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20. UNIAXIAL RECONSOLIDATION TESTS ON POROUS SEDIMENTS: MUDSTONES FROM SITE 897[1]

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ABSTRACT

The porosity and yield stress of clay-rich marine sediments can be sensitive indicators of stress and stress history, if testing of these sediments is done carefully and the results are interpreted with an understanding of sediment mechanical behavior. Consolidation tests on a nannofossil clay from 619 mbsf in Hole 897D indicated a very low yield stress (about 1 MPa), but at a porosity that was also quite low with respect to that of the same sediment when it was disaggregated and consolidated from a slurry. Moreover, no evidence for cementation of the natural sediment was observed, despite its calcareous nature. The lower porosity of the natural sample was shown to result from the much slower geological rates of consolidation than the laboratory rates. The lower compressibility of the natural sample was attributed to "delayed consolidation" during the subsequent laboratory consolidation

Together with the downward increase in porosity and intense fracture/vein development observed at Site 897, the low yield stress indicates near-lithostatic pore pressures in the basal sediments over much of their history and probably at present. This condition would suggest that fluid is rising from below and probably moving laterally toward egress to the ocean at the ridge top. The source and hydrodynamic setting of this fluid are as yet inadequately explored.

INTRODUCTION

Uniaxial reconsolidation-consolidation tests on porous sediments have been run on core samples from many Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) legs but the results on the whole have not been particularly productive. This admittedly very subjective conclusion arises not from a perceived lack of importance of such testing but from the sense that a lack of an adequate understanding of the basis for these tests by the geoscience community has sometimes led to poor-quality results and unwarranted interpretations on one hand, but on the other hand it has also led to a lack of appreciation for the range of geological implications that can be drawn from such tests. To be sure, several papers in ODP volumes have been written by trained geotechnical engineers (e.g., Moran and Christian, 1990; Feeser et al., 1993), but these tend to be couched in terminology that is difficult for most geologists to follow.

Uniaxial consolidation tests involve the variation of effective vertical stress on a sample for which the lateral (horizontal) strain is constrained to be zero. Such tests are presumed to mimic aspects of the deformational history in sedimentary basins, where the lateral strain is assumed to be insignificant. These tests have been assumed to provide a method of estimating the maximum applied in situ effective vertical stress, and, if certain conditions are met, for the estimation of pore fluid pressure *(P)*. More sophisticated tests can include determination of the horizontal effective stress associated with consolidation, which might be a measure of the in situ horizontal stress. Vertical strains associated with consolidation are also valuable in estimating settlement resulting from loading by structures or caused by fluid withdrawal.

Still more consolidation tests, from ODP Site 897, are reported here, but because the general ODP community could benefit from a review of the subject, this paper includes a short section concerning the bases and methodologies of uniaxial consolidation testing. In large part the material presented here is drawn from the extensive and advanced literature on consolidation by the geotechnical engineering community. This literature has been largely ignored by geologists, not merely because it belongs to a different discipline but also because it is couched in a terminology and approach that is difficult for most geologists to follow. One objective of this review is to translate geologically pertinent aspects of this material on consolidation with the hope that it will lead to more sophisticated and more useful consolidation studies by the ODP community. In a sense, this review is an update of that by Bryant et al. (1981), which covered a wider range of mechanical studies on marine sediments.

This paper then reports the results of consolidation tests on a mid-Eocene calcareous mudstone from ODP Hole 897D. Uniaxial strain tests were performed on undisturbed samples as well as on this same lithology after disaggregation. The results are interpreted in terms of constraints on in situ stress and suggest very high pore-fluid pressures near the base of the sediment section. Comparison between test results of the two analogous materials and with those of a silty clay from the Nankai Trough (Karig, 1993; Karig and Morgan, 1994) elucidate problems in extrapolating from laboratory to in situ conditions.

Because acoustic velocities (V_p) were measured during most of these consolidation tests, a short section is included that describes velocity-stress relationships. The difference in V_p between shipboard and in situ stress conditions have important implications for the use of shipboard velocity measurements.

BACKGROUND

Initial, first-time or "virgin" uniaxial experimental consolidation of disaggregated or highly disturbed (remolded) porous sediments results in the well-known relationship between volume and effective vertical stress (σ_v') that shows an approximately exponential decrease in volume or vertical strain with increasing σ_v'. Geotechnical engineers have concluded that there is a linear relationship between void ratio *(e)* and log σ_v' for most sediments over a low-stress range,

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but this linearity does not extend into higher, geologically pertinent stresses (Bryant et al., 1981; Karig and Hou, 1992). Tests of a silty clay in our laboratory demonstrated that for σ_v' up to 30 MPa, log σ_v' is more nearly linear with respect to porosity (η) than it is to *e* (Karig and Morgan, 1994). The constant of proportionality, A_c, in the relationship: $\eta = A_c \log \sigma_v'$ is a measure of compressibility analogous to the index of compressibility, C_c, when void ratio is used. A_c is a function of lithology, with clay having a much higher value than sand.

As σ_v' is increased during uniaxial consolidation, σ_h' also increases, at a ratio with σ_v' ($\Delta\sigma_h'/\Delta\sigma_v'$) that is termed K_o. K_o has been shown to be constant for a clay over a geologically applicable stress range in the laboratory, but for sand it increases moderately with stress, probably caused by grain crushing (Karig and Hou, 1992). K_o ranges between about 0.4 and 0.7, generally increasing with clay content, but with wide variations.

Consolidation is not elastic strain and cannot be described by equations of linear elasticity. Nevertheless, consolidation generates a component of elastic strain in the sample, usually small, that can be measured by reducing σ_v'. Along such a stress path, σ_v' is related to vertical strain (ε_v) by $\sigma_v' = E_c\varepsilon_v$. E_c, termed the constrained modulus, is analogous to Young's modulus and increases with increased consolidation. The equations of linear elastic strain lead to the relationship between $\Delta\sigma_h'$ and $\Delta\sigma_v'$: $\Delta\sigma_h, = (v/1 - v)\, \Delta\sigma_v$, where v is Poisson's ratio; for an anisotropic sediment such as a mudstone, the correct anisotropic components of v must be used (e.g., Atkinson, 1975; Karig and Morgan, 1994). The elastic stress ratio has a lower value than K_o for the same sediment at a given state of uniaxial consolidation.

Progressive consolidation increases the stress range within which the sediment can behave elastically. For a given state of uniaxial consolidation, this field of elastic behavior can be represented on a plot of effective mean stress ($\sigma_m' = ([\sigma_1' + \sigma_2' + \sigma_3']/3)$ against differential stress ($\Delta\sigma = \sigma_1 - \sigma_3$), or in geotechnical parlance, the *q-p'* plane (Fig. 1). On this plane, the elastic behavior is restricted to within an approximately elliptical area with its major axis along the uniaxial consolidation stress path. This elliptical envelope is determined by yield stresses along a wide variety of test paths (e.g., triaxial tests at different constant *q/p'* ratios). Uniaxial consolidation to a given state creates a single and unique yield envelope for all stress paths on that sample but is only a specific point on that yield envelope.

Progressive consolidation of a sediment increases the yield strength and enlarges the yield envelope with a geometrically similar shape (Fig. 1), at least over the lower range of stresses (Graham et al., 1983). A different ratio of *p'* to *q* during consolidation will generate a yield envelope with a different orientation on the *q-p'* plane. Isotropic consolidation, the only other path for which there are significant data, produces a yield envelope that is symmetrical about the *p'* axis (Fig. 1). It is thus presumed that yield envelopes in general are symmetric about the stress paths used to create them, at least if those paths have constant *q/p'* ratios.

