden load that must be supported by the structurally weak chalk matrix, which in turn has undergone significant compaction resulting in over four meters of seafloor subsidence.

An important objective of this cooperative program is to determine the effect of production and pore pressure drawdown on the *in situ* stress state across the reservoir. As the pore pressure is reduced, the effective stresses in the reservoir will increase, but at different rates, depending upon the loading path and boundary conditions on the reservoir. The purpose of this paper is to summarize the results of measurements of the minimum horizontal *in situ* stress determined from closure stresses derived from shut-in pressure data of hydraulic fractures conducted in 32 wells in the Ekofisk field during the past 15 years. These stress results provide an understanding of the stress path followed by reservoir rock during the production history of the field. Laboratory experiments have been conducted on reservoir chalk to simulate the observed stress path at Ekofisk. Experimental results indicate that shear failure can occur during compaction of high porosity chalk as the pore pressure is drawn down. Shear failure during depletion can have a positive effect on producibility of the reservoir because it can increase fracture density and reduce matrix block dimensions, and thereby maintain reservoir permeability.

## 2 GENERAL DESCRIPTION OF EKOFISK FIELD

The Ekofisk field is an elliptical dome, elongate in a north-south direction. The reservoir consists of two fractured chalk intervals separated by a relatively impermeable layer of argillaceous, siliceous, and cherty chalk. The chalks are of Maastrichtian and Danian age. These chalks are draped over what may be a salt diapir, although salt has not been penetrated by any wells. The dome has an areal closure of 49 $km^2$ and an oil column of up to 305 m. Porosity ranges from 5-51%, but averages 32% in the Ekofisk Formation (Danian age) and 30% in the Tor Formation (Maastrichtian age) (Feazel et al, 1990). Despite the high porosities, matrix permeability is only about $1 \times 10^{-15}$ $m^2$ (1 md) because of small pore throat dimensions (Thomas et al, 1987). An extensive natural fracture system forms the primary conductive path for produced hydrocarbons and injected fluids in the field. Permeabilities inferred from the analysis of well tests are as high as $15 \times 10^{-14}$ $m^2$ (150 md) (Brown, 1987), which is at least two orders of magnitude greater than matrix permeabilities.

## 3 HYDRAULIC FRACTURE STRESS MEASUREMENTS

Magnitudes of the minimum horizontal stresses were determined from the closure stresses derived from shut-in pressure data after the initial cool down phase of hydraulic fracture stimulations. In this phase 28-55 $m^3$ of sea water are pumped into the well to breakdown the formation and then the well is shut-in before the main acid treatment. Fracture treatments were made in selected perforated zones in the Ekofisk Formation, Tor Formation, and simultaneously in both formations. The perforated zones were short, discontinuous intervals of less than 15 m, and the gross vertical height of all the perforated zones that were fractured ranged from 32 to 71 m. The pressure versus square-root-of-time method was used to determine the closure stress (Nolte and Smith, 1981).

There are many processes that affect the closure stress, particularly for large fracture treatments, including leakoff of fluid into the rock, *in situ* heterogeneities, partial fracture closure, fracture growth after shut-in, and curvature of the fracture. The error in determined values of the minimum horizontal stress is estimated to be 0.5-2.0 MPa.

## 4 IN SITU STRESS RESULTS

### 4.1 Effect of Pore Pressure Drawdown on Minimum Stress

Over 90 hydraulic fracture stimulations have been conducted in the Ekofisk field over its 20 year production history. Unfortunately, the procedures used in these stimulations and the quality of most of the pressure/time records are inadequate to estimate stress magnitudes. Stress measurements presented in this paper are from 32 wells that had good hydraulic fracture pressure/time records during the cool-down phase of the stimulation.

The effect of pore pressure drawdown on the total minimum *in situ* stress is shown in Figure 1. The data are separated into three groups based on well location with respect to position on the structural dome that forms the Ekofisk reservoir; crest, flank, and outer flank. Total minimum stress has decreased linearly with pore pressure drawdown. The change in minimum horizontal stress is about 80 percent of the net change in pore pressure.

