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# MEASUREMENT OF PORE COMPRESSIBILITY CHARACTERISTICS IN ROCK EXHIBITING "PORE COLLAPSE" AND VOLUMETRIC CREEP

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## ABSTRACT

This paper presents data showing the importance of creep measurements when determining the compressibility characteristics of reservoir rocks that undergo volumetric yield (often referred to as "pore collapse"). Rocks exhibiting pore collapse under hydrostatic loading are characterized by volumetric strains that are predominantly elastic prior to yield and plastic afterwards. Limestones, chalks, and diatomite reservoir rocks have been shown to exhibit pore collapse and high degrees of volumetric creep. Reservoir calculations involving pore compressibility, especially reservoir compaction and subsidence calculations, are often very sensitive to the stress level at which pore collapse is assumed to initiate. This is because there is usually an order of magnitude difference in the compressibility between the elastic (pre-yield) and inelastic (post-yield) regions.

It has been shown by others that materials that exhibit volumetric creep under constant stress can be characterized by a family of compaction curves (porosity or void ratio vs. confining stress) corresponding to different loading rates, from laboratory test rates to reservoir depletion rates. Standard loading rates used in laboratory pore compressibility tests (typically 500 psi/hr) do not allow time for creep to occur and can predict pore collapse stresses that are up to several thousand psi too high, depending on the creep rate of the material and the rate at which the reservoir is depleted. If this overestimated collapse stress is a significant portion of the estimated total pressure drop in the reservoir, pore volume change calculations will result in substantial underpredictions of reservoir compaction.

Test results are presented for two reservoir materials exhibiting pore collapse and substantial volumetric creep behavior. A method for measuring creep is discussed, and it is shown that the creep is generally linear on a log(time) plot. A method is proposed for estimating the correct or "field" compaction curve based on extrapolation of the laboratory data to reservoir depletion rates. Examples are given that illustrate the degree to which reservoir compaction is underestimated using standard, non-creep-corrected laboratory compressibility data.

## INTRODUCTION

Pressure depletion of oil and gas reservoirs causes an increase in the reservoir rock effective stress and consequently a decrease in pore volume, or compaction. In some notable instances reservoir compaction has resulted in substantial operating expenses due to land subsidence, loss of offshore platform air gap, and well casing damage (Mayuga & Allen 1969, Martin & Serdengecti 1984, Yudovich, Chin & Morgan 1989, Sulak & Danielsen 1989). Accurate estimates of reservoir compaction require (among other things) representative laboratory test data. Factors which have been cited in the literature as having measurable effects on the laboratory compaction curve are loading rate (Smits *et al.* 1988, Smits & de Waal 1988, Thompson & Schatz 1986, Johnson *et al.* 1988, Ruddy *et al.* 1989) pore fluid chemistry (Newman 1983, Smits *et al.* 1988), temperature (Schutjens 1991), sample disturbance, and small samples not being representative of inhomogeneities in the larger rock mass (Thompson & Schatz 1986). This paper is concerned with the effects of laboratory loading rates on estimates of reservoir compaction for rocks that exhibit pore collapse and significant volumetric creep at constant effective stress. Hydrostatic compaction tests on two reservoir rocks, a diatomite and a carbonate, are presented which illustrate the effects of pore pressure dissipation during rapid loading and time-dependent volume change at constant effective stress.

## COMPACTION BEHAVIOR OF ROCKS

Reservoir compaction is usually estimated on the basis of laboratory compaction tests which measure the change in pore volume with effective stress. In situ stress conditions within a depleting, homogeneous reservoir are usually assumed to be uniaxial (no lateral strain), and uniaxial compaction tests are generally recommended (Smits *et al.* 1988, Teeuw 1971). Unfortunately, most commercial laboratories that perform pore volume compressibility tests on reservoir rocks are limited to hydrostatic compaction tests. This is not a major concern, however, because with an appropriate constitutive relation for the rock material (for instance a cap-type, elastic, work-hardening plastic model), the equivalent uniaxial compaction curve can be inferred from the hydrostatic test curve (Atkinson & Bransby 1978). As a consequence of the cap-type model, simple assumptions of linear elasticity are not valid for calculating equivalent uniaxial behavior from hydrostatic test data for stress ranges that cause volumetric yield or pore collapse (Johnson & Rhett 1986, Smits *et al.* 1988).

The volume change behavior of porous reservoir rocks subjected to triaxial stress states can usually be described by a cap-type yield surface as shown in Figure 1a. In the figure, the mean effective stress, p, is the average of the three principal stresses

$$p = (\sigma_1 + \sigma_2 + \sigma_3)/3 \qquad (1)$$

and the deviatoric (shear) stress, q, is

$$q = (\sigma_1 - \sigma_3) \qquad (2)$$

which is equivalent to the axial stress minus the radial stress. A hydrostatic stress condition has zero deviatoric stress.

