MEASUREMENTS OF PHYSICAL PROPERTIES AND MECHANICAL STATE IN THE OCEAN DRILLING PROJECT

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SUMMARY AND PRINCIPAL RECOMMENDATIONS

Throughout the history of scientific ocean drilling, the measurement of physical properties and mechanical state has received a relatively low priority. This status is unwarranted in light of the growing quantification of the geosciences, which has led to the demand for more and better values of such quantities as porosity, permeability, stress, and strain. These quantities are necessary, for example, in understanding the consolidation (compaction) of basinal sediments, and for the construction of geomechanical models of accretionary prisms and models of the rheology of porous sediments.

For these objectives, measurements of physical properties and/or mechanical state are necessary from all depths in the drilled section. At present many of the measurements can only be acquired at shallow depths, where push-in probes can be used in unconsolidated sediment, largely because the physical properties program has been oriented toward geotechnical engineering. Because the geoscience community needs data from all depths it has recently turned to downhole logging. However, logging results are more easily used for correlation than for determination of absolute values of physical properties. To provide adequate control on these values, a carefully integrated combination of laboratory, in situ, and logging measurements is required.

Acquisition of this integrated capability will require that the ODP purchase or develop a modest array new of equipment and that they entertain several changes in policy. The strongest recommendation from the workshop is for the development of the ability to measure physical properties and mechanical state in situ at depths greater than a few hundred meters. This will require the perfection of the Navidrill concept, in which a small hole is drilled ahead of the rotary bit, and the development of probes to be employed in such holes. We envisage a self-contained probe with multiple packers, which could be used to measure such properties as temperature, pore pressure, and permeability, but which could be expanded to acquire many other measurements (e.g., velocity, magnetic field strength, in situ stress orientation). This probe would be retrieved on the coring line, would be easy to employ, and thus should be frequently used.

The workshop participants also recommend that several additional physical properties be routinely measured in the shipboard laboratory including: permeability, pore fluid resistivity, bound water state, and thermal conductivity. This will require that some present equipment be augmented and/or replaced. Among the most needed equipment are the following:

a. Differential thermal analysis (DTA) gear for porosity (bound water) studies

b. Ferroelectric ceramic/bender probes for V_p and V_s measurements in soft sediment

c. Harbert pressure vessel for V_p, V_s, Ω, thermal conductivity, and permeability measurements at in situ pressure

d. Hanson Research (UK) 240 Hz, 4-arm electrode cell for pore fluid resistivity measurements

e. Divided bar apparatus for hard rock thermal conductivity measurements

f. Constant flow rate permeameter

g. Sandia anelastic strain relaxation (ASR) gear to measure in situ stress

h. Triaxial compression test equipment

In addition, ODP should consider consolidating all of its continuous-feed core loggers (NRM, ρ, γ, χ) into one operation to save time and should evaluate the following equipment for future acquisition:

a) X-ray backscatter logger to replace GRAPE

b) X-radiography logger for textural scanning

c) neutron activation compositional logger

To insure optimum quality of the measurements of physical properties both in the lab and downhole, the workshop participants further recommended a number of policy changes, the most pressing of which are the following:

1. There must be a more realistic policy concerning the acquisition of whole round samples dedicated to measurements of physical properties and mechanical state. The determination of accurate values of such properties as stress, strength, and consolidation parameters, and of gradients in those values will require whole round samples at regular intervals. Although this interval could vary from site to site, the present limitation one whole round sample per major lithologic unit is totally inadequate.
2. Lab, logging and <u>in situ</u> measurements must be carefully integrated and standardized to optimize the values of each. A policy governing such integration should be developed, including frequency of sampling, and methodologies employed.
3. There is an urgent need for a JOIDES working group for the measurement of physical properties, and mechanical state which would be active until proposed changes are implemented and their initial results are evaluated.

I. INTRODUCTION

The idea of a workshop to review the measurement of physical properties and mechanical state of marine sediments and other rocks during the Ocean Drilling Program stemmed from perceptions that these important aspects of the program were not receiving the care and attention that they deserve. Opinions were often heard that the physical properties measurements during the earlier Deep Sea Drilling Program were inadequate in scope and of uneven, often poor quality, and thus not reliable for many geological and geophysical applications.

In part the inadequacies of the physical properties program were attributed to a low priority that physical properties have received throughout ocean drilling, but the workshop itself revealed other fundamental factors. The first of these is the change in perspective regarding the utility and aspirations for these measurements since the initiation of ocean drilling. Both committee reports and the nature of the shipboard program reveal a strong geotechnical orientation during the early days of DSDP, in which the properties of the sediments at rather shallow depths were stressed. As drilling reached deeper into the sediment column and even significantly into the oceanic basement, the geological community required accurate measurements of physical properties of those materials at all depths.

Second, new objectives, as well as the general quantification of geological processes has led to the requirement for additional physical properties (e.g. sonic and magnetic susceptibility anisotropies; electrical properties). These new directions have also led to a much greater interest in the mechanical state of the oceanic sediments and crust, including components of the stress tensor and the state of strain. This is not to say that the importance of geotechnically-oriented properties in the uppermost and unconsolidated sediments has diminished, but that the need for other properties and at greater depths have greatly increased over the past 5 to 10 years. Moreover, many workshop participants felt that many measurements are not being made to the requisite accuracy.

Perhaps because of these changing perspectives, a much stronger emphasis has been placed on logging and other downhole techniques during the Ocean Drilling Program than previously. Lengthy debates often occur over the relative merits and weaknesses of both downhole and laboratory techniques, but there seems to be very little argument over the need for an integrated program in which both methodologies are employed to calibrate and optimize each other.

With these concerns in mind the workshop participants addressed the problem in several phases. First of all, the scientific and engineering objectives of physical properties measurements were reviewed, as these defined the need for specific properties. After setting this background, the relevant properties were used as a basis to determine the modes of measurement and the need for new techniques and instrumentation. Finally it was clear that some policy changes ought to be made to insure the best use of new and existing techniques.

II. OBJECTIVES OF PHYSICAL PROPERTIES AND MECHANICAL STATE STUDIES

One of the probable reasons that studies of physical and mechanical properties of oceanic rocks have traditionally received a low priority in DSDP and ODP is that the objectives of such studies have not been clear. Another reason is that many of the routine measurement techniques that have been used in DSDP and ODP were developed for geotechnical studies of the uppermost portion of the sediment column (0-100 m) and are not well suited to resolving the properties of the lower, more indurated portion of the sediment column and of the basement, which are generally of greater concern to the geologist and geophysicist. As a result, there is a frustrating mismatch between the techniques available and the objectives that many in the ODP user community have in mind.

Before new techniques can be suggested to provide the needed measurements, one must recognize the objectives for which these measurements of physical properties and mechanical state can be used. Many such objectives now exist and more arise as the geological sciences continue to become more quantitative. In this section we present a few examples of scientific objectives for which physical properties/mechanical state studies form a large component. We outline, as well, two other important objectives for these measurements. It must be emphasized that these examples are not all-inclusive, but only illustrative.

A. SCIENTIFIC OBJECTIVES

1. Compaction and Lithification in Basinal Settings

Compaction and lithification of sediments occur through a combination of mechanisms: (1) mechanical rearrangement of the granular aggregate, (2) outward diffusion of interstitial pore fluid, (3) internal deformation of the grains themselves by fracture or plastic creep, and (4) chemical dissolution and cementation. The first two mechanisms predominate in the shallow part of the sedimentary section, and therefore form the basis for the mechanical consolidation models developed and used by soils engineers. In soil mechanics, the last two mechanisms are collectively referred to as aging, because they are both strongly time dependent. These aging mechanisms are generally not included in models of mechanical consolidation because they operate at higher stresses and at slower rates, and therefore require deeper burial and long intervals of time before they will produce a significant effect. From a geologic perspective, however, they are clearly important.

While each of these mechanisms is fairly well understood, little is known about their relative rates and ultimate contributions to the compaction/lithification process. Of primary interest is: at what depth does the mechanical consolidation model break down and the aging mechanisms start to predominate, and what factors control this transition depth? The relatively simple depositional histories of deep-sea basinal sequences and the generally good paleontological control on the age of these sequences make them ideally suited for the study of this problem. Furthermore, the results of such a study would allow better prediction of the variation of porosity, density and mechanical strength in a sedimentary sequence, which is required for a variety of other investigations, such as (1) the analysis of submarine slope failure, (2) the study of diffusion and advection during diagenesis, (3) the study of seismic wave propagation in sediments, (4) the interpretation of gravity anomalies, (5) the modeling of basin subsidence, and (6) the determination of the initial mechanical properties of sediments accreted and subducted at convergent margins.

To explore the consolidation of basinal sediments adequately we need measurements of porosity, permeability and vertical effective stress. In some situations, horizontal effective stresses may also be needed. Attempts to obtain consolidation data during past DSDP/ODP legs have relied on consolidometer tests, which simulate the uniaxial strain conditions in basins.
Two difficulties have hampered past DSDP consolidation studies. First, since pore-fluid pressure could not be measured in the drill hole, there has been no way to determine the <u>in situ</u> effective vertical stress. In fact, consolidation tests have been used mostly as an indirect means to estimate pore fluid overpressure (e.g., Bryant et al., 1985). Future consolidation studies will require accurate measurements of <u>in situ</u> pore fluid pressure. Second, a more serious problem is the difficulty of obtaining undisturbed samples, without which the results of the consolidation test are meaningless (see Bryant et al., 1985). Even if drilling-related disturbance could be eliminated, the core is

still disturbed by the expansion of pore fluid and dissolved gas. It is quite obvious at this point that the necessary parameters for consolidation studies will have to be obtained by a combination of laboratory and downhole measurements.

2. Structural Response of Accreted Sediments

There have been a number of theoretical models recently published that seek to explain the mechanics and deformation of accretionary wedges. Potentially, these models could be used to determine how material flows within the accretionary wedge and how the wedge itself grows with time. Unfortunately, these models remain poorly constrained because so little is known about the rheology and strength of partially indurated sediments. For instance; are they best modeled as rate-independent frictional materials (e.g., Davis et al., 1983), as linearly viscous (rate-dependent) materials (e.g., Cloos, 1982; Emerman and Turcotte, 1983) or as a perfect plastic material (Stockmal, 1983)? What generalizations can be made about the strength of deforming sediments and what is the range of strength to be expected in natural settings?

Our current knowledge of the mechanics of partially indurated submarine sediments is not sufficiently complete to allow a comprehensive tectonic interpretation of the development of structures observed in them. The magnitudes of potential driving stresses can be estimated theoretically for some problems of interest (e.g., accretionary prisms and large submarine landslides), but without appropriate observations of the in situ strengths and stress, such theoretical modeling must remain largely unconstrained. It is necessary to have a much better understanding of the stress-strain behavior of such sediments, and of the mechanism, differential stresses, and physical property changes associated with faulting.

Pore fluids can play a central role in controlling the development of structures in sediments. In the process of compaction, large quantities of water can be released, resulting in a great deal of volume loss and, under some circumstances, in pore-fluid pressures well in excess of hydrostatic pressures (e.g., Moore and Biju-Duval, 1984). The poorly understood processes of overpressuring can be very important to deformation; in particular to faulting (e.g., Hubbert and Rubey, 1959; Davis et al., 1983). Our understanding of the flow of fluids is limited by, among other things, the fact that it is not clear under what circumstances thrust faults act as either fluid channels or barriers. Because of the relative efficiency of advective heat flow, such uncertainties are central to our eventual understanding of heat flow observations and thermal maturation in deformed submarine sediments, including accretionary prisms.

The lack of in situ data detailing the behavior of fluid-filled and deforming sediments has become the primary factor limiting the advance of our understanding of submarine structural geology. The effects of the compaction process upon the mechanical and thermal properties of sediments are particularly poorly known. In effect, there exists a large, poorly explored mechanical parameter space between soft sediments and hard rocks. This space can be largely filled by a combination of downhole logging and laboratory measurements.

3. Rheology and Strength of Sediments

The understanding of intrinsic behavioral patterns of partially lithified deforming sediments is one of broad scope and application. Such sediments are not confined to accretionary prisms, but also occur in other tectonically active settings (strike-slip faults, foredeep basins, pull-apart and other extensional basins) as well as in such settings as passive continental margins, where gravity supplies the deforming stress. Determination of the constitutive relations of such sediments has fallen between rock mechanics and soil mechanics and therefore has received very little attention; neither is there much information on the relationships among strain (deformational fabric), strength and physical properties.