Consolidation is associated with porosity reduction, which varies significantly as a function of the stress path during consolidation, especially in clay-rich sediments. In general, the greater the *q/p'* ratio along the consolidation path, the larger the porosity reduction (e.g., Wood, 1990). The increased ratio is permanently reflected in the sediment by the increased statistical alignment of poles to platy minerals such as clays, which is reflected in the fabric anisotropy (e.g., Morgan and Karig, 1993). For experimental uniaxially consolidated clay-rich sediments at least, there is a specific relationship among *q, p',* and porosity (η), just as there is among *q, p',* and yield stress (σ_c').

In the Critical State Theory, the yield condition for an ideal sediment can be described as a point on a three-dimensional surface in q-p'-η (or some other parameter of volume) space (e.g., Wood, 1990; Jones and Addis, 1986). As will be shown later, the relationship between porosity and yield stress may become "uncoupled" for naturally consolidated sediments, for instance, by stress rotation or by natural cementation. Such decoupling must be understood to interpret most consolidation tests of natural sediments adequately.

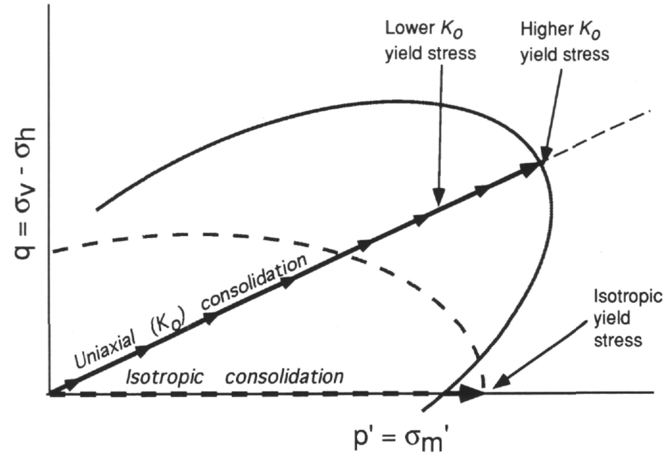

Figure 1. Generalized yield envelopes on a *p '-q* plot for uniaxial and isotropic (dashed) consolidation. The two similar yield envelopes shown represent the enlargement of the elastic field developed during progressive consolidation. The yield envelopes are approximately elliptical and symmetrical about the consolidation path.

METHODOLOGIES

Consolidation tests can be performed either in uniaxial strain cells (odometers) or in triaxial cells. Tests in odometers are simpler, but in only few of these cells can horizontal stress be measured and most have the problem of sidewall friction. On the other hand, consolidation of remolded sediments and slurries are much more easily done in such cells. Tests in triaxial cells are more complicated but, with computer-controlled servosystems, can be run in many modes and generate no sidewall friction.

Consolidation tests are usually run in steps of sequentially higher but constant vertical stress, with each step maintained for about 24 hr. Such step durations allow dissipation of excess pore-fluid pressure and thus measure primary consolidation, but record only part of the secondary consolidation or creep that persists at exponentially decreasing rate with time (e.g., Bjerrum, 1967). Consolidation tests can also be run at constant strain rates, which generate far more data points, but the rate must be sufficiently slow that excess pore pressures do not become significant. Even slower strain rates result in lower porosities because a component of creep is included. The consolidation tests in this study were run at a constant rate of stress increase. The advantage of this deformation path is that, with increasing consolidation, the compressibility decreases and the strain rate drops, which compensates for the tendency for pore pressure to rise as the permeability decreases. This method also includes some creep, which is not well controlled.

A typical uniaxial consolidation test on an undisturbed sediment sample begins at a stress state well within the yield envelope, usually at some isotropic stress state. Although the initial deformation is theoretically elastic, a very low starting stress may produce an initial strain rate greater than that for linearly elastic because of microcrack closing and also because of initial system compliance. Such an initial response is generally followed by a phase of reconsolidation showing linear relationships among stress and strain parameters. This portion of the deformation path appears to provide the best basis for the determination of the elastic moduli of the sediment related to the physical properties at yield (Fig. 2).

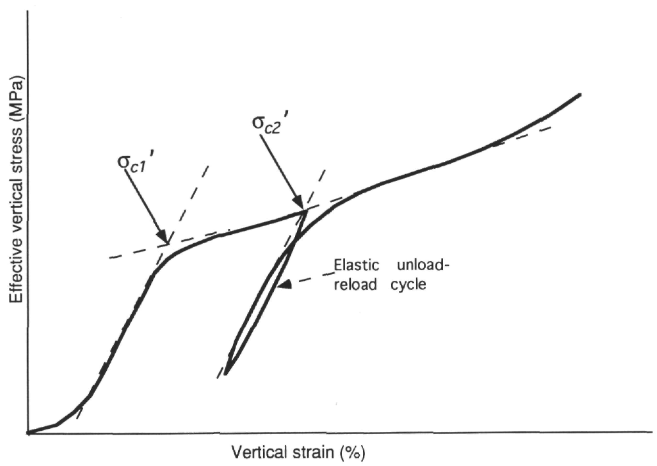

Figure 2. Generalized ε_v-σ_v' plot for a sediment that was previously consolidated to $\sigma_v' = \sigma_{c1}'$ and further consolidated to $\sigma_v' = \sigma_{c2}'$. At σ_{c2}', σ_v' is reduced and then increased to generate an elastic unload-reload cycle. When σ_v' is increased beyond σ_{c2}', further consolidation occurs and a new, higher yield stress, which approximates σ_{c2}', can be estimated by extrapolation of the slopes.

Yield is generally signalled by an increase in strain for an increment of stress as well as by an increase in stress ratio. However, the exact stress state picked as yield is often in question, either because of poor definition of the break in slope or because the stress-strain relationships can be complicated by effects such as cementation. The functional definition of the yield stress in an experimentally consolidated sediment is the maximum effective vertical stress to which that sediment was previously subjected. Tests on experimentally consolidated sediments with unload-reload cycles show that the yield stress can be reasonably well approximated by extending tangents from the linear elastic portion of curves and from the first segment of the subsequent consolidation curves (Fig. 2). More sophisticated methods, involving the extremum of the derivative of the *e-log* σ_v' or ε_a-σ_v' curves, have been developed by geotechnical engineers (e.g., Casagrande, 1936; Janbu, 1985). Some of these methods generate a yield state that lies off the actual stress path of the test (Fig. 2).

Most consolidation tests are performed in odometers that do not have the capability of measuring horizontal stress and thus provide only ε_a-σ_v' relationships for the estimation of yield. In tests on highly consolidated sediments, there may be very little difference in axial strain increment from elastic to plastic regimes and the yield stress can be literally impossible to determine. A few more advanced odometers and triaxial cells have the ability to measure σ_h', providing a much wider range of possible relationships with which to estimate yield. A few of these include $\Delta\sigma$ vs. σ_m', $\Delta\sigma$ vs. ε_a, and σ_h' vs. σ_v'. The best estimate of yield stress relies on as many relationships as possible.

In its most rudimentary geological application, the yield stress is compared with the calculated effective vertical stress applied to the sample when it was collected, assuming a hydrostatic pore-fluid pressure. If the two are equal, the sediment is termed normally consolidated. Very often in geologic settings, the measured yield stress is greater than the calculated in situ effective vertical stress with hydrostatic P, or σ_{vh}'. This implies that the sample has been subjected to a greater σ_v' in the past than the in situ stress when collected, and the sediment is termed overconsolidated. The usage of this term is also similar to that in geotechnical engineering, but the term underconsolidation is unique to geological applications. An underconsolidated sample refers to the condition in which the yield stress is less than σ_{vh}' because of P greater than hydrostatic pressure, although the sediment may actually be normally consolidated with respect to the applied effective vertical stress.

Just as there is a diagnostic relationship between yield stress and σ_v', there is a parallel relationship between porosity and σ_v'. Thus, porosity can also be used as an indicator of consolidation state if a reference curve relating η and σ_v' for the sediment is available. Normally consolidated sediments follow this relationship, whereas overconsolidated sediments have a lower porosity at the same σ_v'. Thus, under some conditions, yield stress and porosity can be parallel indicators of consolidation state.