The yield surface represents the transition from elastic to inelastic deformation as is shown in a plot of void ratio, e, vs. log of effective mean stress (e-log(p) plot) in Figure 1b. Void ratio is defined as the ratio of void (pore) volume to solid (grain) volume.

$$e = V_{voids}/V_{solids} \tag{3}$$

Void ratio is related to porosity, $\phi$, by

$$e = \phi/(1-\phi) \tag{4}$$

This soil mechanics plotting convention is useful because most geologic materials tend to exhibit a bilinear behavior on such a plot, with a distinct slope change at the yield point. The same is generally true for rocks; however, some rocks (especially carbonates) show a much less distinct slope change due to local inhomogeneities in cement and/or strength. These materials may exhibit a gradual transition from the elastic to fully inelastic state due to successive yielding on a microscopic scale. The load-unload loop in Figure 1b demonstrates that void ratio is the hardening parameter (i.e., the yield surface grows as the material compacts to lower void ratios). It is a consequence of this type of model that the hydrostatic and uniaxial compaction curves are parallel on the e-log(p) plot as is demonstrated by the two loading paths in Figure 1b.

Loading underneath the yield surface is usually assumed to be elastic, whereas inelastic deformations and hardening of the material commence once the yield surface has been reached. The onset of inelastic volumetric strains, which is marked by reaching the cap portion of the yield surface, is often referred to as initiation of pore collapse. The term pore collapse is used because the pore compressibility of many rocks increases substantially (e.g. an order of magnitude) as they yield volumetrically.

The yield point or the point of onset of pore collapse may be qualitatively referred to as the "preconsolidation" stress. When the pore collapse stress exceeds the in situ stress, the rock is considered preconsolidated. The preconsolidation effect may come about as a result of a variety of causes such as erosion, cementation, creep, tectonics and pore pressure changes.

## TIME-DEPENDENT VOLUME CHANGE BEHAVIOR

Time-dependent volume change behavior of geologic materials in response to an increase in stress occurs 1) as a result of pore pressure dissipation during a transient consolidation phase and 2) by volumetric creep (which occurs both during consolidation and at constant effective stress after excess pore pressures have dissipated). The former may occur slowly or very rapidly depending on the permeability and compressibility of the material. One dimensional consolidation theory which quantitatively describes this time-dependent flow of water from a compressible porous material is described by Terzaghi (1943).

Volumetric creep occurs in some materials and not in others and is a complex function of stress level, temperature, and pore fluid makeup. It has been observed by numerous researchers (Chase & Dietrich 1988, Ruddy *et al.* 1989, Thompson & Schatz 1986) that reservoir rocks creep. Some have noted that the creep strains reach a limiting value after 10 to 100 days (Johnson & Rhett 1986, Thompson & Schatz 1986) while others have observed continuing creep for an indefinite time period (Ruddy *et al*. 1989, de Waal & Smits 1988). Practically speaking, volumetric creep cannot proceed beyond the point of zero porosity. In general, most laboratory observed creep decays logarithmically with time and becomes increasingly difficult to measure at large times as volume changes become too small to resolve.

## PRECONSOLIDATION EFFECT OF LOADING RATE

Time-dependent volume change behavior implies that rocks may exhibit different compaction curves if tested at different loading rates. This has been acknowledged by a number of previous investigators. For example, Martin and Serdengecti (1984) refer to the preconsolidation effect of loading rate which they observed in compaction tests performed on sand packs. De Waal and Smits (1988) attribute the apparent preconsolidated behavior of several subsiding oil and gas fields to the effect of accelerating the loading rate from one of geologic scale to one of normal oil field depletion rate, which causes a transition from one loading curve to another.

The phenomenon, which is illustrated in Figure 2, is usually associated with rocks which exhibit volumetric creep. Bjerrum (1973) observed that the compaction curves for a soil exhibiting volumetric creep would be a function of the laboratory loading rate or the length of time each load increment was held before the next was applied. He postulated a series of parallel compaction curves on a plot of void ratio vs. log effective vertical stress, with each curve associated with a unique loading rate.

## IMPLICATIONS TO LABORATORY TESTING

The preconsolidation effect of changing loading rates on materials that creep has obvious implications to laboratory test procedures and results. Laboratory tests conducted at loading rates much faster than the field depletion rate (typically 250 to 1000 psi/hr in the laboratory vs. 0.01 psi/hr or less in the field) will exhibit preconsolidation due to the difference in loading rates. Depending on the creep rate, the apparent preconsolidation stress due to the laboratory testing rate may be substantial with respect to the total pressure drawdown over the life of the reservoir. Estimates of compaction made on the basis of uncorrected laboratory data will assume that too much of the stress change in the reservoir will occur elastically and too little stress change will occur inelastically. Hence, estimates of compaction based on uncorrected laboratory data could be significantly too low. The need for correcting the laboratory data to account for the rapid laboratory loading rate has been pointed out by Johnson and Rhett (1986), Ruddy *et al*. (1989) and Smits *et al*. (1988).

## LABORATORY COMPACTION/CREEP TESTS

The following discussion describes the results of several laboratory compaction tests performed on two reservoir rocks which exhibit both pore collapse and significant volumetric creep within reservoir stress ranges. The rocks are 1) a diatomite, which is a high porosity (>50%), fine grained rock composed mainly of the opaline silica skeletal debris of single-celled aquatic plants (diatoms) mixed with subordinate clay and 2) a carbonate reservoir rock of moderate (mainly moldic) porosity (>20%) with patchy dolitimization.