Laboratory triaxial tests can provide some information concerning these relationships, but there are a number of problems with the application of these results. Laboratory tests are done at much higher strain rates than with natural deformation, and "aging" effects (cementation and diagenesis) are not represented. Laboratory conditions are unrealistically simple in a number of respects (stress path, anisotropy, and heterogeneities). Moreover, the large-scale shift between laboratory samples and the in situ state undoubtedly causes shifts in values. Although lab testing will remain an important aspect of sediment deformation studies, in situ measurements must be used to determine "absolute" values for many parameters.

B. CORRELATION OF DOWNHOLE LOGS WITH PHYSICAL PROPERTIES

Logging tools offer the promise of being able to measure the in situ physical properties of sediments rapidly. The use of logging tools in ODP sediments has been primarily to aid in the recognition of downhole stratigraphic features and their correlation with seismic reflection profiles. The present logging systems are adequate for this task. However, logging tools also have the potential to measure porosity and density quantitatively, and to determine composition qualitatively. Unfortunately, logging techniques rely on indirect or empirical relationships with the property sought, and they are subject to environmental problems, such as poor hole conditions in semi-lithified sediments. Also, in the ODP the techniques are being used in formations (e.g., igneous rocks) for which they have not been adequately calibrated. In other cases, direct measurements of a physical property are necessary to interpret a log correctly (e.g., grain density for some porosity logs).

For all these reasons there has been a recognized need for better correlation of physical properties measurements between logging and lab as well as for additional in situ techniques.

C. SCIENCE AND ENGINEERING DATA BANK

Another objective of physical properties and mechanical state measurements that is not related to a specific scientific problem is the creation of a reliable bank of engineering data for conditions on the deep ocean floor. Some engineering properties, such as "shear-strength", may not be of interest to many geologists, but are useful for design of future ocean floor structures, and for ODP engineering applications such as re-entry cones and casing assemblies. Moreover, we feel that it would be irresponsible not to collect useful data that would be relatively easily acquired during the ODP but very difficult otherwise.

III. PRESENT PROGRAM LIMITATIONS

Before launching into a review of the various physical properties and methods of measurements, it is necessary to note several types of limitations in the present program. These consist of policy limitations, the physical problems encountered in the handling of laboratory samples, and environmental effects on down hole measurements.

A. POLICIES

The low priority accorded the physical properties program in the past appears to have translated into the lack of policies concerning the methods and frequency of sampling, as well as sample preservation. The need for whole round core samples and for the very careful immediate preservation of samples are obvious to knowledgeable workers, but they have not been recognized or addressed by the establishment. Certainly standardization has been attempted and improved, but perhaps not pursued vigorously enough. Basically, there is a need for a set of sampling and preservation policies similar to those for organic geochemistry.

B. SAMPLE DISTURBANCE PROBLEMS

Because the quality of measurements for most physical properties is strongly affected by sample disturbance, the various sources of this disturbance were discussed at some length. Sources of sample disturbance or degradation are here discussed in order of occurrence, from those produced at the drill bit to those occurring during storage.

1. Changes During Drilling

a. Stress release. The process of cutting a core and transporting it to the surface removes the effective stresses on the sample and reduces the pore fluid pressure acting at the surface of the sample. Because of elastic rebound, the sample will increase in volume, in some cases up to 8%. This increase is reflected in increased porosity and decreased seismic velocities, as well as in porosity-related changes in conductivity, etc. Relief of pore fluid pressure may engender lack of saturation in low-permeability sediments, but the major effect is to allow any dissolved gases to exsolve and expand, often seriously disturbing the sediment fabric.

The stress-release rebound poses a major problem in the correlation of lab and *in situ* measurements. A large part of this effect can be "corrected" out, if the *in situ* stress is known and if the rebound effect can be determined. Unfortunately, *in situ* effective stresses, especially in tectonically deformed areas, are typically not well constrained.

b. Drilling disturbance. The sample disturbance caused by the drilling process varies widely as a function of coring technique, depth in the section, and lithology. Not only is the sample disturbed during coring, but the material a head of the bit can be subjected to high stresses as a result of vertical oscillations of the drill string. Clearly, deformation is less in shallow sediments with the use of the Hydraulic Piston Corer (HPC) than with rotary coring, but it is still uncertain if the lack of stratigraphic disruption in these cores is equivalent to a lack of mechanical disturbance. The large difference between core diameter and external cutting shoe diameter theoretically should result in severe distortion but the only evidence for such effects might be the excess of core length over penetration in some HP Cores.

It is also obvious that almost all rotary cores in the unconsolidated upper part of the sediment column are so badly disturbed as to be nearly useless for measurements of most physical properties and of mechanical state. For this reason the HPC is the only reasonable method of acquiring lab samples in shallow strata. In this setting, where induced sediment disturbance is likely, we should also rely heavily on in situ measurements, which have been highly developed by the commerical geotechnical community, but have not been utilized in the drilling program.

At greater depths, and in more cohesive sediment than the HPC can efficiently be used, rotary coring still deforms sediments, usually into "drilling biscuits." Whereas those features preclude some measurements of physical properties and most mechanical state measurements, astute use of data from biscuit centers at these intermediate depths may produce reasonable results. At depths greater than a few 100 m, drilling disturbance can vary from nothing to severe fracturing, but the effects are usually easily determined by visual inspection. From this zone downward the sediments can be treated basically as rocks.

2. Changes During Handling

Further changes to the physical properties and mechanical state of ODP cores occur during their processing. Severe bending and shocking of cores during extraction, sectioning, and transport have decreased with the ODP deck configuration, but these probably still contribute to disturbance of mechanical properties, as by inducing fractures in long unbroken pieces of consolidated sediment core.

Cutting of the core into sections causes negligible to moderate disturbance of physical properties, but the bisection of the core precludes or seriously hampers the measurement of mechanical state parameters in consolidation and triaxial tests.

Other effects that occur during lab processing are increase in temperature, loss of water (desiccation), and internal stress relaxation. Temperature-induced changes are measurable and correctable in many cases, but have not been monitored in the past. For some properties (e.g. resistivity) and for more accurate results, such corrections should be considered. Water losses have extremely important effects on many properties, which requires samples to be protected from the air conditioned atmosphere of the shipboard lab and to be analyzed as soon as possible. It has been recognized that not all in situ stresses are immediately relieved in more highly consolidated samples during drilling (Teufel, 1982) but that some decay over time. Although no advantage of this observation has yet been taken during the ODP, measurements of stress relaxation would be degraded with increasing time after core recovery.

3. Changes During Shipping and Storage

Core samples are potentially subject to damage during transit from the ship to the repository, and to further degradation by desiccation and biological activity during storage. The magnitude of these effects is largely determined by the method of core preservation. The geotechnical community has long had techniques for sealing samples in impermeable and shock resistant containers, but at present in the ODP it is up to an individual P.I. to request that samples be so handled. Moreover it was not clear that the efforts now expended are adequate or commonly undertaken.

To summarize, stress release effects are effectively unavoidable but partly correctable. Some effects of drilling disturbance can be minimized by giving careful thought to coring techniques and to the relative weight placed on lab and in situ measurements. Special handling and preservation techniques are needed for samples on which post-cruise measurements are to be made.

C. ENVIRONMENTAL PROBLEMS WITH DOWN HOLE MEASUREMENTS

Measurements of physical properties and mechanical state in the bore hole, both by logging techniques and by in situ geotechnical methods, have been viewed by many as far better than lab measurements. However, not only do both approaches have their intrinsic strengths and weaknesses, but there are also a number of environmental problems associated with down hole measurements in the ODP. Hole conditions in poorly to moderately consolidated sediments can reduce the quality of most logs in several ways. First of all, holes in these shallower sediments are often blocked by swelling clay or by cavings, making logging impossible. If open, they tend to be oversize and/or rugose. In such case the calipers may not centralize the sonde, or eccentric tools may not touch the borehole wall, both of which badly degrade the resulting logs. At present most logs cannot be run through the pipe or if casing is set. In either case this prevents logging in the uppermost sections of the hole.

Both bottom hole and side wall conditions affect various in situ measurements. Most geotechnical probes at the bit face cannot penetrate stiff sediments, or if they are made sufficiently strong, the sediment breakage that is induced by penetration renders the measurements unreliable. Thus, insertion of a piezometer into sediments which are so stiff that shear failure occurs, will result in destruction of any seal and in the recording of ambient borehole pressures. Another bottom hole problem is the collection of caved or sloughed material in the bottom of the hole after circulation is cut off at the beginning of testing. This commonly occurs in poorly cohesive or fractured sediment, leading to the insertion of the probe into a pile of chips rather than into undisturbed sediments, rendering measurements meaningless. Some other in situ measurements are also degraded by the irregular bore wall of less consolidated sediments: packers may not seat, and the bore hole geometry recorded by the televiewer will not reflect the mechanical state. Finally, invasion of the borehole wall by drilling fluid (usually sea water) may affect resistivity logs and the mere act of drilling will change the in situ stress state around the hole.

IV. PHYSICAL PROPERTIES; CAPABILITIES AND REQUIREMENTS

Physical properties are currently measured on board the JOIDES *Resolution* through a combination of logging and laboratory measurements. Although the instrumentation used in the logging program approaches state-of-the-art, major components of the laboratory program remain limited by antiquated equipment. The objectives, present capabilities and weaknesses of the present laboratory and downhole measurements program, together with recommendations for improving the lab program are presented below and in Table 1. Also presented are recommendations for logging improvements which would strengthen the laboratory physical properties program.

DENSITY AND POROSITY

Purpose

Accurate determinations of density and porosity are required as a function of depth in order to calculate sediment accumulation rates, the contribution of the sediment column to the earth's gravitational field and the elastic, mechanical and acoustic properties of the sediment column and the underlying basement.

Laboratory Measurements

Shipboard determination of porosity (ϕ) and density (ρ_b) is presently accomplished by gravimetric, volumetric, and gamma ray attenuation techniques. Gravimetric determination of porosity and density is accompanied by the determination of water content (wc) and grain density (ρ_g). These parameters are calculated by measuring the wet and dry weights and volumes of "chunk" sediment samples. Wet measurements are made immediately after the core is split order to minimize moisture loss. Dry weight is measured after the samples have been "dried" in a 105°C oven for 24 hours or freeze-dried for 12 hours and subsequently cooled in a desiccator. Weights are measured with a pair of electronic analytical balances interfaced with a microcomputer to counterbalance ship motion and have an accuracy of ± 0.01 g. Volume determinations are made with a helium-displacement pycnometer that has a nominal accuracy of ± 0.5%. A salt correction is applied to water content, porosity, and grain density values by assuming an interstitial fluid salinity of 35 ppt and estimating salt weight and volume from the amount of evaporated water. Porosity calculations assume that the samples are fully saturated. Sampling frequency is typically 1-3 samples per core.

Gamma ray attenuation techniques for determination of wet bulk density use the Gamma Ray Attenuation Porosity Evaluator (GRAPE) device that has been described in detail by Boyce (1976). The GRAPE device can be operated in a continuous vertical or horizontal mode to determine density along the length of a core section or in a static mode to determine density of discrete samples. The device operates by placing the sample or core section in a beam of X-rays and the attenuation of this beam is sensed by a scintillation counter, which measures the gamma rays that pass through the material. Density is calculated by using an appropriate gamma-ray attenuation coefficient, typically that of quartz. Density as determined by the GRAPE device is a function of the length of the gamma-ray travel path. This distance is controlled for discrete samples used in the static mode, but in the continuous mode varying core diameter is a common cause of spurious results.

Downhole Measurements

Porosity ($n\phi$) is determined in situ primarily with neutron and gamma ray wireline-logging tools. Sonic and resistivity sondes provide indirect measurements of porosity by using empirical relationships between velocity and porosity and resistivity and porosity.

The neutron log is an indicator of the hydrogen content of a formation. The hydrogen content that is measured reflects both free water in pores and bound water in clays. The hydrogen content in organic matter is also included. The neutron tool contains two pairs of detectors that sense gamma rays resulting from the capture of thermal neutrons in the formation. The ratio of the counts in the two detectors is related to the moderating effect of the formation. This moderation is caused primarily by hydrogen atoms, because the masses of protons and neutrons are essentially equal.