Occasionally, naturally consolidated sediments behave similarly to their experimentally consolidated analogs, but too often they do not and the reasons for the differences are seldom fully appreciated. Reasons for these differences include cementation, inappropriate initial test stress states, and inapplicable natural stress paths. In addition there are serious questions concerning the effect of geologic time on the strains and stress ratio associated with consolidation.

Natural sediments are usually cemented, which refers to the condition where sediment strength is increased without an increase in applied stress and most often with little reduction in porosity. Cementation is widely recognized by geotechnical engineers, who refer to it as structuration, microstructure, bonding, and aging (e.g., Burland, 1990). Cementation includes such effects as electrochemical bonding and secondary mineralization but is usually recognized by its effects on the sediment mechanical behavior as displayed on reconsolidation test curves (Fig. 3).

Cementation leads to a yield stress that exceeds the σ_v' ever applied to that sediment and thus to an expanded yield envelope. In the low-stress environment of geotechnical engineering, this expanded yield envelope is assumed to be geometrically similar to that of the uncemented sediment (Lerouiel and Vaughan, 1990), but this assumes that the anisotropy of cement strength is the same as the intergranular component of strength. It remains to be seen whether this assumption can be applied to the higher stresses of geological environments.

Destruction of cement ("decementation" or "destructuring") leads to the reduction of yield strength and to the contraction of the yield envelope. Cement can be destroyed by a variety of processes including subyield stress and fatigue (Burland, 1990). Disturbance of DSDP/ODP cores during drilling and handling, especially those from shallower depths, is almost certainly a cause of cement destruction.

Cemented sediments are identified by a number of characteristically shaped curves generated during reconsolidation-consolidation tests (e.g., Janbu, 1985). The routine ε_v-σ_v' curve shows a sharper break in slope at yield, followed by a very rapid increase in strain with increasing stress, but this effect can be rather subtle. More pronounced effects of cementation are seen on the σ_h'-σ_v', $\Delta\sigma$-σ_m', and $\Delta\sigma$-ε_v curves. For example, the $\Delta\sigma$-σ_m' curve for a cemented sediment shows a rise well above the K_o line before rejoining it as σ_m' or p' increases (Fig. 3).

The definition of yield stress in a cemented sediment is a contentious issue, as it might be chosen anywhere between the departure from linear elastic conditions and the arrival at K_o condition (Fig. 3). The sharp reduction in the slope of the *q-p'* curve marks an irreversible destruction of cementation and thus represents yielding, but it may not mark the position on the yield envelope appropriate for uniaxial consolidation. On the other hand, the choice of a yield stress at or near the condition where the stress path assumes a K_o ratio (e.g., Janbu, 1985) would seem to represent the virgin uniaxial condition of a decemented sediment, for which the yield envelope has already contracted. The initial isotropic stress condition from which the test is begun may also affect the nature of reconsolidation relationships (Fig. 3). If, as expected, the elastic relationships during the pre-yield phases of the "overconsolidated" and normally consolidated starting conditions, the stress path will meet the K_o line either at an incorrect yield stress or it will produce curves similar to that for cemented sediments (see Mesri and Hayat, 1993).

Cemented sediments generally have higher porosities than uncemented equivalents subjected to the same consolidation stresses because the stress applied to the sample is shared between the cement and simple intergranular contacts. Both strongly cemented sediments and overpressured (underconsolidated) sediments have higher porosities at a given depth than an uncemented reference sediment under hydrostatic pore pressure. In the former case, however, the yield stress will be higher than that for the reference whereas in the latter case the yield stress will be lower. Although this observation and the shape of the test curves serve to qualitatively distinguish the two cases, both cementation and anomalously high pore pressures can occur simultaneously, in which case the contributions of each are difficult or impossible to separate quantitatively (e.g., Karig, 1993).

The effect of strain rate, or, equivalently, of time, is also very important in comparing the results of our laboratory consolidation tests with in situ conditions. Consolidation at geologic loading rates may exceed 2 MPa/m.y. for rapid sedimentation but are at least 10^{12} times slower than our laboratory rates. Secondary consolidation or creep should thus be largely complete during the natural consolidation caused by progressive sedimentation, whereas is it is only partial during laboratory consolidation. Creep during consolidation can lead to quite large porosity reductions for high-porosity sediments (e.g., Bjerrum, 1967), but appears to decrease as porosity decreases and consolidation stress increases (Graham et al., 1983).

In contrast to the obvious and commonly significant effect of time on porosity during consolidation, there appears to be relatively little effect of time on the stress ratio, at least on a laboratory time scale (Karig and Hou, 1992). There is much debate as to whether sediments, especially clay-rich lithologies, maintain their short-term stress ratio over geologic time or tend toward an isotropic stress state (see references in Karig and Morgan, 1994). Thus, the applicability of the laboratory-determined stress ratio for the estimation of in situ σ_h' has not been adequately tested. Perhaps the most critical factor is that the sediment stress history can markedly effect the in situ σ_h'. For instance, the sediment might have been subjected to elastic unloading, which could radically change the in situ stress ratio but not the yield stress.

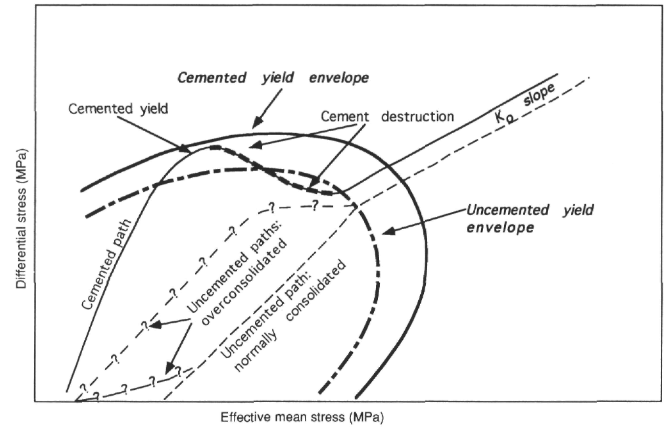

Figure 3. Generalized p'-q plot showing reconsolidation-consolidation stress paths for the cemented and uncemented conditions of a lithologically similar sediment. The cemented condition will have a larger envelope and/or a higher porosity. Its stress path shows a steep rise (higher constrained modulus) to yield, which is not on the K_o line. Yield is followed by reduction of Δs as cement is destroyed and the yield envelope shrinks to that of the uncemented state. An uncemented sediment with the same yield envelope as the decemented case above has a simple bilinear stress path if the initial stress falls close to the previous unloading path (normally consolidated). If the initial stress is significantly lower than that (an overconsolidated condition), an uncertain stress path, possibly with an incorrect yield, may be measured (see Mesri and Hayat, 1993).

TESTING PROGRAM

A major objective of the testing program on the core sample from ODP Site 897 was to deduce or at least constrain the in situ stress conditions at the sample depth, including both the effective vertical and horizontal stresses. Because of the very low apparent yield stress obtained from initial testing, which could reflect either a very high pore-fluid pressure or anomalous sediment behavior, a reference consolidation test was run on mechanically disaggregated remnants of the core. Finally, a reconsolidation-consolidation test with multiple unload-reload cycles was run on an undisturbed sample to explore the effects of the initial test state on the yield stress. Compressional seismic velocities were measured during all tests except the consolidation of the disaggregated material.

Test Apparatus and Procedure

Most of the consolidation tests were performed in a large triaxial cell driven by a computer-controlled servo-hydraulic load frame. All but one of these tests were run with uniaxial strain using a pseudoderivative algorithm that adjusted the confining pressure and axial load to keep the sample cross section constant. The cross-sectional area was monitored with an array of eight linear variable displacement transducers (LVDTs) and was maintained constant to within 0.003%. Axial strains were determined from two LVDTs fitted to rings fastened so as to measure displacement over the middle half of the sample (Fig. 4).