In general, the change in total minimum horizontal stress with pore pressure drawdown is the same across the field. However, magnitudes of minimum horizontal stresses vary spatially across the field as a function of position on the structure. The lowest magnitudes of minimum stress are on the crest of the structure, and the highest magnitudes are on the outer north and south flanks. As the pore pressure was drawn down over the crestal area of the field from about 45 MPa in 1975 to 25 MPa in 1990, the minimum horizontal stresses decreased from about 51 MPa to 35 MPa, respectively. At present, in wells on the outer north and south flanks, which have pore pressures of about 25 MPa, the minimum horizontal stress ranges from 39 to 41 MPa.

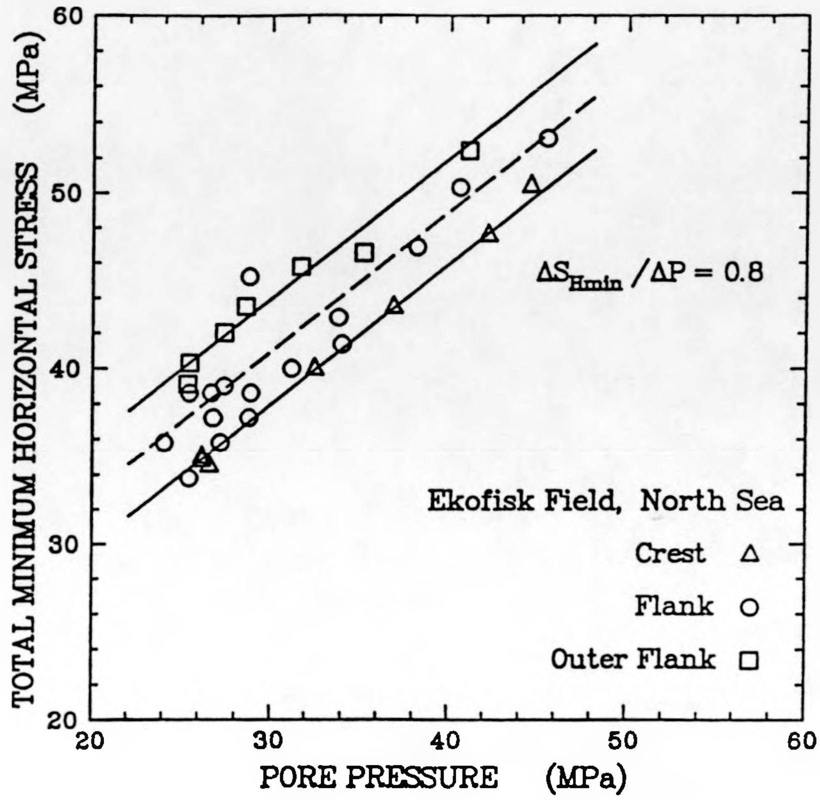


Figure 1. Plot of total minimum horizontal stress versus pore pressure in the Ekofisk field.

Initial minimum horizontal stresses before the start of production are estimated, from linear regression extrapolation, to have ranged from about 52 MPa on the crest to 58 MPa on the outer flanks of the structure. Total overburden stress ranged from 61 MPa on the crest to 65 MPa on the outer flanks.

### 4.2 Reservoir Stress Path During Production

Measurements of the total minimum horizontal stress as a function of pore pressure drawdown can be used to provide an understanding of the boundary conditions on the reservoir and the stress path followed by reservoir rock during the production history of the Ekofisk field. With pore pressure drawdown the effective stresses in the reservoir increase, but at different rates. Following Rice and Cleary (1976) effective stress is defined by

$$\sigma = S - \alpha P$$

where $\sigma$ is the effective stress, S is the total stress, P is the pore pressure, and $\alpha$ is a poroelastic constant. Laboratory poroelastic-deformation experiments on Ekofisk chalk have shown that $\alpha$ is unity for high porosity chalks (Teufel and Warpinski, 1990).

Figure 2 is a plot of effective minimum horizontal stress versus effective vertical stress during primary production from the Ekofisk field. For this plot the total vertical stress in the reservoir is assumed to be constant during the production history of the reservoir and equal to the total stress exerted by the weight of the overburden. Accordingly, an incremental reduction in pore pressure corresponds directly to an incremental increase in effective vertical stress of the same magnitude.