The lithodensity tool emits gamma rays into the formation by means of a radioactive source mounted on a pad applied to the borehole wall by an eccentering arm. The gamma rays are compton-scattered through collisions with the atoms of the formation. The intensity of back-scattered gamma rays reaching two detectors thus depends on the electron density of the formation, which is proportional to the bulk density of the material. Because the gamma tool measures the bulk formation density, knowledge of the average grain density is required to calculate the porosity.

Weaknesses

The weaknesses of the present laboratory/downhole program to measure density and porosity are that:

a) Laboratory measurements of density and porosity in the sediments, even relatively undisturbed sediments, bear only an indirect relation to _in situ_ values because of rebound and degassing.

b) The continuous GRAPE technique is inadequate as a means of monitoring density and porosity in rotary cores because of variations in core diameter.

c) The density and porosity logs are degraded by borehole rugosity and the porosity logs suffer from calibration problems, particularly in basalt.

d) The neutron logs are influenced by the presence of elements that are strong absorbers of thermal neutrons.

e) No capability exists on board ship for open-hole physical properties logging in the unconsolidated sediments of the upper 100 m in most holes.

f) No systematic effort has been made to correlate and intercalibrate the lab and log measurements programs.

g) No systematic or adequate program of sampling and preservation exists for post-cruise physical properties studies and no lab exists to accommodate them.

Recommendations

1) Consolidation tests should be conducted systematically on selected samples so that density/porosity vs. depth curves can be corrected for rebound and compared to logs.

2) The porosity of gassy sediments should be determined from the water content rather than from volumetric methods.

3) Differential Thermal Analysis (DTA) should be systematically run on selected samples in order to determine the ratio of free to bound water in sediments for both mineralogical and log interpretation purposes.

4) A continuous mode x-ray backscatter device should be investigated as a possible replacement for the GRAPE since it can operate on split sections and is not dependent on sample thickness. Whether or not the GRAPE is

eventually replaced, continuous density profiling of core sections is desirable because it makes possible: (1) fine-scale density determination in variable lithology sections; (2) correlation between cores at multi-hole sites; and (3) positioning of cored intervals within the hole by means of correlation with well logs.

5) A comparison study should be made of the pycnometer and constant-volume sample techniques for soft sediment density determination.

6) Push-in logging tools have been developed by the geotechnical industry to determine density in soft sediments. The feasibility of these tools for use by the ODP in the upper 100 m of the sediment column should be investigated.

7) The neutron logging tools should be calibrated for use in igneous rocks by measuring the neutron absorption cross section for representative igneous core samples.

8) Dedicated whole-round samples should be taken routinely for shore based studies. These should be coated with a plastic, microcrystalline wax and store it submerged in saltwater to prevent desiccation.

9) A physical properties lab identical to that on the ship should be established at TAMU for tool modification and repair and for detailed post-cruise investigations by visiting scientists and engineers.

ACOUSTIC PROPERTIES

Purpose

Compressional (v_p) and shear (v_s) wave velocity measurements are needed in conjunction with density data to determine acoustic properties (e.g., impedance) of the sediment column. A comparison of synthetic seismograms derived from these data and seismic reflection profiles makes it possible to correlate core depths with seismic data.

Laboratory Measurements

Velocities are currently measured in the shipboard lab using a Hamilton Frame (V_p), a small uniaxially loaded velocimeter (V_p, V_s) and a continuous velocity logger (V_p). In each case the velocity is determined from the time of flight of an acoustic wave through a sample of known length. Velocities are measured through split core and "chunk" samples with the Hamilton Frame, through minicores with the uniaxial cell and through the liner with the core logger. All measurements are made at STP except in the uniaxial cell, in which case, a small, arbitrary load is exerted down the axis of the sample to improve coupling between the sample and the transducers.

Downhole Measurements

Velocities are measured downhole using a long-spaced sonic tool (V_p), a multichannel sonic tool (V_p, V_s) and occasionally, vertical seismic profiling (V_p). Whereas the long-spaced tool has been initially employed as a first arrival (V_p) tool, move-out and semblance techniques can be used on the full wave form data obtained from the 12-channel tool to determine the velocity of virtually any wave in the borehole. The vertical seismic profiling tool can be used to determine interval velocities from the mudline to total depth, and travel times to reflectors below the tool.

Weaknesses

The principal weaknesses of the current velocity measurement program are that:

a) The lab measurements are only indirectly related to in situ values because of rebound and degassing.

b) The log measurements are degraded by attenuation in some formations and no measurements are made in the upper 100 m of the sediments.

c) Shorebased measurements, if attempted, will be degraded by desiccation since no attempt is currently made to sample and maintain water content for post cruise investigations.

Recommendations

1) Restore selected samples to effective confining pressures (P_e) for V_p, V_s and attenuation measurements.

2) V_p, V_s and velocity anisotropy should be studied in soft sediments using velocity probes equipped with benders and ferroelectric ceramic transducers.

3) The feasibility of push-in velocity logging tools in the upper 100 m of the sediment column should be investigated.

4) Physical properties samples need to be taken and preserved (kept saturated) at a shore lab for post-cruise studies.

ELECTRICAL PROPERTIES

Purpose

Measurements of electrical resistivity are needed to characterize the resistivity structure of the crust. As well, resistivity measurements provide a means of determining porosity.

Laboratory Measurements

None currently made.

Downhole Measurements

Resistivity measurements are routinely made downhole using electrode and induction tools. A very long spaced electrode tool is occasionally used to determine average formation resistivities for large volumes of rock.

The induction tool provides three resistivity measurements with different investigative depths. Transmitter coils contained in the sonde radiate audio and higher frequency alternating currents that induce currents in the formation. These Foucalt currents create new magnetic fields that induce signals in the sonde's receiver coils. These induced signals are related to the conductivity of the formation. Electrode tools operate by using electrodes placed in the borehole fluid to induce currents in the formation. Potentials are then measured along the borehole using similar devices. Formation resistivity is primarily controlled by three factors: porosity, salinity, and the presence of hydrocarbons. In sediments drilled by ODP, hydrocarbons are virtually absent and have a negligible effect on resistivity. Similarly, salinity variations are usually negligible and if present can be detected by interstitial water sampling. Thus resistivity logs can be porosity logs, provided that they are calibrated with other porosity logs or core porosity measurements.

Weaknesses

As with laboratory density, porosity and velocity measurements, laboratory resistivity measurements will suffer from rebound and degassing. In addition, the data must be corrected to in situ temperatures. Shorebased measurements will suffer from desiccation unless adequate steps are taken to maintain saturation. The principal weakness in the current (and past) program, however, is that no routine lab measurements are made at all.

Recommendations

1) Pore fluid resistivity, R_f, should be measured.

2) Sample resistivities should be measured at several spot frequencies within the range from 100 to 10000 Hz. This would allow recognition of any significant complex component of impedance. The measurements should be made at effective confining pressure using a 2-electrode clamp cell with platinum electrodes.

3) The cation exchange capacity should be measured either by a membrane potential method (non-destructive) or by a wet chemistry method (destructive). If a compact membrane potential cell is available, this should be used for measurements on core plugs. Otherwise an ammonium acetate method

should be used on crushed offcuts.

4) Push-in resistivity logging tools should be developed and used in the upper 100 m of the sediment column.

5) Complex resistivity logs should be run to complement lab measurements.

6) As noted above, whole round core samples should be taken and preserved (kept saturated) for shorebased studies at a dedicated lab at TAMU.

THERMAL PROPERTIES

Purpose

Temperature and thermal conductivity measurements are required in order to calculate heat flow over the range of depths available in the borehole.

Laboratory Measurements

Thermal conductivity measurements are currently made in soft sediments using the conventional needle probe technique. A half-space probe in a constant temperature both has recently been put into use for measurement of thermal conductivity in hard rock slabs. The accuracy of the method remains to be determined.

Downhole Measurements

Temperatures in ODP holes are measured to refusal (about 200 m) in soft sediments using the HPC-T tool and the Barnes/Uyeda probe. At greater depths, temperatures are sometimes measured in the open-hole using one of several high resolution temperature logging tools available to the program.

The HPC-T tool is a small, solid state temperature sensor/recorder imbedded in the wall of the HPC cutting shoe. The tool records the sediment temperature for 10 to 15 minutes after each stroke of the HPC and is read at the surface after the HPC assembly is brought on deck. In this manner, numerous equilibrium temperature measurements can be taken to refusal during coring. The Barnes/Uyeda probe operates in a similar fashion but is deployed independently of coring. The temperature log monitors temperature continuously as the tool is brought to the surface. All three tools use thermistors as sensors.

Weaknesses

The weaknesses of the current program are:

a) The laboratory thermal conductivity measurements suffer from rebound and degassing.

b) During drilling, equilibrium temperatures can only be measured to refusal. At greater depths equilibrium temperatures can only be determined by allowing the hole to return to thermal equilibrium (which may take weeks) or by calculating the equilibrium temperature from multiple logging runs conducted after drilling is completed..

c) As with many other properties, thermal conductivity cannot be measured after the cruise because of desiccation.

Recommendations

1) Restore selected samples to effective confining pressure for thermal conductivity measurements in a Harbert-type pressure vessel.

2) Investigate measurement of thermal conductivity of hard rock samples using the divided bar technique.

3) For soft sediments, measure thermal conductivity with a 4-wire resistance device and a digital multimeter.

4) Measure conductivity anisotropy in selected samples.

MAGNETIC PROPERTIES

Purpose

Laboratory measurements of the magnetic properties (NRM intensity, magnetic susceptibility, stable inclination and declination) of core samples are required for plate reconstruction and magnetostratigraphic studies, for the interpretation of magnetic anomalies and for studies of the history of the earth's magnetic field.

Laboratory Measurements

Magnetic measurements are currently made in the lab using a spinner magnetometer (on minicores), a feed-through cryogenic magnetometer (on whole core) and a magnetic susceptibility logger. Facilities also exist for washing samples with an A.F. demagnetizer.

Downhole Measurements

Downhole measurements are made with a variety of tools including a vertical axis fluxgate magnetometer (field intensity), a gyro-oriented 3-axis fluxgate magnetometer (field intensity, inclination, declination), a vertical field gradiometer and a magnetic susceptibility tool (x).

Special Coring Capabilities

Oriented HPC cores can be taken with a core barrel equipped with a multi-shot camera and a compass. Non-magnetic drill collars are also available to minimize the magnetic effects of drill pipe on samples.

Weaknesses

Although the laboratory and downhole equipment is generally adequate, there are two weaknesses in the programs:

1) There is no reliable way to take oriented hard rock samples.

2) The downhole logging tools are too insensitive to operate in sediments.

Recommendations

1) Develop a means of taking oriented hard rock samples.

2) Conduct thermal demagnetization measurements on board ship.

PERMEABILITY

Purpose

Permeability is an important factor in many processes in the sea floor, including sediment diagenesis, low temperature alteration in the basement, hydrothermal circulation, ore deposition and basement-seawater interaction. Despite this importance, no more than half a dozen permeability measurements have been made downhole to date in oceanic basement, none have been made in the sediment column and very few have been made on core samples in the lab.

Laboratory Measurements

Intergranular permeability of highly porous sediments can be measured on board during routine consolidation tests using a back-pressure consolidometer. In this stepwise procedure, determination of permeability at various preconsolidation pressures should provide an approximation of in situ hydraulic conductivity under uniaxial load conditions. With the consolidometers available this procedure is limited to soft, compressive sediments commonly encountered in the upper 200 m of the sediment column. Intergranular permeabilities in less porous sediments and in basement rocks can be measured with a constant-head permeability apparatus. Such tests require the use of pressure intensifiers and pressure vessels to obtain suitable differential pressure heads and in situ confining pressures.