The vertical stresses during these tests were increased or decreased at a constant rates near 10^{-3} MPa/min, which generated strain rates on the order of 10^{-8}/s. These low strain rates, together with drainage from both sample ends, ensured dissipation of excess pore pressure and, in comparison to standard geotechnical consolidation rates, included a significant portion of the secondary consolidation.

The consolidation of the disaggregated material was performed in a large (3-in. diameter) consolidation cell, driven by the same computer-controlled load frame (Karig and Hou, 1992). This consolidation was also performed at a constant stress rate except at stresses less than 1 MPa. The sample was prepared as a slurry and loaded in the cell to a depth such that, when consolidated to a porosity of 25%, it would be just thick enough to cover the lateral stress sensor in the cell wall. In addition to making the sample as short as possible to reduce sidewall friction, the cell wall was coated with lubricant (Karig and Hou, 1992).

The sediment used for testing was a burrow-mottled calcareous mudstone from Section 149-897D-3R-2, 73-103 cm, representing a depth from 618.7 to 619 m below seafloor (mbsf). This mudstone lies near the base of stratigraphic Subunit IIC, of probable middle Eocene age, and has an estimated 45% carbonate content (Shipboard Scientific Party, 1994a). Smear slide analysis indicates that most of this carbonate is in the form of nannofossils, primarily coccoliths, and that there is a very low ratio of silt to clay size fraction. Although no detailed clay mineralogy was available, the shipboard analyses and the plastic behavior of the sample during handling indicate a fair fraction of smectitic clay. This type mudstone is a very common deep sea lithology and it is useful to compare its mechanical behavior with that of a nearly noncalcareous silty clay from the Nankai Trough, which was previously tested (Karig, 1993; Feeser et al., 1993).

Bulk densities of these subsamples, measured in our laboratory from sample volumes and wet weight, varied between 2.18 to 2.0 g/cm^3, with a strong mode near 2.195 g/cm^3. The bulk density of adjacent sections of core from shipboard measurements was 2.21 g/cm^3 (Shipboard Scientific Party, 1994a). The corresponding porosity was

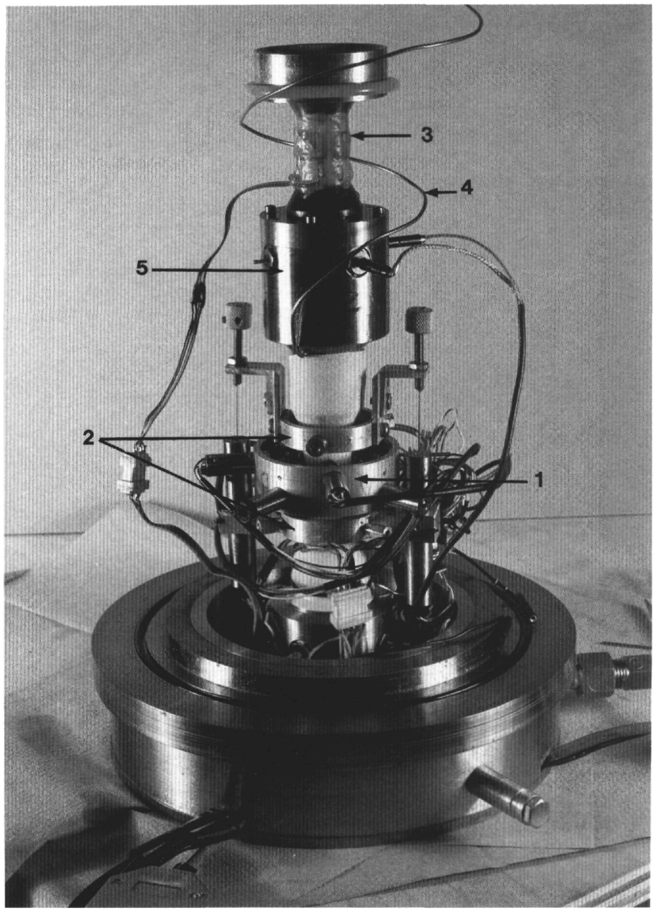

Figure 4. Photograph of the sensor array used to measure sample stress and strain in the triaxial cell. Lateral strains are measured by four pairs of LVDTs in a ring at sample midsection (1) and axial strains by a pair of LVDTs attached to rings spanning the central section of the sample (2). Axial stress is measured with a load cell mounted above the upper platen (3). Pore fluid can be drained from either or both ends of the sample (4) and compressional seismic transducers are imbedded in both platens (5).

given as 36.2%, but calculated from the given grain density of 2.78 g/cm^3, it would be 32.6%. With that grain density, the porosity of our subsamples is 33.4%.

Because this sediment appeared to be much more plastic than previously studied Nankai clays, the plasticity index (PI) was determined by measuring water contents at the plastic limit (PL) and liquid limit (LL): the PI is the difference in water content between that at the LL and the PL. For this sediment, LL = 42.7%, and PL = 19.2%, resulting in a PI of 23.5%, which indicates moderate plasticity for an inorganic clay (e.g., Holtz and Kovacs, 1981). The water content of the core sample before testing was 18.4%, indicating that the material was naturally quite close to its PL. This relatively high water content and high PI can account for the more plastic behavior during handling of this sample than for the previously tested silty clays.

The core section was subsampled with a water-lubricated rotary coring tube that cut cylinders 20 mm in diameter. For this test series, the cylinders were all cut with vertical axes and trimmed to lengths near 55 mm. For the tests, the cylindrical subsamples were placed in latex jackets and fitted with LVDT arrays.

RESULTS

The reconsolidation-consolidation tests showed clearly that yield stresses for this section of core are very low considering its depth of burial. Test T-70 displayed the clearest definition of yield stress, which ranged between 0.9 and 1.3 MPa using various mechanical relationships (Fig. 5). A similar low yield stress was observed on or constrained by two other tests. At the estimated yield stress the effective horizontal stress was 0.8 ± 0.1 MPa.

Such a low yield stress might be confused with mechanical effects sometimes encountered near the initiation of a test, such as the dissipation of negative pore pressure (e.g., Bishop et al., 1975), but the stress path beyond this apparent yield condition clearly shows a virgin consolidative behavior. For example, the compressibilities at higher stress decrease continuously (Fig. 5) to effective vertical stresses greater than 10 MPa, which is well above any expected in situ stress. In addition there were no indications in the shape of the test curves for any sediment cementation.

Post-yield stress paths for three uniaxial strain tests defined a stress ratio with a slope of 0.56 ± 0.1 and was quite constant with respect to stress over the stress range probed. Extrapolation of the stress ratio curves did not pass through the origin; at $\sigma_v' = 0$, σ_h' would be 0.2 ± 0.05 MPa.

The consolidation characteristics of this material were corroborated and extended by a uniaxial strain test with multiple unload-reload cycles, which also provided data on the elastic characteristics of sediment (Fig. 6). The primary objective of this test was to explore the nature of the reconsolidation stress path as a function of the initial test stress state. Starting at an isotropic stress of 0.69 MPa, the vertical stress was increased, under uniaxial strain conditions, to 3.5 MPa, which is well beyond the yield stress. From this state an unload-reload cycle was run, with the vertical stress during the reload phase increased to 6.5 MPa. This reload path constituted a "normally consolidated" stress path. The sample was again unloaded from the 6.5-MPa stress under uniaxial strain, but was then returned to the same stress state as that at the first unload phase, which required a triaxial strain path. The final phase was another uniaxial reconsolidation-consolidation to σ_v' = 8.5 MPa, with the sample maintaining a constant but slightly larger cross-sectional area from that during the earlier phases. This last phase provided an "overconsolidated" path (or initial stress state).