The compaction experiments were performed with a special coreholder that permitted independent control of axial and radial confining pressures. The equipment had a maximum operating pressure of 10,000 psi at room temperature. This "biaxial cell" can accommodate core plugs with dimensions of 3.81 cm in diameter and lengths of 3 to 10 cm. Plugs were isolated from the radial confining fluid by a 0.64 cm thick 90 durometer viton® rubber sleeve.

The axial strain was monitored with a linear variable differential transducer. For uniaxial compaction tests the axial pressure could be adjusted to maintain zero radial strain. However, for the tests reported in this paper, all tests were performed in the hydrostatic mode.

The change in sample pore volume was determined by monitoring the volume of fluid produced to a 25 ml flask being weighed on a data-logging balance. During compaction experiments, there was no externally applied pore pressure. Both ends of the core plug drained to the balance. Once a stress state had been achieved, the liquid permeability could be determined by measuring the pressure drop across the sample and the fluid flow-rate produced to the balance.

To reduce the correction required for evaporation of pore fluids from the flask on the balance, tetradecane was used as the core plug pore fluid and the working fluid of the compaction apparatus. The measured rate of tetradecane evaporation from the flask was 0.0011 ml per day, which is insignificant for compaction experiments. However, when monitoring long term creep the evaporation correction can represent a significant correction to the volumetric strain rate.

The compaction equipment was controlled and monitored by a computer/data logger system. The compaction equipment was such that the rate of confining stress applied, but not the rate of strain, could be controlled. For the experimental data cited here, the hydrostatic pressure was increased stepwise in increments of 10 or 100 psi. The pressure increase would occur within the first minute of the pressure step. For example, a 1000 psi/hr ramp would consist of a 100 psi hydrostatic pressure increase during the first minute of every six minutes, whereas a 10 psi/hr ramp would be a 10 psi increase during the first minute of every hour.

Prior to compaction, the diatomite and carbonate core plugs were saturated and flushed with synthetic formation brine. The plugs were then flushed with tetradecane to displace any oil and leave a residual water saturation.

The presence of residual water is shown to be important by both Newman (1983) and Smits *et al.* (1988). Smits *et al.* (1988) report that the presence of chalkified pore water in carbonate rocks results in a compressibility before and after pore collapse of twice that of air- or oil-saturated samples. At the end of the compaction tests the samples were Dean-Stark extracted to determine final pore volume and water saturation. The Boyle's law technique was used to measure grain volumes to calculate porosity and void ratio.

## CORRECTION OF LABORATORY DATA FOR FIELD PREDICTIONS

Most reservoir rock is cemented to some degree and will exhibit preconsolidation with respect to the in situ effective stress. Consequently, it is important to accurately determine the yield point to differentiate between the portion of pore pressure decline that will cause elastic volume changes and that which will cause inelastic volume changes. Figure 3 illustrates the point for a diatomite reservoir rock. The test data shown are from a hydrostatic compaction test in which the loading rate was varied from 1000 psi/hr to 100 and 10 psi/hr.

The vertical separation between the e-log(p) curves for the three loading rates indicates that the void ratio change is 0.05 per log cycle loading rate. Assuming that the same mechanism operates in the field and that the creep decays logarithmically with time, a correction from the laboratory loading rate to the "field" loading rate is about five log cycles (1000 psi/hr vs. 0.01 psi/hr). This correction or shift of the compaction curve results in a change in the estimate of the yield point of about 250 psi (400 psi versus 650 psi).

A constant-effective-stress creep test was also performed at an effective mean stress of 1500 psi in which the sample was allowed to creep for 10 days before loading was resumed. The volumetric creep exhibits a linear void ratio vs. log(time) relationship after about 0.1 day as can be seen in Figure 4. We have found this to be the case for the twenty diatomite samples we have studied to date. On several of these samples, the volumetric creep was monitored for 30 days with no detectable departure from a linear e vs. log(time) relationship. The void ratio change of about 0.05 per log cycle time shown in Figure 4 is the same magnitude as was measured from the vertical separation in the different loading rate e-log(p) curves in Figure 3. This implies that a similar compaction curve correction could be made on the basis of a constant-stress creep test.

Constant stress creep tests can be performed at one or two stress levels on the inelastic portion of the compaction curve to evaluate the volumetric creep behavior of the material. If measurable creep occurs, sufficient data should be acquired to allow an estimate of the shift of the compaction curve from laboratory to field loading rates. Usually about 10 days of creep will account for more than half of the effect of the approximately 5 log cycles (rate or approximately time) variation between lab and field curves.