The ratio of effective minimum horizontal stress to effective overburden stress varies spatially across the field with the lowest ratios on the crest and the highest ratios on the outer flanks of the structure. In general, the incremental change in effective minimum horizontal stress with an incremental increase in effective overburden stress is nearly constant over the entire reservoir. Using a linear regression analysis the ratio of change in effective minimum horizontal stress to change in effective overburden stress, K, is approximately 0.20. Hence, with pore pressure drawdown the effective minimum horizontal stress has increased at a much slower rate than the effective vertical stress.

The stress path measured in the Ekofisk reservoir during pore pressure drawdown clearly indicates that the boundary condition on the reservoir is not a strict stress boundary condition, where an incremental increase in effective overburden stress is matched by an identical increase in effective horizontal stress (i.e., K equals 1.0). Rather, the boundary condition is a displacement boundary condition or a combined displacement/stress boundary condition in which an incremental reduction in pore pressure produces a greater incremental increase in effective overburden stress than in effective horizontal stress (i.e., K is less than 1.0).

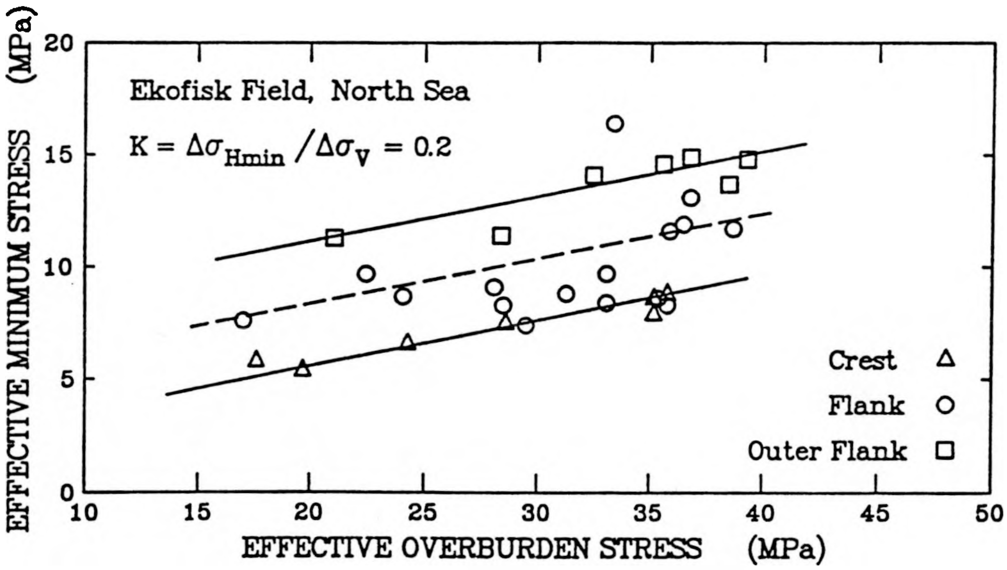


Figure 2. Diagram of effective minimum horizontal stress versus effective overburden (vertical) stress in the Ekofisk field. Change in effective stress is caused by pore pressure drawdown.

## 5 LABORATORY STRESS PATH EXPERIMENTS

Previous work to quantify compaction deformation and consequent seafloor subsidence resulting from pore pressure reduction has assumed that pore collapse is the dominant process responsible for chalk deformation, and the strain in the reservoir is essentially uniaxial (i.e., all strain is vertical and horizontal strain is zero). To simulate this deformation path in the laboratory uniaxial strain, compression tests were conducted on cylindrical specimens in which the increase in effective overburden stress accompanying production is achieved by reducing the pore pressure while maintaining the total axial stress constant and by increasing the effective confining pressure as required to maintain zero radial strain. The primary objective of these tests is to obtain axial (vertical) strain as a function of effective axial (overburden) stress. These tests also provide a quantitative measure of $K_0$, the ratio of effective horizontal stress to effective overburden stress, required to maintain the uniaxial strain condition of zero radial strain. $K_0$ for a given chalk is usually considered to be a material property.