Because of the similar elastic and plastic compressibilities at higher stress levels, axial stress-strain relationships did not define the yield stress clearly during this test. Yield stresses were more clearly delineated during both reload phases by changes in other ratios, but were at values of σ_v' slightly less than the previous consolidation stresses. The stress ratios during consolidation phases were well-defined at 0.55 ± 0.1, and the elastic stress ratios were less well defined at about 0.44. ± 0.3. A phase of constant σ_v' at 8.5 MPa produced some axial creep, but no significant change in lateral stress (σ_h').

The overconsolidated path during this test did not show any similarities to those of cemented sediments (Fig. 6), which could reflect a number of possible causes. The relatively small differences in elastic and consolidation behavior, plus the relatively small degree of overconsolidation, was probably the greatest cause. In addition, the K_o line progressively shifted upward on the q-p' plane with each cycle, which reduced the need for a "cementation" effect.

The reference consolidation test involved the primary consolidation of disaggregated remnants of the section of core remaining after subsampling. Disaggregation was accomplished by crushing the dried material to millimeter size followed by reduction in a ball mill to a mean diameter of less than 5 µm, as estimated optically. Because there were very few grains in the original sediment larger than 5 µn, the disaggregated material was presumed to closely mimic the phys-

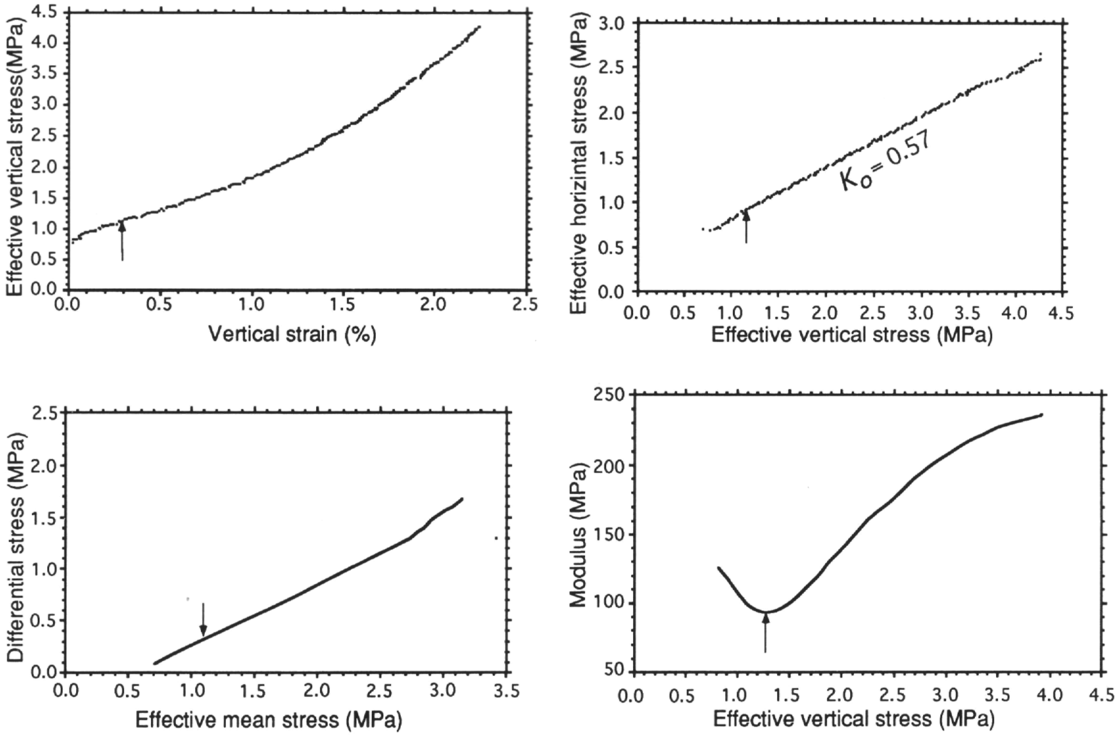

Figure 5. Several stress-strain relationships describing the mechanical behavior of an undisturbed sample from Section 149-897D-3R-2, 73-103 cm. The yield stress is well-shown by the minimum in constrained modulus *(M),* where $M = \partial\sigma_v'/\partial\varepsilon_v$. The yield stress (shown by arrows) is estimated from all relationships as 1.2 ± 0.1 MPa, and K_o is constant and well defined at 0.57 ± 0.01.

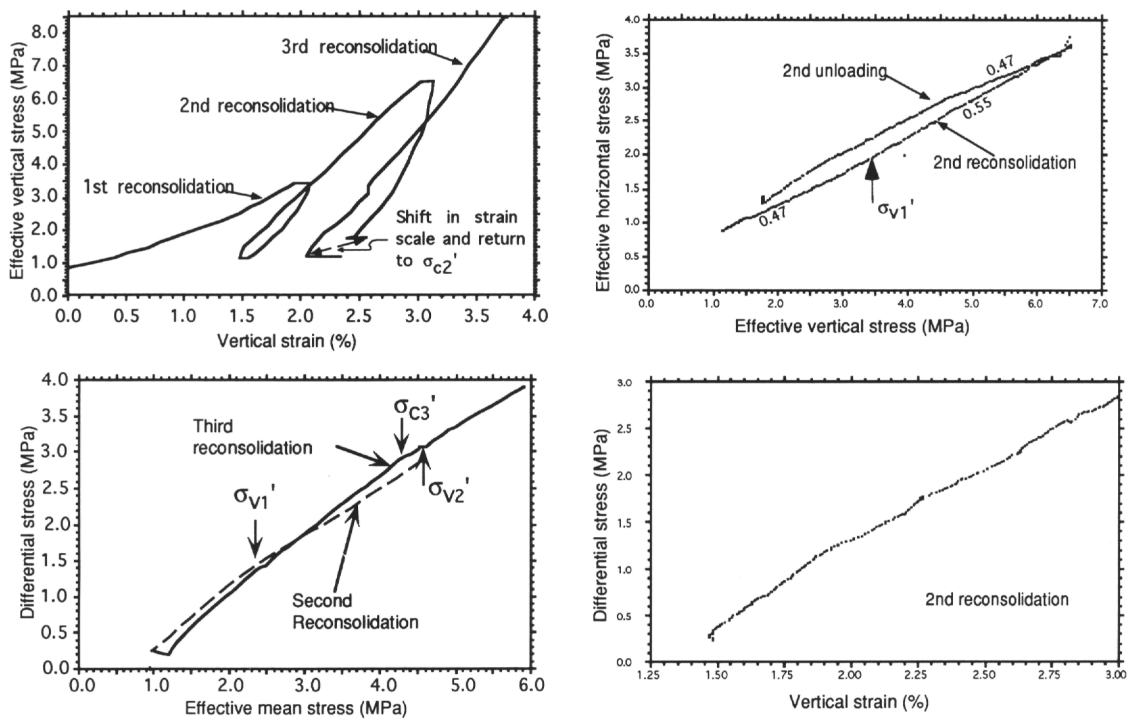

Figure 6. Multiple reconsolidation-consolidation cycles on a sample from Section 149-897D-3R-2, 73-103 cm. The yield stresses (σ_c') are very poorly defined on ε_v-σ_v' plots, but are more clearly shown by other relationships. The second (normal) reconsolidation produced yield stresses (both σ_v' and σ_h') identical to the stress state at the end of the first reconsolidation. The third (overconsolidated) reload produced yield stresses significantly less than those at the previous consolidation state.