## IMPLICATIONS TO COMPACTION ESTIMATES

The following examples illustrate the impact of using uncorrected laboratory data to make reservoir compaction estimates. Consider a hypothetical comparison of compaction estimates which, for the convenience of directly using the data in Figure 3, assumes that reservoir stress changes during depletion are hydrostatic and that the total vertical stress remains constant. The reservoir thickness (h) is assumed to be 200 ft, the in situ mean stress is 350 psi (point A), and the initial e ($e_o$) is 1.9. Hence the reservoir is actually only about 50 psi preconsolidated with respect to the "field" rate compaction curve (this could be due to creep over geologic time and/or cementation). Further, it is assumed that the mean stress change due to depletion is 350 psi, which increases the mean stress to 700 psi (point B on 1000 psi/hr curve and point C on the 0.01 psi/hr curve). For this case, compaction ($\Delta h$) is calculated as

$$\Delta h = h(\Delta e)/(1+e_o)) = 200(\Delta e)/2.9 \qquad (5)$$

Use of the uncorrected laboratory compaction curve measured at 1000 psi/hr would result in a prediction of 4 ft compaction, while use of the curve corrected to the field loading rate would result in a predicted compaction of 20 ft.

A similar conclusion can be found in the case of the data for the carbonate reservoir rock shown in Figure 5. Based on the results of the variable loading rate test, the separation between the 1000 psi/hr and 10 psi/hr curves is about 0.0022 void ratio (0.0011 per log cycle). Assuming that creep is linear with log time, the estimated separation between the laboratory (1000 psi/hr) and "field" compaction curves is approximately (5 log cycles)x(0.0011 void ratio/log cycle loading rate) = 0.0055 void ratio. Applying this correction to the laboratory compaction curve lowers the estimate of the yield stress by about 1300 psi (difference between points B and A in Figure 5), which could be a significant portion of the reservoir pressure drop.

## LABORATORY LOADING RATES AND PORE PRESSURE DISSIPATION

While this paper deals with the effects of volumetric creep on laboratory data, incomplete pore pressure dissipation during a compaction test can produce a similar effect. The following discussion illustrates that any such complications can be minimized by judicious choice of laboratory loading rates.

The time required for pore fluid to flow out of a sample following a single small step increase in total confining pressure, $\Delta p$, is a function of the compressibility and permeability of the material and the pore fluid viscosity (Lambe & Whitman, 1969). The time required for about 99 percent pore pressure dissipation in a cylindrical sample of length, L, with drainage at both ends can be expressed as

$$t_{99} = \pi(L/2)^2/c_v \qquad (6)$$

where $c_V$ = coefficient of consolidation = $k/m\mu$,

$k$ = absolute permeability,

$m$ = coefficient of volume change = $(\Delta e/\Delta p)/(1+e_o)$,

$\mu$ = absolute viscosity, and

$e_o$ = initial void ratio.

Reservoir rocks usually have sufficiently low compressibility and high permeability as to allow pore pressures generated during compaction tests to dissipate rapidly (in a few minutes or less). Not all reservoir rocks fall into this category, however, and for those rocks precautions are necessary to ensure that testing rates are slow enough to allow time for pore pressures to dissipate. This is especially true of reservoir rocks which derive most of their bulk permeability from flow through fine fractures. A permeability measured from a flow-through type test may be dominated by a few fractures; whereas, the permeability which controls the expulsion of pore fluid due to the application of an increment in confining stress may be dominated by matrix flow.

A good example of the above is the diatomite rock tested in this study. The permeability back-calculated from the time rate of volume flow following a increment in confining stress from 4250 to 4500 psi was 0.003 md, while the permeability measured using a flow-through test on the same sample at the end of the pressure step was 0.05 md, an order of magnitude higher. Based on the flow-through permeability, one would estimate that the next load increment could be applied in about 10 minutes without test results being influenced by incomplete consolidation. In actuality, the time interval between loading increments should be approximately two hours. Hence, it is advisable on low permeability and/or high compressibility reservoir rock to analyze the time rate of volume flow from samples during selected stages of the compaction test to insure that full pore pressure dissipation is being achieved. The implications of this effect to the test results shown in Figure 3 are discussed below.

## Constant Rate-of-Loading Compaction Tests

Instead of applying load incrementally, many tests are conducted with a constant loading rate. In this case the effects of incomplete pore pressure dissipation are more important in the initial part of the test. Aboshi, *et al.* (1970) present the solution for consolidation of a sample subjected to a constant rate of loading (which can be used to approximate the case of frequent small stepwise increases in total confining stress). Equation 6 above dealt with the time required for 99 percent pore pressure dissipation for a single change in confining pressure. According to Aboshi, *et al.*, approximately 90 percent of the ultimate volume change due to complete pore pressure dissipation occurs in a constant-rate-of-loading test after a time since initiation of loading of

$$t_{90} = 3(L/2)^2/c_v \qquad (7)$$

At times less than this value, the degree of pore pressure dissipation is less than 90 percent, and at later times it continues to increase and eventually approaches 100 percent. The result is that if a constant rate of loading test is conducted too fast to allow adequate pore pressure dissipation, the e-log(p) curve will be shifted to the right (if corrections are not made) because the sample is actually at an effective stress lower than the confining stress. The effect is illustrated in Figure 6. With time, the compaction curve will approach the fully dissipated curve as is shown in Figure 6. This results in an overestimate of the yield stress and an overestimate of the slope of the inelastic portion of the e-log(p) curve.