Downhole Measurements

In situ permeability tests provide the best means of assessing the gross permeability of the oceanic crust and overlying sediments as it pertains to large scale hydrogeological processes. When conducting tests in a single drill hole, a rubber packer with either one or two inflatable elements is used to hydraulically isolate a section of the borehole, and permeabilities are measured using either the pulse-decay technique (Bredehoeft and Papadopulos, 1980) or the steady-state injection test (Ziegler, 1976). The pulse-decay and steady-state injection tests are best suited for use in formations of low or high permeability, respectively. In the pulse-decay, or slug, test the background borehole pressure is monitored for a brief period and water is rapidly injected into the test interval to create a pressure pulse. This pulse then decays with time as water flows radially outwards into the formation. The permeability, and to a lesser extent the storage coefficient, of the formation can then be determined from the shape and duration of the pressure decay curve. In the injection tests, water is pumped into the test interval at a constant flow rate until the borehole pressure stabilizes at some equilibrium value. Formation permeability is then determined from this flow rate and borehole pressure (measured relative to the undisturbed formation pore pressure). When three or more flow rate/borehole pressure combinations are obtained for a given test interval, this test provides insight into the sensitivity of aquifer permeability to changes in effective stress, the extent of turbulent flow in the aquifer during testing, and the degree of leakage past the packer. Use of these techniques is limited to well-indurated sediments and basement rocks where the hole may be left open (uncased) and accessible to the borehole fluid without fear of encountering hole stability problems. In situ permeability tests in soft sediments require a very different testing technology.

Weaknesses

1) Permeability measurements made with a consolidometer, while far superior to those made at atmospheric pressure, will still depart from tests at in situ confining pressures and will suffer from degassing.

2) No shipboard capability yet exists for downhole measurement of permeability in soft or semi-consolidated sediments.

Recommendations

1) As a complement to the consolidometer permeability tests that are now conducted, both sediment and basement rock permeabilities should be measured in the laboratory on recovered core at in situ effective confining pressures in a small pressure vessel. In conjunction with in situ tests, these data could be used to assess the relative contribution of natural fractures and the rock matrix to in situ permeabilities. By using a combination of steady-state and transient techniques with such an apparatus (e.g., Bernabe et al., 1982) a wide range of permeabilities

could be measured in both soft and well-indurated sediments as well as in basement rocks. Laboratory permeability tests in poorly-indurated sediments are especially important because packer permeability tests have been difficult or impossible to conduct in these materials owing to hole stability problems.

2) To evaluate the magnitude of permeability anisotropy in the oceanic crust and sedimentary cover, permeabilities should be measured in both horizontal and vertical directions on selected samples (e.g., parallel and perpendicular to bedding in the case of sediments and sedimentary rocks).

3) In situ determination of permeability in very soft sediments should be done by inserting a piezometer probe through the drill bit into the undeformed sediments. Permeability is then determined by monitoring the insertion-induced pressure rise and post-insertion decay (Bennett and others, in press), in a manner analogous to the pulse-decay test. This procedure also provides an in situ determination of undrained shear strength, and hence is critical not only to assessing in situ conditions, but to evaluating the permeability and shear strength determinations made in the shipboard laboratory.

4) The feasibility of measuring permeability in semi-consolidated sediments with a self-boring pressure meter adapted for ODP use should be explored.

ENGINEERING PROPERTIES

Purpose

Several measurements of particular interest to geotechnical engineers have been made during past ocean drilling, and several more might usefully be made. Such measurements as undrained shear strength, Atterberg limits, and uniaxial compressive strength are not directly applicable to mechanical state studies but are of great importance in a comparative sense in the study of the engineering behavior of the sea floor sediments. Moreover, there have been attempts to relate some engineering properties to mechanical state parameters.

Laboratory Measurements

The shipboard mechanical properties program is currently limited to the measurements of undrained shear strength of soft-sediments. This is done using a motorized vane shear device or a hand-held Torvane. Most measurements are made with the vane axis parallel to bedding.

Downhole Measurements

No borehole geotechnical capabilities exist within ODP.

Weaknesses

1) The routine shipboard mechanical properties program is limited to shear strength measurements in unconsolidated sediments. Because the measurements are undrained and the samples have suffered rebound and degassing, the data cannot be closely related to in situ data. Moreover, because most of the data is taken in a direction perpendicular to that in conventional tests, they cannot easily be related to other data.
2) No mechanical properties measurements are made in consolidated sediments or hard rock.
3) No capability exists within ODP for conducting borehole geotechnical measurements.
4) No provision is made for routine collecting and adequately preserving core in the round for post cruise testing.

Recommendations

1) Laboratory vane shear measurements should be taken perpendicular to bedding using established ASTM procedures, preferably on the ends of core sections.
2) Atterberg limit and triaxial compression tests should be conducted on selected samples at a dedicated shorelab.
3) Whole round core samples should be taken routinely for post-cruise

geotechnical properties studies. To prevent desiccation, they should be covered with wax and stored underwater.

4) The geotechnical properties of soft and semi-consolidated sediments should be studied in situ using piezocone, vane shear and pressuremeter techniques developed by the geotechnical industry.

"GEOLOGIC" CORE LOGGING

Purpose

The objective of continuous coring is to obtain a continuous record of, well everything, versus depth. Perhaps the most important information to measure continuously is composition since it can be used (for example) to distinguish sedimentary environments, to determine source areas and to study diagenesis in sediments and to identify different eruptive units in basement.

Laboratory Measurements

At the present time, the composition of each core is described visually with qualitative spot checks provided by smear slide analysis and semiquantitative spot checks by XRD and XRF.

Downhole Measurements

Qualitative determinations of composition are made downhole using natural and spectral gamma logging tools (K, U, Th) and neutron activation (Fe, Si, Ca, S, Al, Mn, H, Cl).

Weaknesses

1) The quantitative laboratory measurements, though complete, are discontinuous.

2) The downhole measurements are not very accurate and take prohibitively long to run.

Recommendations

1) The shipboard lab should be equipped with a continuous spectral (K, U, Th) natural gamma ray core logger.

2) The measurement of physical properties should be conducted on samples for which composition (grain size, chemical composition) has been determined.

3) Continuous-feed X-radiography should be evaluated for shipboard textural scanning of the core.

4) Continuous-feed neutron activation analysis should be evaluated for post-cruise geochemical analysis of the core at a dedicated shore lab.

V. MECHANICAL STATE

Closely related to physical properties of rocks is their mechanical state, which includes the states of stress and strain, and parameters of strength (e.g., cohesion, internal friction). Because the measurement of stress and strain has received so little attention during ocean drilling and because of the growing interest in these quantities, a somewhat expanded discussion of techniques applicable to the ODP is included here.

STRESS STATE

Knowledge of the magnitude and direction of in situ stresses is critical to the understanding of the nature of the forces driving plate motion and rock deformation. Because many outstanding questions exist about the state of stress at depth, determination of in situ stress should be an important goal of the drilling program. Unfortunately, with the exception of a determination of the direction of maximum horizontal compression made near the Costa Rica Rift by Newmark et al. (1985), no direct measurements of stress magnitudes or orientations have yet been made in the oceanic crust. The method currently used to determine in situ stress orientation and magnitude at depth is the analysis of induced hydraulic fractures. The orientation of the stress field can often be inferred from well bore breakouts. In addition, a new stress measurement method based on stress-induced polarization of Stoneley wave particle motion has been successfully used to determine stress orientation in several wells on land and has the potential for estimation of relative stress magnitudes. Other potentially useful methods to determine the orientation of stress include stress release strain anisotropy and the orientation of natural fractures. In each case the stress measurement method is perceived to be relatively robust and has the potential for working under the extreme environmental conditions likely to be encountered in oceanic drill holes.

At the same time, it is important to have accurate measurements of pore pressure, if we are to develop realistic models for consolidation of sediments in basins and for the mechanical behavior of oceanic sediments at convergent margins. This importance stems primarily from the control that pore pressure has on the effective stress in geologic materials. Evidence for pore pressures that are well in excess of hydrostatic pressures is widespread (Hottmann et al., 1979; Carson et al., 1982; Moore et al., 1984; Westbrook and Smith, 1983). In addition, measurements of non-hydrostatic pore pressures in basement rocks have been shown to be indicative of active geothermal systems near mid-ocean ridges (Anderson and Zoback, 1982; Hickman et al., 1984; Anderson et al., 1985). Determination of pore pressure requires downhole measurements, although estimates can be made from consolidation tests of suitably high quality.

A. Pore Pressure Measurements

In well-indurated sediments and basement rocks, in situ pore pressures are best measured using inflatable rubber packers and a variety of measurement techniques. In the passive shut-in technique (Apps and Doe, 1979), the borehole is hydraulically isolated ("shut-in") at the packer and the borehole pressure is monitored with a downhole pressure recorder as the interval pressure converges toward an equilibrium value. The time required to reach an equilibrium shut in pressure in a test depends upon such factors as aquifer permeability, test interval length, aquifer and borehole coefficients, and the length of time during which water was injected into or withdrawn from the hole prior to shut in. This is the preferred method for <u>in situ</u> pore pressure measurements at sea because the results from this test do not depend upon knowledge of aquifer geometry and boundary conditions and can provide an unambiguous upper or lower bound on the near-field pore pressure in the formation even in cases where an equilibrium shut-in pressure in never reached.

Alternate measurement techniques, which require pumping water into the formation at constant flow rate and monitoring the recovery of borehole pressure following cessation of pumping (see Pickett, 1968), should also be attempted where possible (for example, in conjunction with steady-state injection tests). Regardless of the techniques employed, the most representative pore pressure measurements are obtained when the packer tests are conducted as soon as possible after the completion of drilling.

Determinations of pore pressure in near surface, less consolidated sediments have been made by the geotechnical community routinely for nearly a decade using push-in piezometers (Hirst and Richards, 1977; Dunlap et al., 1978; Bennett and Faris, 1979; Bennett et al., 1982), but this technology has not yet been successfully adapted to the ODP. With this technique, induced pore pressures are allowed to dissipate, and ambient values are recorded. For ODP, piezometers might be mounted on a probe or on the hydraulic piston corer. In either case, pressure determinations must be made in the "undisturbed" sediment ahead of the bit, <u>during</u> the drilling phase. The time required to obtain an equilibrium pressure depends on the permeability and storage coefficient of the sediment, the configuration of the probe, and the rate of insertion. Note that the pore pressure data, when recorded from time of insertion to return to ambient pressure, simultaneously provide the data upon which <u>in situ</u> shear strength and permeability can be calculated.

B. Deviatoric Stress Measurements

1. Hydraulic Fracturing

The hydraulic fracturing method is discussed in detail elsewhere (e.g. Zoback and Haimson, 1982; Hickman and Zoback, 1983) and will only be briefly outlined here. When conducting a hydraulic fracturing test, an unfractured section of the borehole about three meters in length is selected using the borehole televiewer and other logs. This section is then isolated from the rest of the borehole using inflatable rubber straddle packers and the pressure in the interval is raised until a hydraulic fracture is formed along the azimuth of maximum horizontal compression. Repeated pressurization cycles of increasing duration are then conducted to extend the fracture. The magnitudes of the minimum and maximum horizontal principal stresses, S_h and S_H respectively, are determined from the pressure-time curve obtained during the test. After the test is completed, a borehole televiewer or impression packer is used to determine the azimuth of the induced fracture at the borehole wall and hence the azimuth of S_H.

The validity of the hydraulic fracturing method relies upon a number of fundamental physical assumptions which should be taken into account when attempts are made to measure in situ stresses in future ODP holes. 1) It is assumed that one of the principal stresses is parallel to the borehole. Any deviation from this assumption will produce errors in the inferred orientation of the stress field, with the magnitude of this error depending upon the relative magnitudes of the three principal stresses (Richardson, 1983). 2) When determining the magnitude of S_H it is assumed that the borehole is cylindrical and that the material around the borehole behaves in a perfectly linear elastic manner. This assumption is not likely to present a problem in basement rocks, but may be seriously violated in sections of ODP holes penetrating even moderately indurated sediments. Repeat televiewer logging (in the travel-time, or caliper, mode) might be conducted in sedimentary sequences where hydraulic fracturing measurements are being contemplated in order to avoid intervals exhibiting time-dependent relaxation of the borehole wall. This should be supplemented by triaxial creep tests on core recovered from these intervals in order to identify non-linear or visco-elastic material behavior. 3) When determining the magnitude of S_H it is further assumed that fluid diffusion into the rock surrounding the borehole prior to breakdown or fracture reopening is insufficient to raise the interstitial pore pressure and alter the stress concentration at the borehole wall (see discussion by Alexander, 1983). In order to ascertain that the intrinsic permeability of the host rock is sufficiently low so as to satisfy this assumption, we suggest that the laboratory permeability tests proposed previously also be conducted on core recovered from the intervals where hydraulic fracturing tests have been conducted.