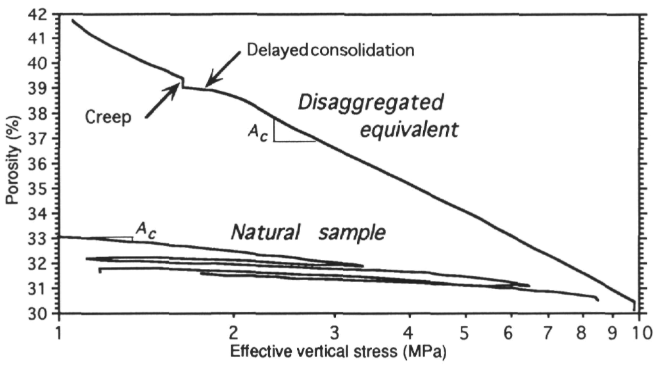

Figure 7. Comparison of consolidation response at post-yield stresses for the undisturbed sample and for the sample material after disaggregation. The disaggregated equivalent displays a much higher A_c, which is approximately constant over the measured stress range. A constant stress hold at 1.6 MPa shows secondary consolidation (creep), followed by a phase of delayed consolidation and low apparent A_c during renewed consolidation. The multiple unload-reload test on the undisturbed sample shows a much lower A_c, which is interpreted as resulting from delayed consolidation. The slopes, $\delta\eta/\delta \log \sigma_v'$, of the unload-reload cycles show even lower compressibilities and reflect an approximately elastic response.

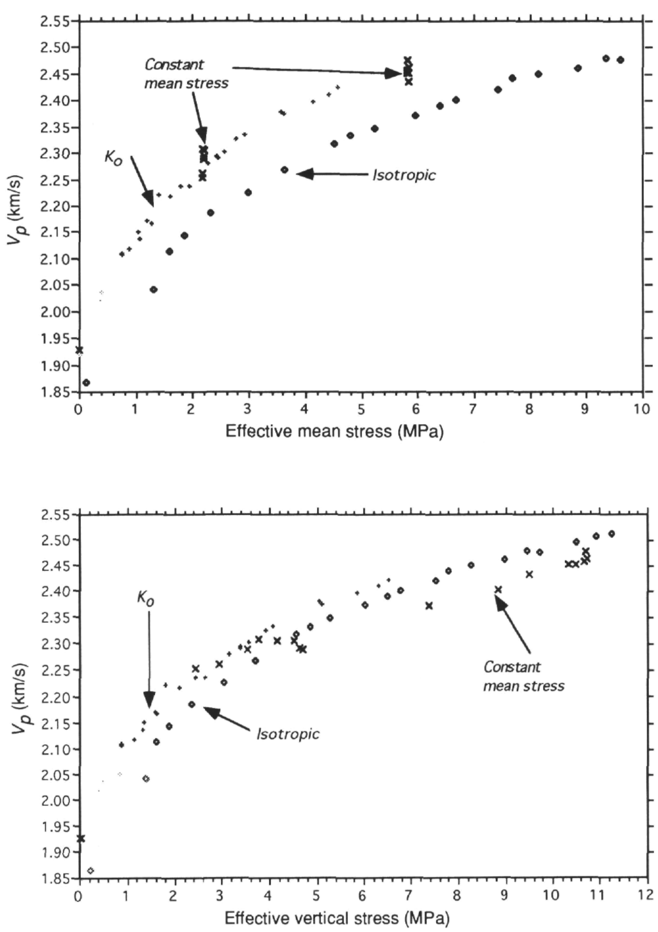

Figure 8. Compressional seismic velocities (V_p) as functions of σ_v' and σ_m'. These plots show that V_p is primarily a function of σ_v'. They also demonstrate the large sensitivity of V_p to σ_v' at low stress levels.

ical characteristics of the original sediment. The powdered material was mixed with distilled water into a slurry with a porosity of approximately 70%.

Consolidation of this slurry began with several steps of constant vertical stress, but from a stress of less than 1 MPa, proceeded at a constant rate of stress increase of 0.035 MPa/hr, except for a short stress hold at 1.6 MPa, to a maximum stress of 9.82 MPa, which was maintained for 26 hr. A sidewall correction, based on past experience (Karig and Hou, 1992), would have increased K_o by 0.01 or less and was ignored. Strains and porosities were determined by back-calculating from the final sample dimensions and weight, assuming a grain density of 2.78 g/cm^3 (Shipboard Scientific Party, 1994a).

Porosity decreased logarithmically with σ_v' to 30.4%, with an additional 0.3% porosity decrease during the final stress hold (Fig. 7). The porosity-log σ_v' curve generated a value for A_c of 1.3%/decade of log σ_v' The stress ratio ($\Delta\sigma_h'/\Delta\sigma_v'$) was constant at 0.60 between σ_v' from 1 to 9.8 MPa, the range over which σ_h' could be reliably measured. These parameters differed significantly from those of the post-yield consolidation on the natural samples (Fig. 7). The disaggregated equivalent had significantly lower porosities, was more compressible, and had a higher K. During the final period of secondary consolidation, σ_h' increased by only 0.016 MPa and that occurred during the first 1.5 hr of the hold. This increase resulted from dissipation of a very small degree of fluid overpressure during the constant stress-rate test, with the subsequent stability in σ_h' demonstrating the relative insensitivity of K_o to secondary consolidation.

OTHER TEST RESULTS

An initial consolidation test, run with constantly increasing isotropic stress, allowed the estimation of elastic strain anisotropies, as well as producing a yield stress on the p' axis. The yield stress, p' = 0.85 MPa, was clearly defined on the plot of σ_m' vs. ε_v. This value strengthens the validity of the yield stress determined from K_o tests in that it is also very low. More specifically it leads to a value of $(p'^2 + q^2)^{1/2}$ of 0.85, less than the 0.95 MPa value for this measure of the major axis of the yield envelope along the uniaxial strain path. This comparison shows that the axis of an elliptical yield envelope would be closer to the K_o line than to the p' axis.

Both the isotropic stress test and the initial isotropic stress steps during the K_o tests showed the samples to have a very strong vertical vs. horizontal elastic strain anisotropy, with vertical strains being about 3 times the average horizontal strain. The anisotropy within the horizontal plane appeared to be 30% or less as defined by A = 100 $(\varepsilon_{max} - \varepsilon_{min})/\varepsilon_{ave}$ but was not investigated further because the core section was not oriented with respect to north.

Compressional acoustic wave velocities were determined during all tests except the consolidation of the disaggregated material. Velocities for a given test have a precision better than ± 0.01 Km/s, but the accuracy is limited to about ± 0.02 km/s because of unmeasured changes in sample length between the initial physical measurement and the time of the first LVDT measurement.

The increase in velocities with increasing stress above yield represents the effect of consolidation, but the large (0.2 km/s) increase from 1 atm to σ_c' can be attributed to microcrack closing (Fig. 8). Furthermore, the sum of all the tests demonstrates that there is a large scatter in 1-atm velocities, which can be attributed most reasonably to variations in microcrack development. Because V_p was measured during tests run at isotropic stress increase, under K_o conditions, and at critical state failure (not reviewed here), data were generated that show V_p to be primarily a function of stress in the direction of wave propagation. If V_p is plotted against σ_v', there is relatively little difference between the stress paths and no consistent relationship with respect to σ_m', which increases for a constant σ_v' from the critical state failure test to isotropic stress test. If plotted against σ_m', V_p shows a significant increase at a given σ_m' with increasing σ_v', most obviously during the constant effective mean stress tests to critical state (Fig. 8).

These results indicate the importance of measuring V_p, not only at the correct σ_m', but also at the correct stress ratio. They also imply that appropriate V_p-η relationships should be generated from sets of values obtained at in situ conditions rather than from the relationship generated from a single sample.

INTERPRETATIONS AND DISCUSSION

Although only one core section was available for testing, a number of useful insights can be drawn concerning the mechanical behavior of this nannofossil clay, and some constraints can be placed on the in situ stress conditions at the sample depth. Some of these implications have significant bearing on the general application of laboratory measurements to the evaluation of the geological environment.

One fundamental observation from these consolidation tests is that the measured yield stress is very low for the depth from which the sample was collected, which implies a high pore-fluid pressure as well as a very low degree of cementation. The lack of any of the characteristics of cemented sediments in the response curves during these tests was further evidence of an uncemented in situ condition. The low yield stress and lack of cementation cannot have been caused by coring disturbance, in which case a higher porosity would have been preserved.