A constant rate-of-loading test that allows incomplete pore pressure dissipation will be marked by an overshoot of the e-log(p) curve just after yield as can be seen for the diatomite sample in Figure 3, which was tested at 1000 psi/hr applied in increments of 100 psi each 6 minutes. Caution is needed to ensure that this shift of the position of the e-log(p) curve is not mistakenly construed to be the result of a loading rate phenomenon due to volumetric creep effects.

## CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made with respect to laboratory determination of reservoir compaction curves.

1) Laboratory compaction tests should be performed at a uniform rate of loading. That is, the stress changes and time intervals between them should be uniform.

2) The loading rate should be chosen such that pore pressure dissipation does not affect the compaction curve. The best way to accomplish this is to observe the time for volume change due to pressure dissipation to be completed following several confining stress increments in the inelastic (post-yield) portion of the compaction curve.

3) The laboratory compaction curve of materials exhibiting volumetric creep should be corrected for loading rate effects so that the pore collapse stress or yield point is not overestimated.

4) One approximate means for correcting the curve has been presented wherein the rate of loading is varied by several log cycles during the compaction test. Data collected to date (subject to further verification) suggests that similar corrections also may be made on the basis of constant stress creep tests.

5) Stress ranges applied in the laboratory should extend well beyond the "expected field stress range" in case a significant correction for creep effects is warranted. The authors recommend carrying all tests

to the upper limits of the equipment. This usually allows better discrimination between elastic and inelastic compaction regimes.

6) Based on the findings of others as discussed, the core samples should have at least connate water saturation and the water should be in chemical equilibrium with the rock unless a different water is to be injected into the reservoir. Consideration may also need to be given to the temperature and pore pressure used in the tests.

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## REFERENCES

Aboshi, H., Yoshikuni, H., and Maruyama, S., 1970, "Constant Loading Rate Consolidation Test", Soils and Foundations, Vol. 10, No. 1, pp. 44-56.

Atkinson, J.H., and Bransby, P.L., 1978, The Mechanics of Soils: An Introduction to Critical State Soil Mechanics, Maidenhead, England, McGraw-Hill.

Bjerrum, L., 1973, "Problems of Soil Mechanics and Construction on Soft Clays", State-of-the-Art Report to Session IV, in Proceedings, 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, Vol. 3, pp. 111-159.

Chase, C.A., and Dietrich, J.K., 1988, "Compaction Within the Belridge Diatomite", SPE 17415, SPE Calif. Regional Meeting, pp. 169-178.

de Waal, J.A., and Smits, R.M.M., 1988, "Prediction of Reservoir Compaction and Surface Subsidence: Field Application of a New Model", SPE Formation Evaluation(June), p.347-356.

Johnson, J.P., and Rhett, D.W., 1986, "Compaction Behavior of Ekofisk Chalk as a Function of Stress", SPE 15872, SPE European Petroleum Conference, London pp. 221-231.

Johnson, J.P., Rhett, D.W., and Siemers, W.T., 1988, "Rock Mechanics of the Ekofisk Reservoir in the Evaluation of Subsidence", Proceedings 20th Annual Offshore Technology Conference, Houston, Tx., OTC 5631, pp. 39-50.

Lambe, T.W., and Whitman, R.V., 1969, Soil Mechanics, John Wiley & Sons, New York, 553p.

Martin, J.C. and Serdengecti, S., 1984, "Subsidence Over Oil and Gas Fields", GSA Reviews in Engineering Geology, v. VI, pp. 23-34.

Mayuga, M.N., and Allen, D.R., 1969, "Subsidence in the Wilmington Oil Field, Long Beach, California, USA", Proceedings of the Tokyo Symposium on Land Subsidence, Sept. 1969. Published also in Land Subsidence, v.1: International Association of Scientific Hydrology, AIHS publication no. 88, pp 66-79.

Newman, G.H., 1983, "The Effect of Water Chemistry on the Laboratory Compression and Permeability Characteristics of Some North Sea Chalks", JPT(May), pp. 976-980.

Ruddy, I., Andersen, M. A., Patillo, P. D., Bishlawl, M., and Foged, N., 1989, "Rock Compressibility, Compaction, and Subsidence in a High-Porosity Chalk Reservoir: A case Study of Valhall Field", JPT(July), pp. 741-746.

Schutjens, P.M.T.M., 1991, "Experimental Compaction of Quartz Sand at Low Effective Stress and Temperature Conditions", J. Geol. Soc., London, v. 148, p. 527-539.

Smits, R.M.M., and de Waal, J.A., 1988, "A Comparison Between the Pressure-Lag Model and the Rate-Type Model for the Prediction of Reservoir Compaction and Surface Subsidence", SPE Formation Evaluation (June), pp. 357-363.

Smits, R.M.M., de Waal, J. A., and van Kooten, J. F. C., 1988, "Prediction of Abrupt Reservoir Compaction and Surface Subsidence Caused by Pore Collapse in Carbonates", SPE Formation Evaluation(June), pp. 340-346.