2. Breakouts

Stress-induced wellbore breakouts have become increasingly important in the last few years because they have proven to be reliable indicators of the direction of the horizontal principal stresses (e.g., Bell and Gough, 1979; Plumb and Hickman, 1985; Hickman et al., 1985). Breakouts result from failure of the rock around the wellbore in response to the concentration of compressive stress (Gough and Bell, 1981; Zoback et al., 1985). The region of spalling is centered at the azimuth of the least compressive horizontal principal stress. The process of breakout formation may be evaluated theoretically through the well-known equations derived by Kirsch (1898). The equations define the stress distribution for a cylindrical hole in a thick, homogeneous, isotropic elastic plate subject to effective maximum and minimum principal stresses. At the point of maximum stress concentration around the wellbore the compressive hoop stress is $3S_{Hmax}-S_{hmin}-P_0$, where P_0 is fluid pressure, a value which can increase rapidly with depth. For the case when fluid pressure in the wellbore is equal to that in the formation, Figure 1 shows the variation of hoop stress as a function of azimuth around a well for nominal values of S_{Hmax} and S_{hmin}. If the uniaxial compressive strength of the rock is sufficiently high, as at C_1, the strength exceeds the concentrated stress and no breakouts occur. However, when the strength of the intact rock is exceeded by the concentrated stress, as at C_2, the rock will fail in a restricted section of the wellbore (at angles of 0 to θ'). However, if the rock is sufficiently weak, as at C_3, failure would be expected to occur at all azimuths. The depth of occurrence of breakouts depends upon the state of stress (orientation of regional principal stresses), rock strength and density of the drilling fluid.

3. Stonely Wave Polarization

The propagation characteristics of Stonely waves in boreholes is described by White (1962) and Cheng and Toksoz (1984). This type of borehole surface wave, often called a tube wave, propagates along the borehole at phase velocities less than the shear velocity of the medium. These waves are very commonly observed during vertical seismic profiling (VSP) experiments. In a borehole drilled into a homogeneous, isotropic, elastic solid, the tube wave particle motion is prograde elliptical, with the major axis along the borehole and the minor axis oriented in a radial direction. Based on the fact that seismic wave velocities near the borehole are very anisotropic due to the concentrated stress field, a new stress measurement technique is described by Barton and Zoback (1986) involving analysis of stress-induced polarization of tube wave particle motion.

If the rock around a wellbore has a uniform velocity distribution the horizontal component of tube wave particle motion is radial. However, by studying three-component open-hole VSP data in two different wells it has been found that the particle motion direction is not radial, but is polarized into

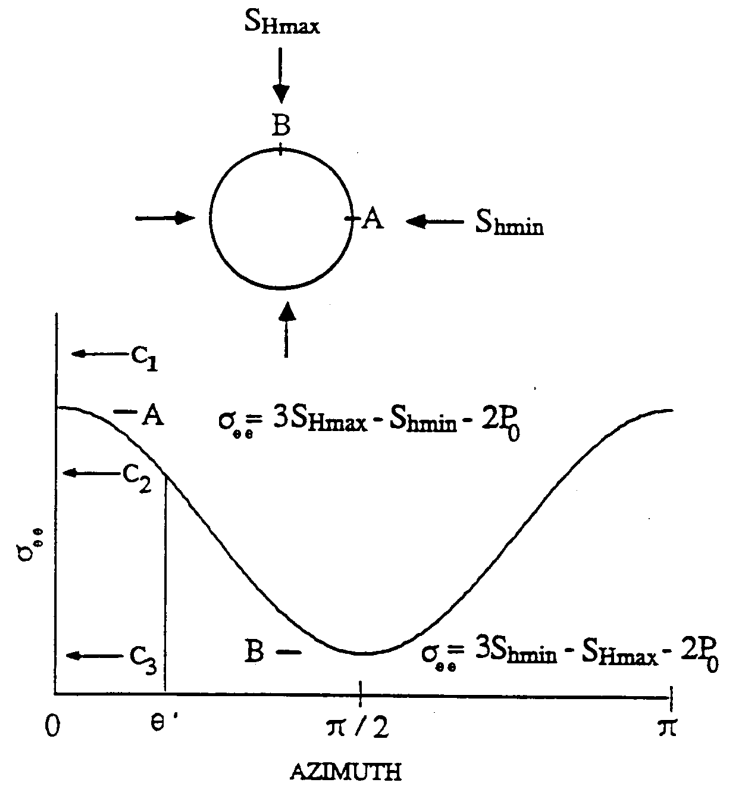


Figure 1. Azimuthal distribution of stress in a borehole, governing the occurrence of "break-outs."

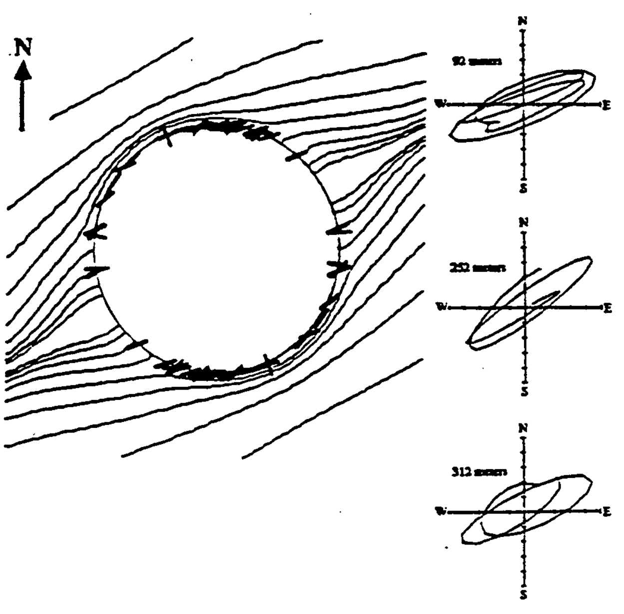


Figure 2. Maximum principle stress trajectories (left) and the tube-wave particle motion (right) in a Paris Basin well.

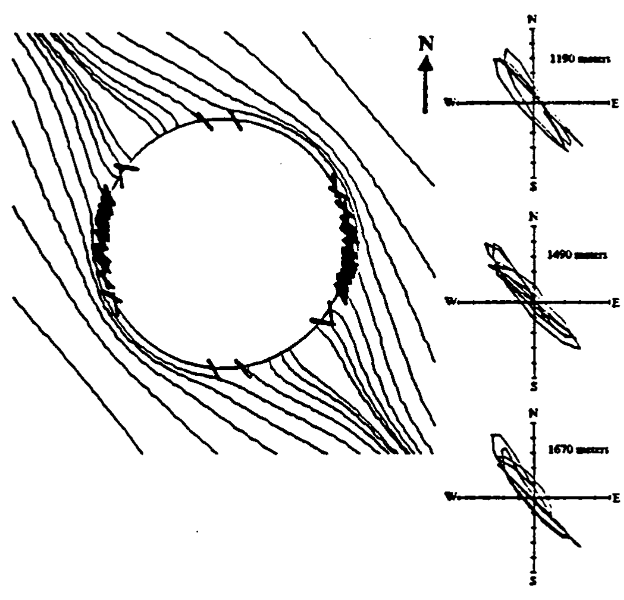


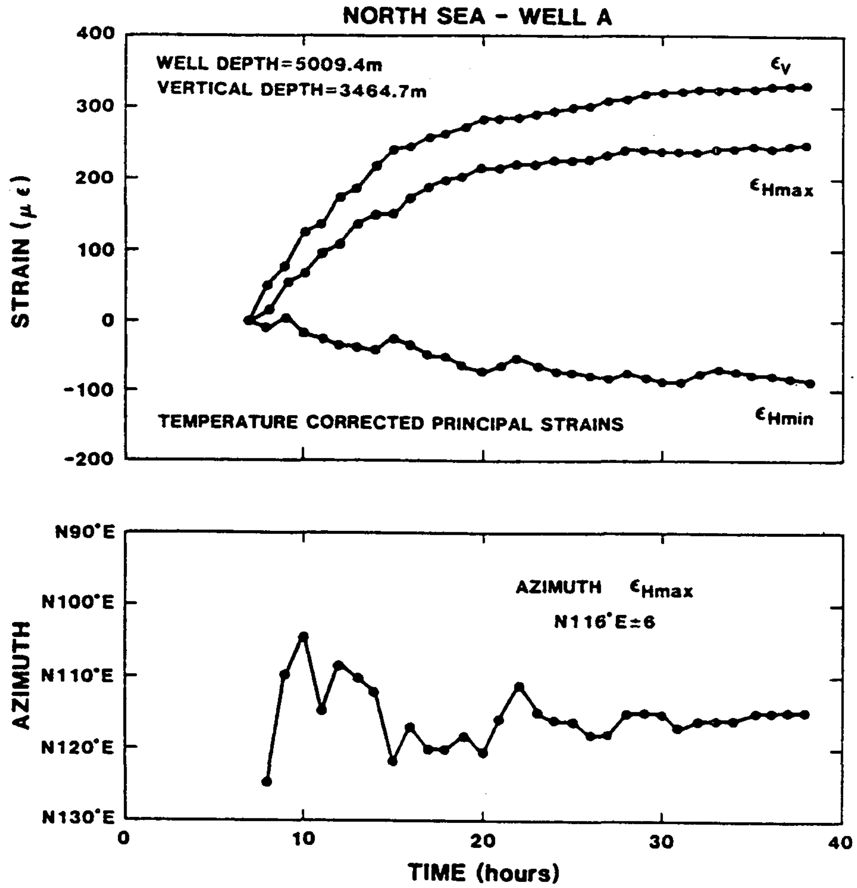
Figure 3. Maximum principle stress trajectories (left) and the tube-wave particle motion (right) in a Paris Basin well.

the direction of maximum horizontal compression. On the right sides of Figures 2 and 3, tube wave particle motion plots are presented for three depths for wells in the Paris Basin and Oklahoma. In the case of the Paris Basin (Fig. 3), the polarization direction is about N35°W, consistent with the regional stress field for central Europe. The particle motion is polarized in the N60°E direction in the Oklahoma well (Fig. 2), again consistent with the regional stress field.

Perhaps one of the best ways to view the influence of the stress field on the tube wave particle motion is to project onto a single cross-section all of the particle motion polarization directions for the various depths and azimuths at which the seismometers were emplaced during the VSPs, and to show on the same plot the trajectories of maximum principal stress around the wellbore. This is shown on the left sides of Figures 2 and 3. It is clear that the horizontal projection of particle motion is not radial, but instead follows the direction of the local stress maximum. The difference between the particle motion ellipticities in Figs. 2 and 3 is clearly reflecting a difference in the local stress states and material properties. Current research involves solving the theoretical problem to separate out these effects and make determination of stress magnitude possible.

4. Anelastic Strain Recovery

The determination of in situ stress orientation from creep recovery has been shown to be a reliable and easily undertaken technique (e.g., Teufel, 1982). In this anelastic strain recovery (ASR) method, a core, which has been sealed against water loss, is placed, as soon as possible after coring, in a simple apparatus in which diametral and axial changes in dimension are measured over a period of several days (Fig. 4). If a sample is isotropic or, with sediment cores, if two principle stresses lie within bedding, three different radial displacements over a 90° arc in the plane of the bedding will define the



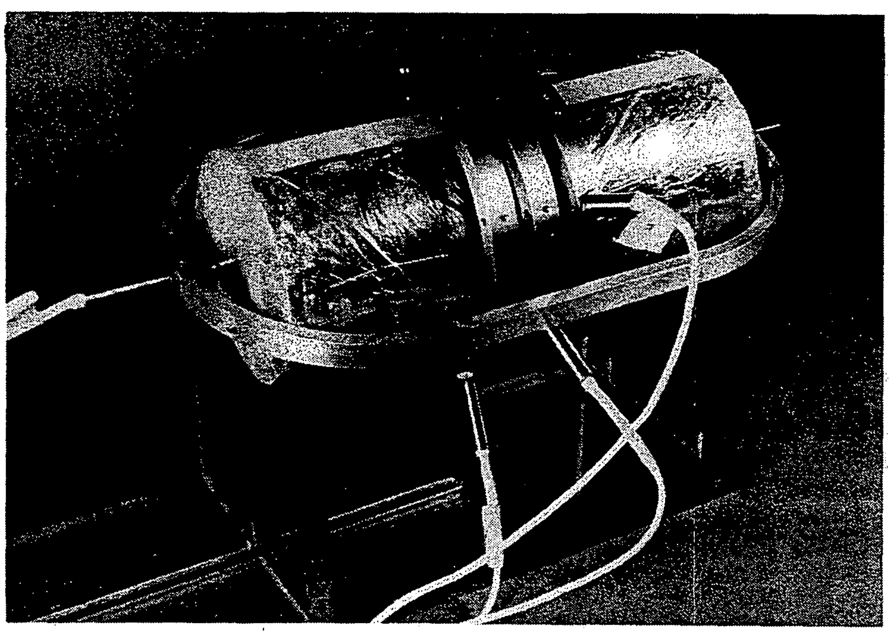


Figure 4. Upper - Plot of principle strains and azimuth of maximum horizontal strain with time, from ASR analysis.
Lower - Photo of core with instrumentation for anisotropic strain recover (ASR) measurements.

orientation of the stress ellipse. More recently Teufel and others (e.g., Blanton and Teufel, 1983; Teufel and Warpinski, 1984) have shown that under appropriate conditions it might be possible to determine in situ stress magnitudes from anelastic strain recovery measurements. These measurements would appear very suitable to the ODP, where cores can be quickly processed.