The consolidation test on the disaggregated equivalent lithology was designed to test this conclusion by generating consolidation parameters for an uncemented "reference" state. If the core sample were totally uncemented, it might be expected to have a porosity similar to the disaggregated equivalent at its yield stress and at higher values of σ_v'. Instead, the disaggregated equivalent had significantly higher porosities and compressibility than the core sample at stresses above yield (Fig. 7). Clearly the disaggregated equivalent cannot be used as an uncemented reference condition, at least before understanding the reasons for these differences. Therefore, before discussing any implications concerning the stress conditions and stress history at the sample depth in Hole 897D from test results on the core sample, the results of the reference consolidation test must first be considered.

A similar comparison of consolidation parameters can be generated from results of tests on a silty clay and its disaggregated equivalent from the Nankai Trough (Karig, 1993, and Karig, unpublished data). Samples of this silty clay from the trench fill (DSDP Site 582) were highly cemented, whereas other samples of this same lithology, from beneath the accretionary prism (ODP Site 808) were decemented (Karig, 1993). This array of data provides the basis for comparison between laboratory and field consolidation data as well as between the silty clay and nannofossil clay. Some of the consolidation tests were performed in a uniaxial cell, whereas others were done in the triaxial cell. Consolidation parameters for the disaggregated Nankai clay obtained from both cells were quite similar and demonstrated that the difference was not in the method of testing. In addition, replication of consolidation tests on the same core produced effectively identical results.

On the other hand, there are parallel differences between the consolidation parameters from tests on core samples and on their disaggregated equivalents for both a sample of the Nankai decemented silty clay and the calcareous clay of Hole 897D (Fig. 9). Both these natural samples have lower porosities than their disaggregated equivalents at the same consolidation stresses. In addition, both samples not only have lower compressibilities than their disaggregated equivalents, but their compressibilities, as measured in terms of A_c values, are quite similar (Fig. 9). In both comparisons the K_o values for the natural samples during post-yield consolidation were lower than for their disaggregated equivalents.

In striking contrast to the similarity of the behavior of the decemented Nankai clay to the clay from Site 897, a core sample of highly cemented silty clay from Site 582 had higher porosities at yield than its disaggregated equivalent (Fig. 9), but a similar stress ratio. The greater porosity of the cemented sediment was associated with its high yield stress, and attributed to the combined effects of cement and high in situ pore pressure (Karig, 1993). The high post-yield compressibility can be interpreted as reflecting the rapid breakdown of cement.

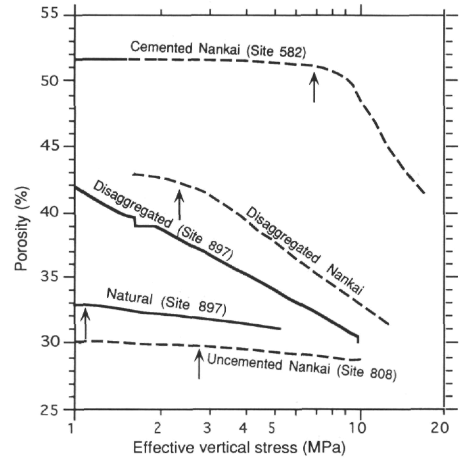

Figure 9. Comparative η-log σ_v' curves for natural samples from Site 897 and from the Nankai Trough (Sites 582 and 808) as well as for their disaggregated equivalents. The disaggregated equivalents for both clays show similar, relatively high porosities and high A_c values compared to those of the natural, uncemented samples. These differences are interpreted as reflecting delayed consolidation during the testing of the natural samples. The cemented variant of the Nankai clay shows higher porosities than the disaggregated equivalent and a higher A_c, which reflects cement destruction and rapid porosity loss.

It is less obvious why there are such large differences in response between the uncemented natural samples and their disaggregated equivalents. Clearly the experimental consolidation of a clay rich sediment does not seem to reproduce the consolidation response of an uncemented natural sample. This could be the result of changes in physical/mechanical properties during the disaggregation process but more likely it reflects differences in secondary consolidation resulting from the very different rates of consolidation in the laboratory and in nature.

A crude idea of the total secondary consolidation that would occur over geological time can be obtained by analyzing the secondary consolidation that occurred during the 26-hr constant stress hold at the end of the consolidation test on the disaggregated sample. Secondary consolidation, as expressed in terms of vertical strain, is thought to be linear with respect to the log of time after cessation of primary consolidation: $\varepsilon_v, = C_\alpha \log t$, where C_α is a function of the sediment lithology and of the porosity at the end of primary consolidation (e.g., Wood, 1990). Although the secondary consolidation during test C-34 was of marginal duration, it generated a C_α of 0.004/cycle of log *t,* which leads to a porosity reduction of about 5% over geologic time for this sample at a σ_v' of 9.8 MPa. The porosity reduction of secondary consolidation is largest when a given sediment is at its normally consolidated state, and appears to decrease as the consolidation stress increases (e.g., Graham et al., 1983).

C_α was not obtained for the disaggregated material at 1 MPa, which is the apparent yield stress of the undisturbed sediment, but it should lead to a porosity reduction for secondary consolidation significantly higher than 5% and might explain the 9% lower porosity of the undisturbed sample at its yield stress (Fig. 9). The lower compressibility of undisturbed sample above yield can be explained as "delayed consolidation" (Bjerrum, 1967), which is a state of apparent overconsolidation generated by secondary consolidation (creep). Such a phase of delayed consolidation is seen following the stress hold during the consolidation of the disaggregated equivalent (Fig. 7). If laboratory consolidation of the core samples had been continued, the porosity-stress curve should have approached that of the disaggregated equivalent.

The effects of creep appear to explain the differences in response between the natural sample and its disaggregated equivalent. The combination of low σ_c' and the relatively low porosity for the mudstone from 619 mbsf in Hole 897D can reasonably be explained by very high pore-fluid pressure in an effectively uncemented sediment that has undergone extensive creep.

For normally consolidated sediments, $P = \sigma_v - \sigma_c'$, where σ_v can be estimated from the integration of shipboard bulk densities over the depth range above the sample. Because porosity rebound is neglected in this approach, the calculated value of σ_v = 11 MPa is probably a minimum, but leads to $P \sim 10$ MPa and an overpressure of 5 MPa. The overpressure ratio, λ, is equal to P/σ_v, where the mass of overlying water is ignored (Davis et al., 1983), and is greater than 0.9, implying that P is nearly lithostatic.

The stress ratio at yield was about 0.85, but the validity of this value as a measure of in situ σ_h' is questionable. The first problem is whether or not the value of σ_h' and the stress ratio at yield during reconsolidation is the same as that at the maximum previous σ_v'. At the yield stresses measured during the reconsolidation segments of the multiple unload-reload test, σ_h' and K_o were quite similar to the values at the previous consolidation stresses, indicating that, at least for laboratory conditions, the "in situ" σ_h' can be accurately estimated.

The natural samples, however, have undergone more complete secondary consolidation as well as having been under stress for >10^{7-} yr, the effects of which are uncertain. Secondary consolidation did not seem to affect σ_h' over short periods, but extrapolation of this response to times many orders of magnitude longer is dangerous at best. The higher K_o ratios for the natural samples during delayed consolidation (0.61) than for their disaggregated equivalent (0.57) may reflect the effect of fabric modification. The higher stress ratio measured for the undisturbed samples at their yield condition (0.73), relative to that of either of the other two conditions, could be interpreted either as the effect of regional compression or as relaxation (e.g., Warpinski, 1989). Evidence for Tertiary regional compression was presented by the Shipboard Scientific Party (1994b).

A related problem is how best to apply laboratory-acquired mechanical parameters to in situ geological conditions. Clearly, laboratory-generated σ_v'-η curves cannot be assumed to represent in situ conditions for either cemented or uncemented sediments. If total geological creep could be estimated as a function of σ_v', primary consolidation results might be "corrected," but the variable cementation of sediments makes this a very questionable procedure.