The compaction behavior of Ekofisk chalk under uniaxial strain conditions has been extensively studied in the laboratory (Johnson et al, 1989; Rhett and Teufel, 1991; and others). Uniaxial strain tests of Ekofisk reservoir chalks resulted in measured $K_0$ values ranging from about 0.4 to 0.5. These values are much higher than the K value of 0.2 indicated by *in situ* stress measurements in the Ekofisk reservoir.

To examine the deformation behavior of Ekofisk chalk under stress paths that are more representative of those observed in the field, a series of compression tests were conducted in which the pore pressure and confining stress were controlled to give K values of 0.17, 0.25, and 0.33. In these tests the axial stress was held constant at 62.1 MPa, initial confining stress was 55.2 MPa, and the pore pressure was 48.3 MPa. Pore pressure was reduced at a constant rate of 5.5 MPa/hour and confining pressure was adjusted to maintain the pre-determined K value. Radial strain was not controlled in these tests, but it was measured, along with axial strain, pore pressure, confining stress, and axial stress.

The most significant result of these stress-path tests is that they all resulted in shear failure of the specimen. Figure 3 is a diagram of shear stress versus normal stress showing Mohr circles representing the effective stress states when shear failure occurred for different stress-path tests on 39% porosity chalk specimens. As K was increased from 0.17 to 0.25 to 0.33, shear failure occurred when pore pressures were reduced by progressively larger increments of 10.7 MPa, 12.6 MPa, and 16.5 MPa, respectively, from the initial reservoir pressure of 48.3 MPa.

The different stress-path tests provide consistent results with regard to the definition of a Mohr-Coulomb failure envelope. Over a limited range of shear ($\tau$) and normal ($\sigma_N$) stresses the failure envelope is linear and defined by

$$\tau = 0.23\ \sigma_N + 4.1\ \text{MPa}$$

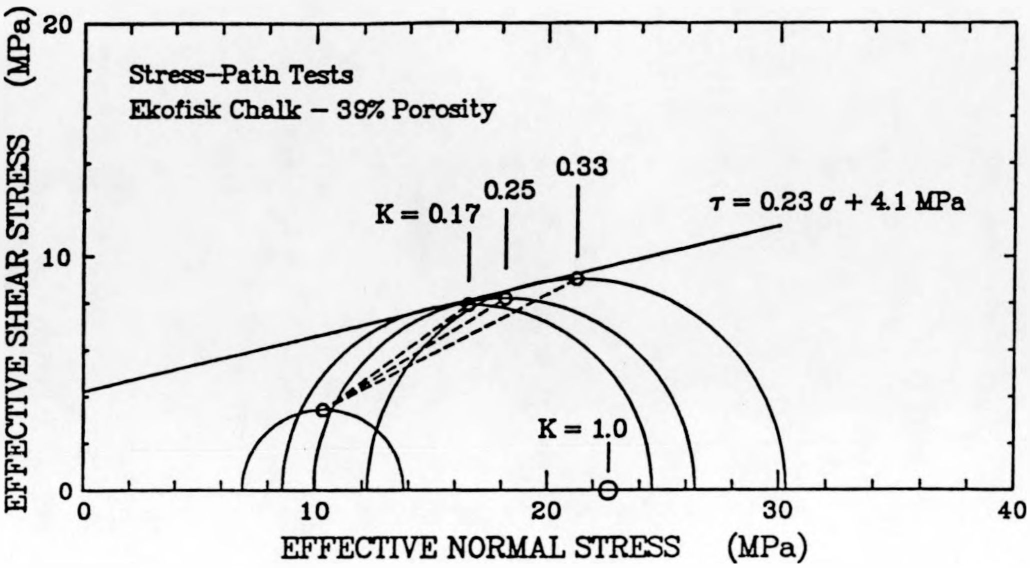


Figure 3. Plot of shear stress versus normal stress showing a Mohr-Coulomb failure envelope constructed from stress-path tests on 39% porosity chalk.

A stress path of K equal to 1.0 (hydrostatic loading) was also conducted. The onset of yield (pore collapse) is shown on the normal stress axis of Figure 3.

Pore collapse and pore volume reduction were occurring in the chalk specimens for each of the stress-path tests which resulted in shear failure. Almost all of the compaction occurred in the axial direction; there was very little radial strain prior to shear failure (i.e., the deformation path was essentially uniaxial strain), which suggests that this chalk was not particularly sensitive to variations in lateral stress.