5. Natural Structural Features

Finally, natural fractures and other structural features observed in drill cores can provide evidence for the orientation of the stress tensor. A conjugate set of shear fractures observed in slightly deformed sediments of the Nankai accretionary prism, coupled with paleomagnetic data was capable of indicating the orientation of σ_1 as well as the relative orientations of σ_2 and σ_3 (Karig, 1986). This technique requires that the core be oriented and also assumes that these strain features reflect the stress tensor that exists at the core location.

Recommendations

1) Employ, on an experimental basis, the various downhole techniques suggested above for the determination of deviatoric stress components in both basement rocks and the more highly indurated sediments.

2) Develop a technique for taking oriented samples in semi-consolidated sediments and hard rock.

3) Measure in situ stress direction and magnitude on selected oriented core samples using strain relaxation techniques.

4) In situ determinations of pore pressure in soft sediments using the geotechnical push-in probes described above should be adapted to ODP use.

5) Investigate the feasibility of in situ stress and pore pressure measurements in semi-consolidated sediments with a self-boring pressuremeter adapted to ODP use.

PARAMETERS OF STRENGTH

When deformed, sediments and other rocks will either yield plastically, as occurs in compaction of basinal strata, or will fail, as in the case of land slides. Plastic yielding is defined as the permanent strain acquired before the material fails. Failure is defined as that point when a biaxially or triaxially strained material attains its peak strength or supportable differential stress. Variations of rock strength as a function of mean stress, porosity, strain rate, temperature, etc., provide information concerning the constitutive relations that define mechanical behavior. As discussed in the section on scientific objectives, a better understanding of the yield and failure behavior of sediments is important to answering a number of fundamental geologic questions. Furthermore, such information is essential for the proper construction and quantification of geomechanical models of the subduction accretion process.

Measurements of yield and failure can be made both in situ and on laboratory samples, but the most common technique is laboratory triaxial testing. The details of modern triaxial testing, particularly as they apply to porous sediment is discussed by Schofield and Wroth (1968), Atkinson and Bransky (1978) and Bishop and Henkel (1962). Triaxial testing equipment varies widely in capability, depending on the application. The apparatus used by geotechnical engineers for highly porous soils is designed for low stress, large sample volume, and is very sensitive to pore fluid behavior. Testing equipment used in geophysical rock mechanics is generally capable of very high stresses, uses small samples, and is not generally well-suited for measurements of pore fluid behavior. The samples collected in the ODP will require a very wide range of capability, from the low stress, pore fluid sensitive cells for shallow sediments to higher pressure cells for basement rocks.

Triaxial testing is time consuming and requires carefully designed test programs if useful results are to emerge efficiently. If in situ strength is sought, the correct effective stress state must be chosen. On the other hand, if a series of tests at different effective mean stresses and porosities is undertaken, the constituitive relationships of that material can be generated; if a pressure-dependent Coulomb criterion is assumed, the coefficient of cohesion and internal friction, at both peak and ultimate (residual) strength can be estimated. If carefully performed, these tests can also provide elastic moduli. Triaxial testing of ODP sediments would be a highly appropriate undertaking as there are very few data concerning the strength of marine sediments with the range of porosities (60% to 30%) represented by most ODP cores.

Triaxial testing of the more porous, lower strength sediments could be made in the shipboard lab, whereas testing of the stronger sediments and basement rocks would have to be done in labs on shore using carefully preserved samples. Because of the test duration (often up to several days), only selected samples could be tested, and triaxial tests would not be considered a routine operation.

The angle between conjugate shear fractures is a measure of internal friction in the Coulomb criterion. Natural shear fractures, if they can be shown not to be subsequently deformed, can thus provide an in situ estimate of one mechanical parameter. This technique was attempted, apparently successfully on D.S.D.P. leg 87, and deserves further attention.

Recommendations

1) Develop a realistic shipboard triaxial testing program for the more porous, lower strength sediments to determine in situ strength. Because these are so time consuming, careful choice of samples and objectives would be necessary.

2) Encourage triaxial testing programs on lower porosity, higher strength

rocks in suitably equipped shore-based labs.

3) Whole round samples of selected sediments should be taken and carefully preserved for post-cruise triaxial studies of various types.

DEFORMATION, STRAIN AND STRUCTURE

Analysis of the displacement field in oceanic rocks is inextricably linked to physical properties and to the state of stress. From displacements and their gradients come information necessary for determination of crustal kinematics, for structural and tectonic analyses, for consolidation studies and for the determination of mechanical moduli. Gross displacement and strain have been deduced from seismic profiles and from other stratigraphic data, but this approach breaks down where deformation reduces seismic coherence and almost never affords enough control to determine the strain tensor or even its components.

Although very few quantitative analyses of strain have been undertaken during ocean drilling, the capabilities for these exist elsewhere and can be applied to the ODP. Both in situ and lab techniques exist, but the laboratory methods seem most immediately applicable to deep ocean drilling. These include microfabric analyses, and anisotropies in seismic velocity, magnetic susceptibility and mineral orientation.

Structural studies of cores on the detailed (cm scale) and microscale level can be used to determine the style of deformation (e.g. brittle or ductile), which in turn can be related to the consolidation state or the effective mean stress (e.g., deformation via intergranular flow, cataclasis, pressure solution). These studies also can, if markers can be identified, be used to determine the finite strain, as well as giving information on progressive strain paths.

Recent studies have demonstrated that anisotropies in several parameters can be related to the state of strain; particularly in sediments that have principal strains parallel and perpendicular to bedding. To date, anisotropies in Vp (Engelder, 1979), magnetic susceptibility (Kissel et al., 1986), and in X-ray goniometric patterns show deviations from the radially symmetric initial bedding-parallel fabric in these properties. Because these methods are quantitative, they show the ratio of 2 principle strains as well as their orientations. Systems in which strain is not coaxial are more complex and difficult to interpret, but for most structures encountered in the ODP, bedding remains approximately horizontal. There is still much work to be done on the magnitude of ratios of anisotropies, but advances are rapidly being made in this area.

Recommendations

1) Determine magnetic susceptibility anisotropy on selected samples as part of the shipboard lab routine.

2) Encourage the measurement of seismic anisotropies at in situ mean stresses on board and in shore-based labs that have suitable equipment.

3) Make quantitative measurements of structural fabric a standard and routine component of shipboard lab routine.

VI. SUMMARY OF RECOMMENDATIONS

In order to accomplish the scientific objectives associated with the measurement of physical properties and mechanical state in the ODP we are recommending several new or improved coring and in situ measurement capabilities, new laboratory equipment, and several policy changes with respect to sampling.

NEW LABORATORY EQUIPMENT

a) DTA (differential thermal analysis) gear for porosity studies

b) constant volume cylinders for sediment density measurements

c) Ferroelectric ceramic/bender probes for soft sediment V_p, V_s measurements

d) Harbert pressure vessel for V_p, V_s, Ω, thermal conductivity and permeability measurements at in situ pressure

e) membrane potential cell for cation exchange studies

f) Hanson Research (UK) 240 Hz 4-arm electrode cell for pore fluid resistivity measurements

g) divided bar apparatus for hard rock thermal conductivity measurements

h) digital voltmeter, 4-wire resistance device for soft rock thermal conductivity measurements

i) thermal demagnetization gear for paleomag lab

j) constant flow rate permeameter

k) Sandia anelastic strain relaxation (A.S.R.) gear to measure the in situ stress ellipsoid

l) Atterberg limit equipment

m) triaxial compression tester

n) Harbert spectral natural gamma core logger

In addition, ODP should consider consolidating all of its continuous-feed core loggers (NRM, ρ, γ, χ) into one operation to save time and should evaluate the following equipment for future acquisition:

a) X-ray backscatter logger to replace GRAPE

b) X-radiography logger for textural scanning

c) neutron activation compositional logger

NEW DOWNHOLE CAPABILITIES

Recommendations

a) The biggest single improvement related to the measurement of physical properties and mechanical state would be the ability to make measurements in semi-consolidated to more consolidated sediments, as well as in igneous rocks. As reviewed earlier, probes or other devices cannot be pushed into the formation ahead of the bit without destroying the probe or the environment; clearly a new approach is needed. For some measurements, such as pore pressure or bulk

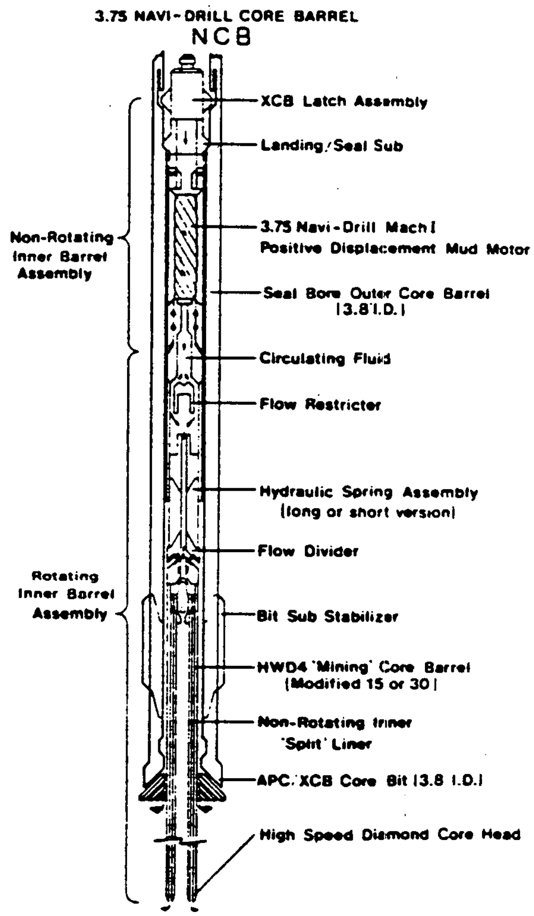


Figure 5. Diagram of mud-motor driven Navidrill assembly now being developed by ODP.

permeability, a section of the entire hole could be packed off, but this is inefficient or unreliable for some other types of measurements.

A much better way to collect in situ data in more in more indurated material would be to create a small diameter "probe" hole in front of the bit, which would be a controlled-environment cavity, in which a large number of measurements could be made. Thus this recommendation has two distinct aspects; (1) the ability to create a probe hole and (2) the development or modification of probes to measure properties and conditions in the probe hole.

The ability to drill a probe hole ahead of the bit is already being developed by ODP in the Navidrill project (Fig. 5). The Navidrill assembly uses a mining type, continuous diamond core bit that drills a 3.75" diameter hole up to 10 m in front of the rotary bit and collects a well-gauged 2.40" diameter core. Although initially developed to collect higher quality and more complete cores in hard rock, this core assembly would be well-suited for the creation of a probe hole. Such a hole, even only 3 or 4 m long, if packed off near the bit face, would come to equilibrium with the formation relatively quickly, as well as being protected from sloughing and settling of chips in the main hole. Moreover, the stability of such a small diameter cavity would be much better than that of a large hole. The core obtained from the probe hole would be slightly smaller than normal core, but would be optimal for physical properties and mechanical state measurements as it precisely represents the material being tested.