To the extent that deformation to yield can be considered elastic and accepting that creep effects during this deformation are small (e.g., Graham et al., 1983), especially if tests are run at very low strain rates, stresses and porosities at yield should be fairly representative of in situ conditions. Parameters acquired during post-yield deformation do not represent natural geological conditions, but are probably applicable to problems of settlement from fluid withdrawal or rapid loading.

GEOLOGICAL IMPLICATIONS

The obvious question arising from the above interpretations of the test results is why such an elevated pore pressure exists near the base of the sediment column at Site 897. A possibly related question is why this clay has remained in an uncemented condition, especially considering its relatively high carbonate content.

The test core was recovered from the base of Subunit IIC, a calcareous turbidite and pelagic sequence, overlying about 20 m of noncalcareous terrigenous claystone (Subunit IIIA), which in turn overlies mass flow and polymict "breccia" deposits (Subunits IIIB and Unit IV). It is clear that porosities in the basal section of Subunit IIC and in Unit III are significantly higher than in the overlying sediments despite a wide scatter in the data within Hole 897D and between Holes 897C and 897D (Fig. 10). Some of this scatter may result from small-scale lithologic variations, but the general trend must reflect stress conditions. The test core lay within the zone of downward increasing porosity, which appears to increase smoothly across the lithologic unit boundary between Units II and III.

This zone of downward-increasing porosity is consistent with the low yield strength and high pore-fluid pressure interpreted from the tests reported here. Moreover, the location of the section of downward increasing porosity at the base of the post-rift sediments strongly suggests that both the elevated η and implied high P are associated with fluid expulsion from the basement and/or the overlying massive breccia unit. Such elevated η and P are not expected from consolidation-induced permeability reduction, assuming a typical permeability on the order of 10^{-17} m^2 for a clay with a porosity of 32% (Lambe and Whitman, 1969) and with 45 m.y. of consolidation under a relatively thin sediment cover. Although the data are insufficient for quantification, it seems most reasonable that such a period of elevated P must have begun early in the postrift depositional history of Site 897 to arrest consolidation at a relatively early stage. That the tested sediment has a low yield stress implies that the source of the high-pressure fluid must have persisted until recently, or else these uncemented basal sediments should have resumed consolidation.

Additional corroboration of the proposed fluid expulsion from the basement is derived from the intense fracturing and veining described by the Shipboard Scientific Party (1994a). Of particular interest is the reported upward increase in brecciation and calcification in the basement. These observations support not only a high degree of upward fluid transport but also a very low effective stress state. Because Site 897 lies on a ridge crest there is probably a component of lateral flow through a more permeable basement toward a relatively lower pressure environment at the sediment surface. The relatively thin sedi-

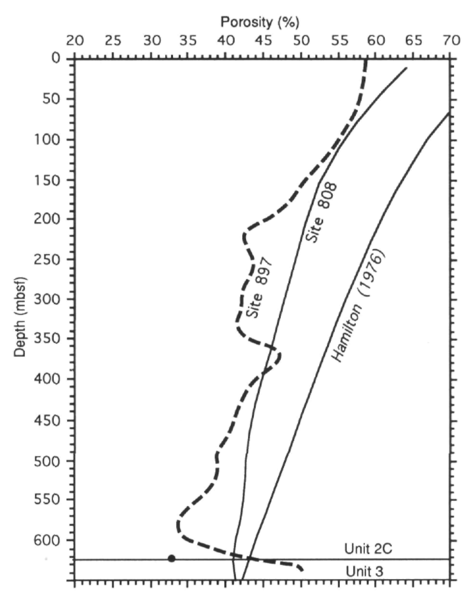

Figure 10. Porosity-depth curve for Site 897 (Scientific Party, 1994a), compared with that of Site 808 (Taira, Hill, Firth, et al., 1991), and with a typical mudstone section. (Hamilton, 1976). The mudstone porosities at Site 897 are less than for a typical section, presumably because the former are uncemented. Porosities at Site 897 are even less than those at Site 808, which have been reduced by deformation. The sample studied here (solid circle) has a porosity well below the mode at the same depth in Hole 897, but is similar to the shipboard value for the same core section. Deviation from an exponential porosity-depth relationship can probably be attributed to differences in lithologies and cementation above 500 mbsf, but the sharp downward general porosity increase below 600 mbsf must reflect high pore pressure.

ment cover over the ridge crest should induce a steeper pressure gradient toward the free-water surface there and lead to concentrated flow (Fig. 11). The source of this fluid remains unknown; two speculations are that meteoric water might have migrated down a structurally deeper décollement, or conversely the water might have been generated in the mantle beneath the rifted crust through pressure-release mechanisms. The large flow of water through the system could be responsible for the lack of cementation in the sediments, but the chemistry associated with this flow is not apparent.

High pore pressures near the base of the postrift sediment section should also engender a zone of structural weakness with a disposition toward gravity sliding. This may not be likely on a ridge top as at Site 897, but might be important elsewhere along rifted margins.

CONCLUSIONS

The consolidation tests on the single core sample available raised more questions about the stress history at Site 897 than they answered. Unfortunately, most of these questions could only have been answered with additional drilling and sampling, but the tests did strongly imply very high pore pressures at the base of the sediment section. As importantly, these tests revealed a number of differences between consolidation in the geological environment and under laboratory conditions. An understanding of these differences permits more realistic analyses of natural consolidation through laboratory testing.

The complications resulting from creep and cementation can account for many of the common deviations of observed porosity-depth curves from laboratory (experimental) consolidation curves or even from any exponential porosity-depth relationship. If uncemented or nearly so, deep marine sediments should tend to have in situ porosities less than their experimentally consolidated equivalents (Bryant et al., 1981), an effect that can be attributed to creep. However, with higher degrees of cementation, which is also a common condition, the in situ porosity of a sediment can be greater than that of its disaggregated equivalent (e.g., Hamilton, 1976). Small variations in cementation with depth are most probably the cause of large excursions from an exponential porosity-depth relationship that cannot be attributed to excess P.

This creep-cementation interaction might explain some of the porosity excursions at Site 897 but not all, and certainly not the radical porosity variations at the depths from which the test sample was collected. The sum of evidence points toward very high pore-fluid pressures over most of the stress history of the basal sediments. The hydrodynamic picture is incomplete, but fluid egress from the basement seems to be an important process during rifting.

If there is a moral to be drawn from this study, it is that there is more to the understanding of consolidation than can be derived from simple porosity or void ratio vs. log σ_v' curves. Conversely, careful, extended experimental consolidation tests can provide valuable information not only concerning the in situ stress but also for other mechanical characteristics of marine sediments.

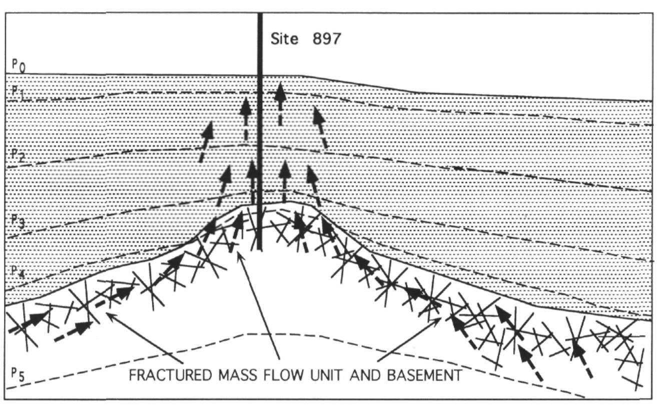

Figure 11. Hydrologic model of Site 897 portraying proposed fluid flow through the fractured mass flow unit and basement, both upward and laterally. Preferred escape at the ridge crest would be attributable to a thinner sediment cover and resultant higher pressure gradient in that setting.

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