Failure envelopes with end caps constructed from the previously described stress-path tests on 39% porosity chalk and from similar stress-path tests conducted on 34% porosity chalk are shown in Figure 4. The lower porosity chalk is stronger. The end caps correspond to yield in confined compression and indicate the departure from linear elastic-strain behavior and the onset of non-recoverable, plastic strain in the rock. The intersection of the end cap with the normal axis is the stress at which yield occurs under hydrostatic stress. The shape of the end cap and its intersection with the brittle failure envelope are only approximate. The intersection of the end cap with the brittle failure envelope approximates the transition between strain softening (i.e., dilatant behavior) and strain hardening (i.e., pore collapse compaction) behavior.

Pore collapse compaction of a given chalk can be viewed as an evolving process. As chalk compacts, there is a progressive decrease in porosity and a corresponding increase in rock strength that can be represented as an expansion of the failure surface. The onset of pore collapse compaction in chalk does not preclude the occurrence of brittle shear failure because pore collapse compaction tends to occur initially in discrete domains of weakest chalk that are volumetrically small relative to the remaining, undisturbed volume of chalk, which largely retains its original cohesion and behaves as a brittle material (Rhett and Teufel, 1991). Consequently, chalk undergoing pore collapse compaction may still fail by shear as brittle materials even as pore collapse compaction proceeds. The stress path that chalk follows during deformation will determine if the material will ultimately fail by shear.

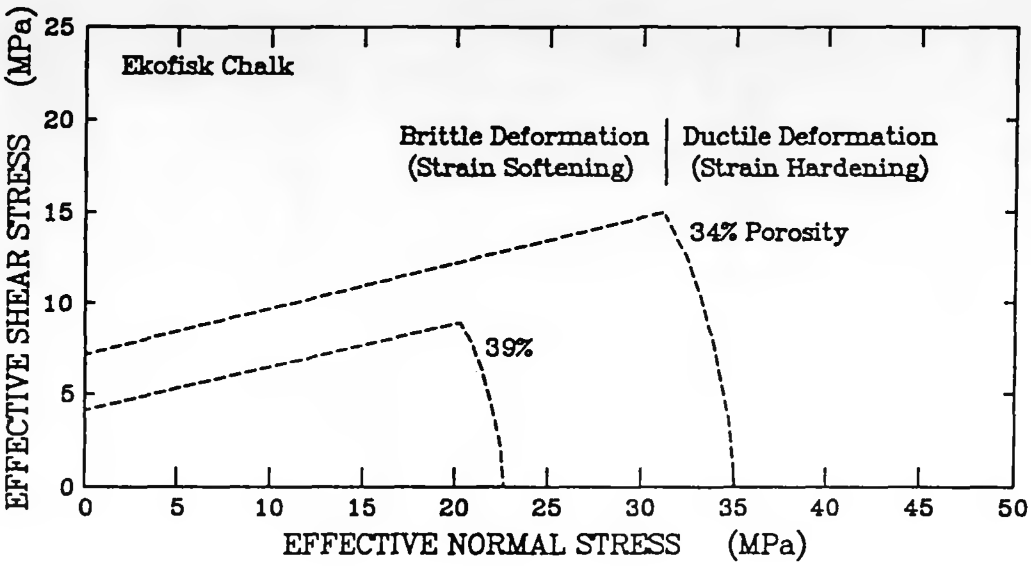


Figure 4. Plot of effective shear stress versus effective normal stress showing failure envelopes with end caps for 39% and 34% porosity chalk. Failure envelopes are derived from stress-path tests.

## 6 DISCUSSION

Measurements of the minimum horizontal stress as a function of pore pressure drawdown have provided an improved understanding of the boundary conditions and stress paths followed by reservoir rock during the production history of the Ekofisk field. The K value measured in the reservoir is approximately 0.2 and is much smaller than the $K_0$ of about 0.5 measured in uniaxial strain tests of reservoir chalk. The consequence of the lower K value is that the magnitudes of the deviatoric or shear stresses in the reservoir have increased more rapidly during pore pressure drawdown than they would have for the larger $K_0$ values.