Whereas the Navidrill system will undoubtedly be developed, even without our encouragement, the development of instrument systems and packers to be deployed in the probe hole remains a problem. Some existing probes such as the Barnes-Uyeda pore pressure-temperature-pore water device would seem to require only minor modifications, but development of permeability measuring devices and other probes would require more effort. In particular, a small packer system needs to be developed. Although this could be operated on a wireline, we would hope that a self-contained unit, activated by drilling fluid pressure, could be developed. An integrated probe and packer system that could be dropped free and retrieved on the coring line would permit and encourage frequent in situ measurements in consolidated sediments.

b) To complement the laboratory physical properties program in soft sediments, a "push in" combination logging tool should be developed for use in less consolidated sediments. This could be fashioned after geotechnical industry "push in" tools and could use many of the sonde elements (natural gamma, ρ, ϕ, V_p, Ω) already developed by the scientific and engineering communitites.

c) To obtain better quality and less disturbed cores for physical properties measurements, ODP is encouraged to complete the development of a break away piston head for the HPC.

d) ODP should develop a reliable technique for obtaining oriented hard rock samples for in situ stress and paleomagnetic studies.

POLICY CHANGES AND ADDITIONS

Several policy additions or changes concerning sampling and subsequent use of samples are strongly recommended. Without an adequate set of policies the benefits produced by changes in techniques and instrumentation will not be fully realized.

1. Integration of Testing

One of the most important and unanimously agreed upon recommendations is that suites of physical property and mechanical state measurements should be made on the same or extremely similar samples. Because properties can change radically over a short vertical range with changes in lithology, sample lithologies must be carefully characterized on all measured samples.

We also recommend that laboratory measurements be carefully integrated with down hole measurements. This integration requires considerable thought and will probably differ with the property concerned. As an example, comparison of lab and in situ porosity measurements may provide more adequate values of intergranular porosity, or may show differences between intergranular and fracture porosity. In either case rebound effects on lab samples and calibration problems of downhole techniques using lab data must be considered. Appropriate integration among other studies that deal with physical properties and mechanical state should also be insured. In particular, post cruise tests on whole round samples should include measurements of most of those properties made in the shipboard lab (e.g. porosity, lithology, and permeability if possible) at the appropriate confining and pore pressures. In the case where in situ measurements are made in a "probe" hole, the cores from these holes clearly should be of the highest priority for physical properties and mechanical state studies.

2. Standardization of Testing

Because the unevenness in quality and quantity of past measurements was of great concern to the workshop participants, it is recommended that standards be set for the minimum frequency of sampling and for the methods of measurements. Certainly more frequent measurements than those required in the past, are appreciated, but the variations in technique that typified the DSDP should be controlled. In essence, uniform high quality of measurements must be insured, even if fewer total data are collected.

3. Core Handling and Preservation

Physical properties and parameters of strength are some of the most perishable characteristics of sediment cores; if good measurements are to be made, appropriate steps must be taken to preserve material in the best possible condition until analysis. We have several recommendations to improve data quality, some of which are very simply implemented.

The first is to take advantage of the ends of core sections for some measurements, such as vane shear, which ought to be run perpendicular to bedding.

Whole round sections are absolutely necessary for a number of measurements, such as consolidation and triaxial tests. Preserved whole round samples also represent the only undisturbed material remaining after the cores are cut and analyzed. Whole round cores for physical properties and mechanical state measurements have occasionally been taken during past legs, but no policy exists that addresses the frequency of sampling and other constraints concerning sample acquisition. Although the workshop participants were in agreement that there should be such a policy, no specific sampling frequency was suggested; rather it was felt that this should be determined for each hole based on the setting, purpose of the site, etc. It is clear however, that the present policy that permits one 10 cm whole round sample per major lithologic unit is entirely inadequate and unrealistic.

A second recommendation is that whole round cores should be taken at specific intervals even if no shipboard scientist requests them. Such regular sampling is done for various geochemical studies. Only if an "archive" of physical properties samples is created can post-cruise studies of these properties be undertaken. Because even well-preserved cores slowly degrade over a period of several years, and because these cores would be kept in a core repository, material would simply be returned to the regular collection after a fixed length of time if not used.

As important as the frequency of whole round sampling is the quality of preservation. Core samples must be protected from mechanical disturbance, freezing or overheating, and dehydration. Although questions were raised concerning the ability to do this with ODP cores, it was pointed out that geotechnical engineers routinely transport cores world wide and store them for significant periods with satisfactory results. These techniques basically consist of covering the sample, in its liner, with aluminum foil and a low permeability wax, shipping it in a foam packing, and storing it underwater.

4. Effort Dedicated to Physical Properties and Mechanical State Studies

The frequency of sampling for physical properties and the range of measurements made on these samples have varied widely during past drilling programs. The workshop did not come to any agreement about the specifics of either point, but did recommend that minimum standards be established and that special studies with objectives based on physical properties/mechanical state measurements be recognized.

Sampling and measurements fall into two catagories: routine and special. Routine sampling frequency depends on the noise level of the measurement and on the lithologic variations, and might vary from one situation to another. A general consensus was that at least one sample should be taken from each section of core. Routine lab measurements would include those already made, with some modifications and with the addition of pore fluid resistivity, differential thermal analysis, permeability, and thermal conductivity. In addition, physical properties should be measured routinely on a smaller subset of samples at elevated pressures for comparison with logs. Routine *in situ* measurements, such as temperature, ought to also be considered, as in the past these have depended upon the interest of the leg staff.

Special studies clearly depend on the leg objectives and setting. In some cases the objectives may not specifically address physical properties but there may be very valuable data to be collected by a leg scientist or for an outside worker. A policy that would guide such piggy-back studies ought to be developed. At the other end of the spectrum is the possibility of a hole or a leg for which the objectives would rely strongly on the measurements of physical properties and mechanical state. An example of this would be a hole in an accretionary prism where the investigation of the stress state, deformational fabric, and fluid behavior would be principal objectives. The workshop wishes only to remind the panels of the growing need for such specialized drill holes.

5. Staffing

The workshop was in agreement that two shipboard scientists would be required to carry out a normal program of laboratory measurements of physical properties and mechanical state. Since many of the measurements will have to be done early in the stream of lab measurements, physical properties measurements will have to be made around the clock. On sites where special programs related to physical properties are undertaken, an even larger staff might be necessary. In either case, a very close liaison should be established between the physical properties staff and the logging staff.

We also strongly recommend that one shipboard technician devote full time to physical properties and mechanical state measurements, using both lab and in situ techniques. This commitment would insure uniform high standards of measurements, minimize downtime due to equipment failure, and provide emergency help during periods of "stress". We visualize this technician as instructing the scientific staff in use of equipment, maintaining that equipment, and running some of the more technically involved studies, such as in situ measurements.

6. Other recommendations

A. Onshore lab. Characterization of the materials on which physical properties/mechanical state measurements are made requires quantitative description of mineralogy and grain size. These measurements are seldom made on ODP samples, and in any case are too time consuming to be done in the shipboard lab. On the other hand, these analyses can be made at any time after the core is collected, and on bagged samples. We recommend that an on shore lab measure such parameters as grain size and clay mineralogy under contract to

ODP; a typical candidate would be a Civil Engineering Department with interests in marine sediments.

B. Because many of the measurements made in the shipboard lab are those which have been highly refined by geotechnical engineers, it was suggested that the ODP Physical Properties Program would benefit from a one-time "site visit" by a geotechnical engineer from one of the companies specializing in deep water measurements, as well as a "one-shot" geotechnical school for DMP and PCOM members similar to the DMP's logging schools.

C. The present workshop concentrated on the overall physical properties program and its integration with other programs. It was suggested, however, that the program would benefit greatly from small workshops devoted to the improvement of specific techniques.

D. A final recommendation that was strongly endorsed is that the physical properties/mechanical state program be better represented in the ODP. At the very least there ought to be a working group concerned with the problems that we have outlined, which would be active until proposed changes are implemented and their initial results are evaluated.

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TABLE I

SUMMARY OF ODP PHYSICAL PROPERTIES CAPABILITIES AND REQUIREMENTS

Density-Porosity	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	ρ_b, ϕ	GRAPE (H,V)	rebound, degassing	1) ϕ:measure by ASTM method and differential thermal analysis
	ρ_b, ϕ, ρ_g, wc	Balance		2) ϕ, ρ_b:correct for rebound using consolidation data
	ρ_g	pycnometer		3) determine ϕ from water content for gassy sediments
Downhole	ρ_b (insitu) nϕ (insitu)	γ density neutron porosity		4) make systematic shipboard lab measurements of ρ_b (corrected) for rebound), ρ_g to correct nϕ 5) push-in nϕ, ρ_b logging tool for soft sediments.
Shorebased	-	-	dessication	6) coat in beeswax; store in submerged anaerobic jars 7) ρ_b:comparison study of cylinder vs. pycnometer methods 8) ρ_b:evaluate continuous mode x-ray transmission or x-ray backscatter technique to replace GRAPE 9) nϕ:hard rock neutron absorbtion x-section study by Sandia neutron activation; calibration by Sandia/BP 10) replicate shipboard lab at TAMU

Acoustic	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	V_p	Hamilton Frame	rebound, degassing	11) soft seds; velocity probe technique (ferroelectric ceramics, benders)
	V_p	velocity logger	rebound, degassing, liner	12) reconsolidate selected samples (seds), measure V_p, V_s, Q,
	V_p, V_s	axially-loaded velocimeter	arbitary uniaxial P, degassing P_e not met	anisotropy @ P_e in Harbert vessel (soft & hard)
Downhole	V_p, V_s, full wave	LSS, MCS	attenuation in pillows	13) push-in V_p tool for soft sediments

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	ρ_b, ϕ, ρ_g, wc	Balance		2) ϕ, ρ_b:correct for rebound using consolidation data
	ρ_g	pycnometer		3) determine ϕ from water content for gassy sediments
Downhole	ρ_b (insitu) nϕ (insitu)	γ density neutron porosity		4) make systematic shipboard lab measurements of ρ_b (corrected for rebound), ρ_g to correct nϕ 5) push-in nϕ, ρ_b logging tool for soft sediments.
Shorebased	-	-	dessication	6) coat in beeswax; store in submerged anaerobic jars 7) ρ_b:comparison study of cylinder vs. pycnometer methods 8) ρ_b:evaluate continuous mode x-ray transmission or x-ray backscatter technique to replace GRAPE 9) nϕ:hard rock neutron absorbtion x-section study by Sandia neutron activation; calibration by Sandia/BP 10) replicate shipboard lab at TAMU

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	V_p	velocity logger	rebound, degassing, liner	12) reconsolidate selected samples (seds), measure V_p, V_s, Q,
	V_p, V_s	axially-loaded velocimeter	arbitary uniaxial P, degassing P_e not met	anisotropy @ P_e in Harbert vessel (soft & hard)
Downhole	V_p, V_s, full wave	LSS, MCS	attenuation in pillows	13) push-in V_p tool for soft sediments

Electrical	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	Ω	-	rebound, degassing	14) measure R_f @ STP using Hanson Research 240 HZ 4-electrode cell
			T ≠ insitu	15) reconsolidate selected samples, measure Ω @ P_e, 100-10 KHz in Harbert vessel using 2 electrode cell, impedance meter; correct for T.
Downhole	Ω	SFL, laterology, long-spaced resistivity		16) measure cation exchange capacity using membrane potential cell or ammonium acetate method
	conductivity	induction log		(see 14, 15 above)
Shorebased	-	-	dessication	17) push-in Ω tool for soft sediments (see 6 above) 18) run complex Ω logs (see 10 above)

Thermal	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	conductivity	needle probe	rebound, degassing, no hardrock capability	19) reconsolidate selected samples, measure conductivity @ P_e in Harbert vessel 20) hardrock: divided bar 22) softrock; replace bridge with digital multimeter, thermal cond. with 4-wire resistance device
Downhole	T	HPC-T Barnes/ Uyeda	refusal limit refusal limit	(see 19 above)
	T, ΔT	HRT	T ≠ T equilibrium	
Shorebased	-	-	dessication	(see 6, 10 above) 22)selected samples; triaxial measurements

Magnetic	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	NRM,	spinner, cryogenic	hardrock never, sediments rarely oriented	23) oriented samples
	NRM (stable)	spinner, AF demag	only useful in hardrock	
	χ	χ logger		
Downhole	NRM	vert. flux gate mag gyro oriented 3-axis fluxgate vert. gradiometer		
	χ	susceptibility meter		
Shorebased	-	-		(see 10 above) 24) thermal demag