Sulak, R.M., and Danielsen, J., 1989, "Reservoir Aspects of Ekofisk Subsidence", JPT(July), pp. 709-716.

Teeuw, D., 1971, "Prediction of Formation Compaction from Laboratory Compressibility Data", SPEJ(Sept), pp. 263-271.

Terzaghi, K., 1943, Theoretical Soil Mechanics, New York, John Wiley and Sons, Inc., pp.265-296.

Thompson. T. W., and Schatz, J.F., 1986, The Time-Dependent Compaction of Porous Rocks and Its Consequences for Laboratory Testing", 27th Soc. Mining Eng. Rock Mech. U. S. Symp. (Tuscaloosa, Ala) Proc. (Rock Mechanics: Key To Energy Production), pp. 539-546.

Yudovich, A., Chin, L.Y., and Morgan, D.R., 1989, "Casing Deformation in Ekofisk", JPT(July), pp. 729-734.

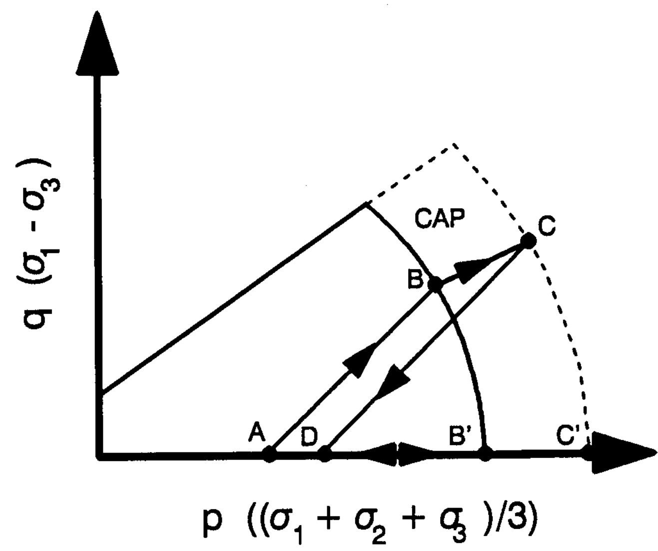

FIG. 1a Cap-type Yield Surface

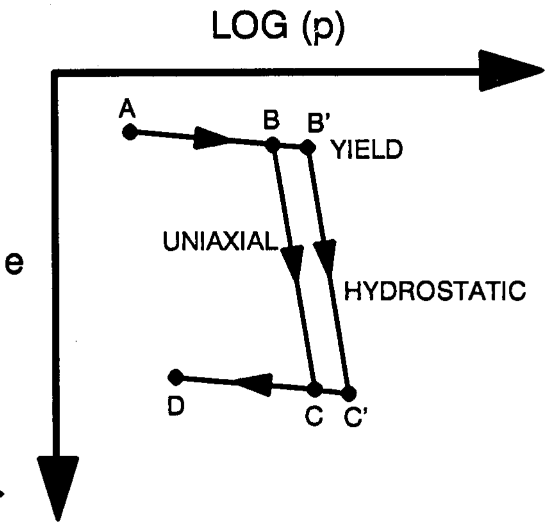

FIG. 1b Idealized Compaction Curves

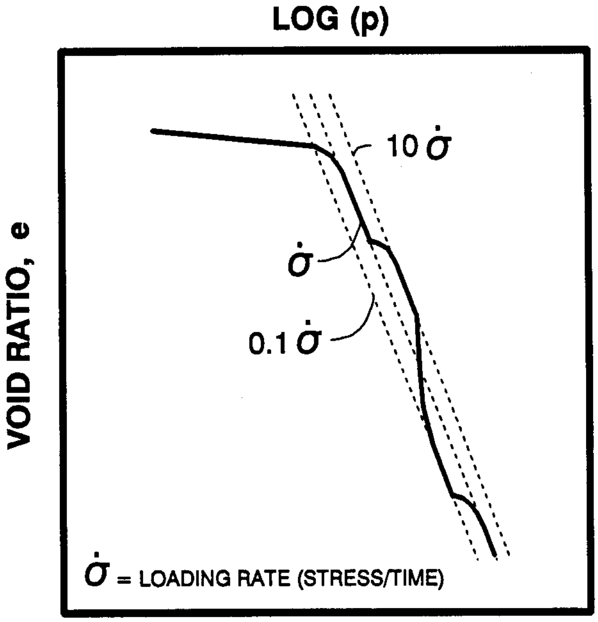

FIG. 2 Illustration of Loading Rate Effect on Position of Compaction Curve for Rock Exhibiting Volumetric Creep