Figure 5 is a shear stress versus normal stress diagram showing failure envelopes with end caps for 39% and 34% porosity Ekofisk chalk and a series of Mohr circles illustrating how the effective stress state on the flank of the Ekofisk reservoir has evolved along a stress path of 0.2 during pore pressure drawdown. The first Mohr circle represents the initial effective stress state prior to production when the pore pressure was 48.1 MPa, and the last Mohr circle represents the effective stress state in 1990 when the pore pressure was 24 MPa. The deviatoric or shear stress is more than sufficient to cause shear failure of chalk with porosities of 34% or more. Accordingly, it is likely that in the Ekofisk reservoir shear failure has occurred in high porosity chalks as the *in situ* shear stress increased with pore pressure drawdown.

It is commonly assumed that permeability and productivity of a reservoir will decrease with reservoir compaction and porosity reduction. However, shear failure during depletion can have a positive effect on production because it can increase fracture density and reduce matrix block dimensions, thereby maintaining reservoir permeability. Pore pressure increases associated with water injection may lead to additional shear failure (Teufel and Farrell, 1990; Rhett and Teufel, 1991), which would further increase fracture density and fracture surface area, and therefore improve imbibition rates and waterflood sweep efficiency. Accordingly, the shear failure process may account for the continued good producibility of the Ekofisk field, in spite of compaction, as well as the very good performance of the Ekofisk waterflood. The influence of shear failure on reservoir compaction and subsidence is currently being evaluated.

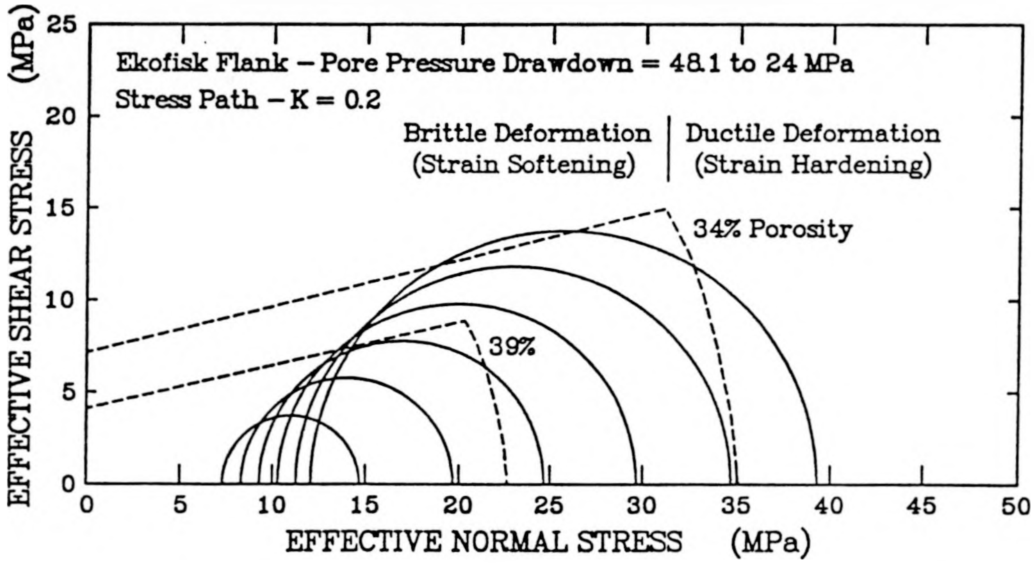


Figure 5. Plot of effective shear stress versus effective normal stress showing failure envelopes with end caps for 39% and 34% porosity chalk and a series of Mohr circles representing the stress path in the Ekofisk reservoir during pore pressure drawdown.

## 7 CONCLUSIONS

During reservoir depletion the effective stresses in the Ekofisk field have increased linearly with pore pressure drawdown, but at different rates. The ratio of the change in effective minimum horizontal stress to change in effective vertical stress, K, is about 0.20. Laboratory experiments, which simulate the stress path followed by reservoir rock, suggest that shear stresses have increased sufficiently during primary production of the reservoir to cause both compaction and shear failure of high porosity chalk.

## 8 ACKNOWLEDGMENTS

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