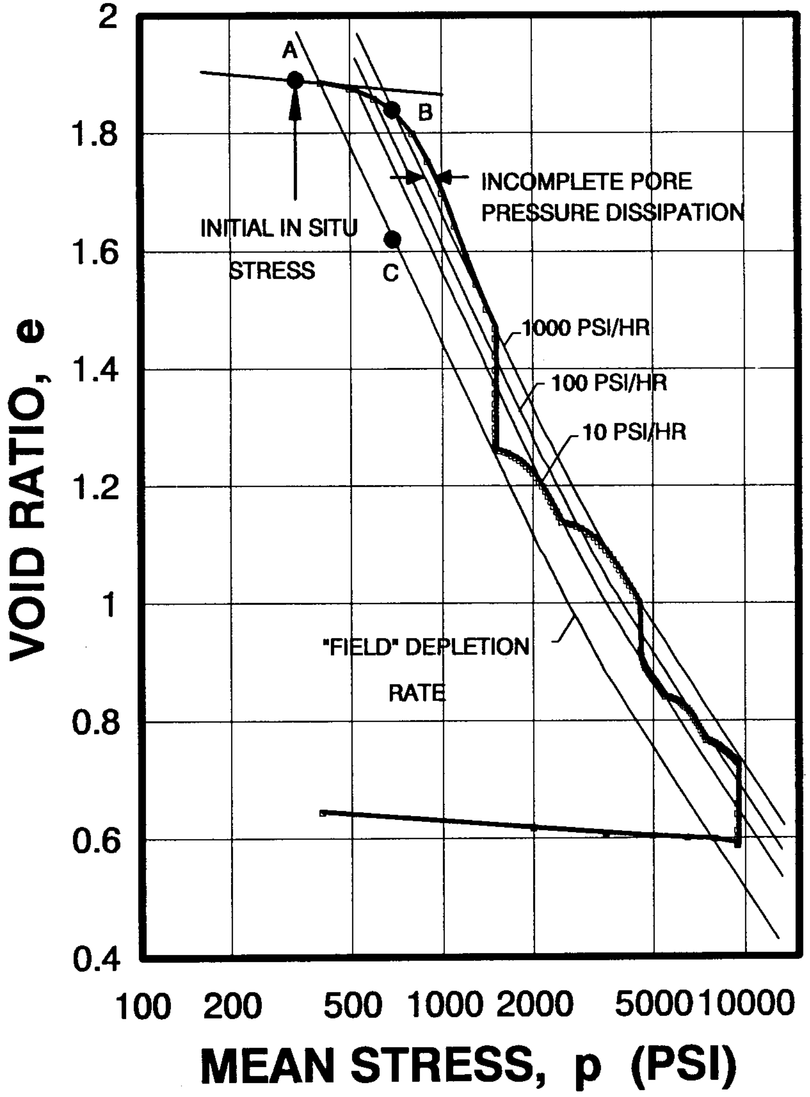

FIG. 3 Variable Loading Rate Hydrostatic Compaction Test on Diatomite

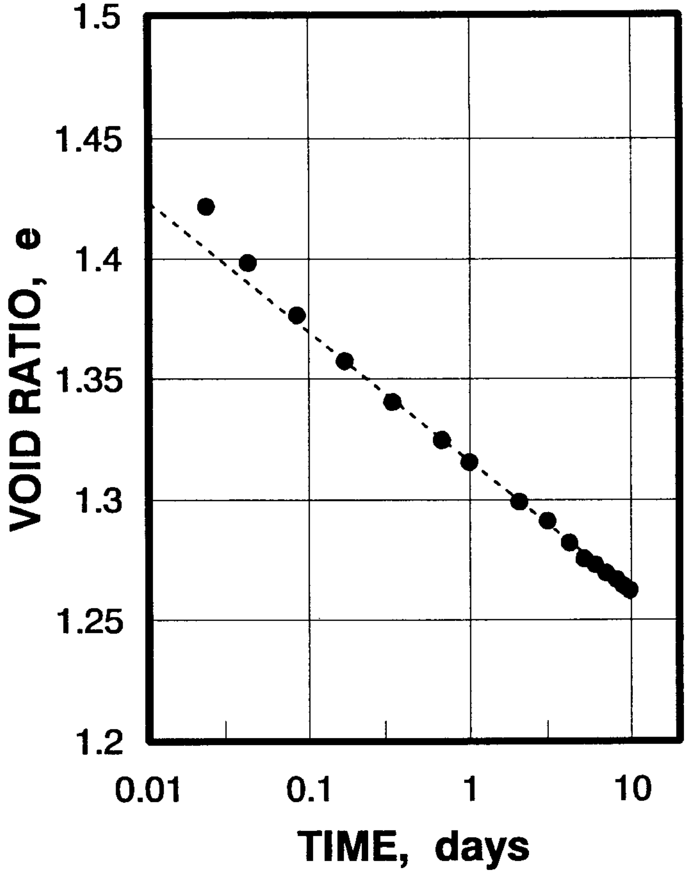

FIG. 4 Volumetric Creep Data for Diatomite Hydrostatic Stress = 1500 PSI

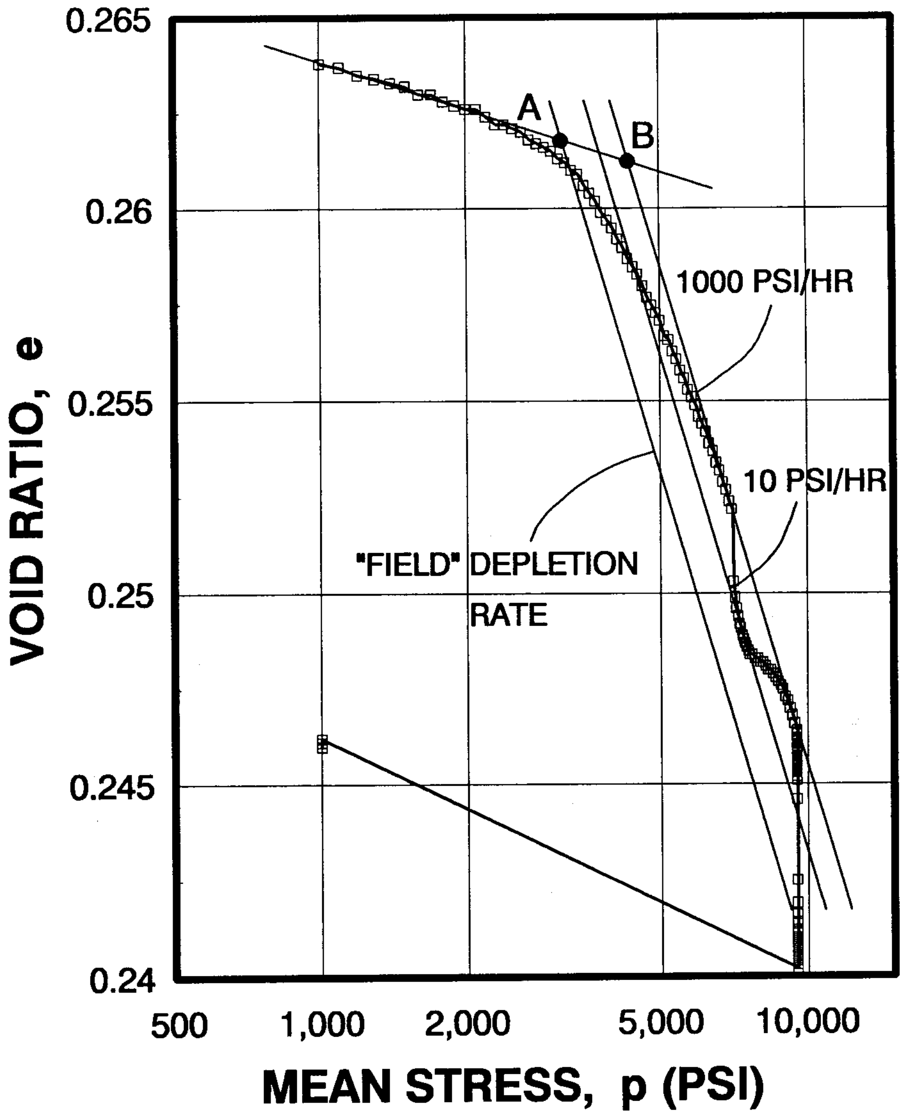

FIG. 5 Variable Loading Rate Hydrostatic Compaction Test on Carbonate Rock

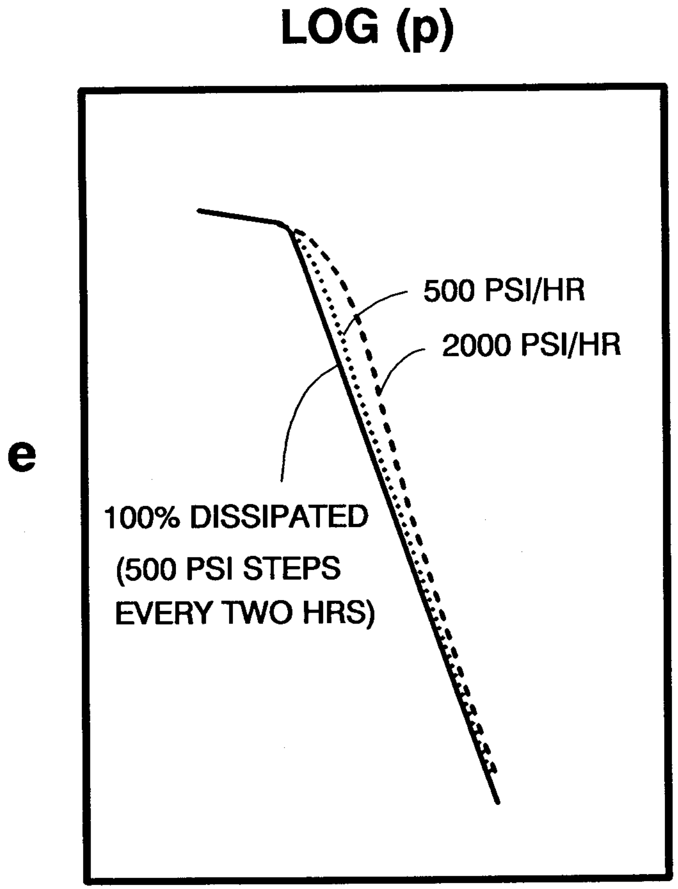

FIG. 6 Example Effect of Incomplete Pore Pressure Dissipation During a Constant-Rate-of-Loading Compaction Test