Permeability	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	permeability	back pressure consolidometer	rebound, degassing	25) hardrock; constant flow rate permeameter @ P_e
Downhole	permeability	Lynes, TAM packer	no soft or semi-consolidated sediment capability	(see 30 below) 26) develop drill-in pressuremeter for ODP use
Shorebased	-	-		(see 10 above) 27) selected samples; triaxial measurements @ P_e

Magnetic	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	NRM,	spinner, cryogenic	hardrock never, sediments rarely oriented	23) oriented samples
	NRM (stable)	spinner, AF demag	only useful in hardrock	
	χ	χ logger		
Downhole	NRM	vert. flux gate mag gyro oriented 3-axis fluxgate vert. gradiometer		
	χ	susceptibility meter		
Shorebased	-	-		(see 10 above) 24) thermal demag

Permeability	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	permeability	back pressure consolidometer	rebound, degassing	25) hardrock; constant flow rate permeameter @ P_e
Downhole	permeability	Lynes, TAM packer	no soft or semi-consolidated sediment capability	(see 30 below) 26) develop drill-in pressuremeter for ODP use
Shorebased	-	-		(see 10 above) 27) selected samples; triaxial measurements @ P_e

Mechanical State Properties	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	pore pressure	-		
	in situ stress	structural fabric	partial orientation only	28) oriented core 29) strain relaxation measurements on selected samples
Downhole	pore pressure	Lynes, TAM packer	no soft or semi-consolidated sediment capability	30) magnetic and seismic anisotropy (see 26 above, 31 below)
	in situ stress	Lynes packer, BHTV		
Shorebased	-	-		

"Engineering" Properties	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	undrained shear strength	vane shear, torvane	rebound, degassing rebound, degassing	
Downhole	-	-		31) deploy piezocone 32) deploy downhole vane shear 33) deploy pressuremeter
Shorebased	-	-	dessication	(see 6, 10 above) 34) Atterberg limits 35) Triaxial compression tests on selected samples

"Geologic" Properties	Present Capabilities Parameter	Equipment	Weaknesses	Recommendations
Shipboard	-	-		36) Harbert natural γ logger (K, U, Th) 37) x-radiography 38) grain size 39) composition
Downhole	Σ, K, U, Th	natural γ,		
	K, U, Th	spectral γ,		
	composition	neutron activation	slow tool	

APPENDIX ONE

PRELIMINARY REVIEW OF THE GEOPROPS PROBE

BACKGROUND

The Physical Properties workshop revealed the need for the capability to obtain in situ measurements of a number of physical properties and mechanical state parameters in moderately to highly consolidated sediments and also in basement. Push-in probes cannot be used in such settings, and use of the full-size hole has numerous drawbacks, but the Navidrill concept, now under development at ODP, would provide an excellent "probe" hole in which to make such measurements.

The Navidrill core barrel (NCB) is a downhole mud motor married to an XCB-type core barrel. The mud motor transforms pumped sea water (or drilling mud) into high speed rotation of the core barrel. A diamond core head cuts a core as the NCB advances ahead of the main core bit. When the NCB is retrieved a 3-3/4" diameter pilot hole is left behind before the main core bit is advanced in preparation for the cutting next core.

Following the workshop several participants pursued the idea of designing a "Geoprops Probe" to be deployed in Navidrill holes. Further discussions led to a meeting at ODP, College Station, on April 8, at which the scientific capabilities, engineering constraints, and logistic problems of such a probe were reviewed. Participants at this meeting were Dave Huey, Tom Pettigrew, Elliott Taylor, and Dennis Graham of ODP, Bill Bryant, Rick Carlson, and Wayne Dunlap of TAMU, and Dan Karig of Cornell.

CONCEPT AND GENERAL OPERATION

The Geoprops Probe would occupy the small diameter hole created by the NCB to measure quantities not obtainable by lab or logging techniques, at depths below the capability of push-in probes. The longer a hole is subjected to open hole conditions, the longer time is required to estimate in situ conditions, so that the Geoprops probe should be able to be rapidly deployed. For this reason it should be an internal recording, wire-line retrievable probe that can remain locked in the probe hole by inflated packers for time periods of about an hour, the estimated time necessary for conditions to approach those in situ.

The length of the probe chamber will be determined by the Navidrill coring capability, which will initially be 15' (5 m). Of this length, the bottom section is the most useful for the measurements because it was the last drilled and because it is furthest from the bit loading and subsequent stress-release effects in the large diameter hole. Two packer elements on the probe would not only provide two areas of investigation (between the packers, and below the lower packer), but also the capability of pressing probes firmly against the bore wall (Figure 1). The Navidrill holes should be quite clean, except for chips that fall or are knocked in during the probe run-in sequence, but to prevent the probe from hitting the hole bottom or fallen chips, it should be slightly shorter, perhaps 4.5 m. A possible packer layout would place the lower packer element close to the bottom and the second element 2 meters above (Figure 1).

The probe should be lowered down the pipe on the sandline with the bit slightly above the bottom of the hole to reduce flushing of the probe hole. Because the bit will have been off bottom during lowering of the probe, the probe hole will be subject to some (minor) filling. Furthermore, the probe may not be exactly aligned with the probe hole, so that a shaped nose piece or other centralizing mechanism will have to be devised. It was determined that the probe should be decoupled from the drill string so that circulation and even some rotation could be maintained during the period of measurement. This will help maintain the hole stability for the hour or so during which the probe in place. The packers should prevent movements induced by seal drag and friction.

Packers should probably be about 2 feet long and hydraulically inflated. A mechanism must be designed to limit the packer fluid pressure to a value within the (estimated) elastic strength of the sediment. Both packers will operate in series. A number of sensors will have to be held tightly against the bore wall, which could best be done by implanting them in the packer membrane. Because this might jeopardize the integrity of the main packers and because the sensors could be abraded or destroyed as the probe was lowered down the pipe, some thought was given to using auxiliary packer units for the sensors. These might be adjacent to or extensions of the sealing packers. They might also be inflated by a secondary hydraulic system activated by the main system (like the captive air bladder in a water tank).

Recording of data will be done by self contained electronics packages, preprogrammed for the most part. There was some discussion of triggering by pressure (depth) or by other environmental signals, but the space for memory devices is virtually unlimited and complexity should be held to a minimum in the probe. The idea of modular design, with the capability of interchangeable probes was also discussed but the relatively short time to desired deployment (2 years) and need for initial reliability indicated that such sophistication should be deferred. Similarly, communication with the probe, via telemetering (MWD technology) or "smart" sand line is deferrable.

The probe would be retrieved by a sand line with an overshot in which a core orienting device had been integrated. This would orient the Geoprops Probe before the packers were deflated, much in the way that HPC is presently oriented.

MEASUREMENTS TO BE MADE

A variety of measurements that could be made with the Geoprops Probe have been suggested, and certainly more will be devised in the future. However, for the initial probe it is important that only the most necessary and least complex measurements be included in order to maximize the success and benefit/cost ratio. At the meeting the highest priority measurements were identified as: 1) pore pressure; 2) permeability; 3) temperature; 4) pore fluid content (including gas); and 5) components of stress.

The detailed description of the methodology of measurements will depend on consultations with specialists, but some ideas and constraints surfaced at the meeting.

1. Pore Pressure

Pore pressures in sediments are most easily measured with transducers mounted behind highly permeable porous discs. Such discs could be pressed against the probe hole wall or sense the annulus between and beneath the packers. Bulk permeability will require the latter type emplacement, but more rapid return to pressure equilibrium might be obtained by the former. Firm contact of the sensor with the wall could be obtained by imbedding the porous disc in the auxiliary packer unit. Integration of the pore pressure and permeability measurements, and the possibility of large pore pressure disturbance near the major hole suggest that 2 sensors be mounted in the lower packer and on the probe body between the packer. Not only will the 2 sensors respond to slightly different conditions, but will also provide redundancy.

After the packers are set, fluid pressure in the sediment at the bore wall and in the annulus will exponentially change from hydrostatic pressure to the formation pressure. The shape of the pressure/time curve will depend on the formation permeability and time since the hole was drilled, as well as the hole diameter. Estimates of the required times will be calculated in the near future, but the experience of DSDP Leg 84 and ODP Leg 112 suggest that approximately an hour will be needed.

The pressure transducers used should be differential with respect to hydro static pressure in order to improve the precision of measurement. Such devices are presently used in the Barnes/Uyeda tool.

2. Permeability

Bulk permeability measurements in the probe hole will measure both fracture and intergranular permeability, dominantly in the horizontal direction. A combination of rate of pore-pressure build up and negative pulse decay is visualized as the most appropriate technique, as is presently used on the Barnes-Uyeda tool. The negative messure pulse is generated when the fluid sampler is opened. The annulus between the two packers would provide a well-calibrated volume.

3. Temperature

The formation temperature is another quantity that requires time approach to equilibrium after the probe is emplaced. In the context of the probe hole, the best measurements will be obtained by sensors pressed to the hole wall, as close to the bottom as possible. Two thermistors, imbedded in lower and upper auxiliary packers, will not only provide redundancy, but will measure the local temperature gradient. The von Herzen and Uyeda tools now employed by ODP should be easily modified for use in the Geoprops Probe.

4. Pore Fluid Samples

Pore fluids, especially the gas composition, are increasingly important tracers of fluid systems in the subsurface. In-situ fluid sampling preserves gas content and water geochemical traits so that it is unnecessary to destroy core by squeezing for the interstitial fluids. However, in-situ fluid sampling will probably be one of the more complex measurements to be made by the Geoprops Probe. To minimize sampling of bore hole fluid, a porous intake element will be pressed against the bore hole wall. The pressure gradient between formation fluid pressure and a 1 atm collection cylinder will provide drive for the fluid as in the Barnes system. Such a system might best be mounted in the upper packer, where it will not interfere with other measurements.

5. Stress Measurements

One of the most desireable, but also most difficult, quantitities to obtain is the state of stress in the bore hole. Several ideas, concerning both stress tensor orientation and magnitude were discussed. The orientation of maximum and minimum stress in the horizontal plane is probably the easiest measurement to make, either by active or passive determination of strain in various horizontal directions. Anisotropic horizontal stress may induce an ellipticity to the hole which might be sensed by a series of strain gauges and/or LVDT's in a packer assembly. Increase of pressure in the packer will induce an anisotropic strain in a anisotropic stress field, which might also be sensed. In the "pressure-meter" concept of geotechnical engineering, this pressurization can lead to estimates of in-situ stress and strength, but several factors, such as the initial hole relaxation and possible anisotropy, pose serious problems in this setting. Hydrofracturing is another proven technique for the determination of both stress orientation and magnitude, as outlined in the workshop report. This process although complex, should be explored further.

OTHER POSSIBLE MEASUREMENTS

Other measurements, which might be pursued, particularly in the future as Geoprops Probe is refined, include seismic velocity (both V_p and V_s), porosity/density, and stratal dip (both direction and magnitude), all of which would utilize well-developed logging technologies. Velocity measurements can be made both by logging and in the lab, but in situ measurements, with core available will permit cross calibration of techniques, and will allow good shear wave velocities to be made. Moreover, these would be bulk velocities of known lithologies. In short, this method would provide excellent reference data for general use. Similarly, porosity/density measurements would provide cross-calibration of logging and lab measurements of those quantities. Dipmeter measurements would allow the core from such holes, to be oriented if these had a measurable dip. Orientation of core from the Navidrill holes is very important for the interpretation of anelastic strain relaxation tests, paleomagnetic studies and in other directional properties.

SCHEDULE AND TIME CONSTRAINTS

The Geoprops Probe is intended for general use in the ODP but the impetus is admittedly motivated by the desire to use this tool in a proposed hole in the Nankai Accretionary prism. This hole is tentatively scheduled for mid 1989. The steps identified to create the Geoprops probe can be summarized as follows:

1. Proposal to NSF for the Feasibility Study - submitted May 1987.
2. Feasibility Study - estimated time of 3 months; estimated cost of $20,000 (by December 1987)?
3. Proposal to NSF for construction of Geoprops Probe - submitted January 1988; start?
4. Identify builder and build probe (including initial testing) - will take 10-11 months
5. Sea Trials - must be by March 1989.

It was estimated that there is sufficient time to produce the Geoprops Probe for use in May 1989, with the recognition that the time for processing of proposals by NSF is unknown.

PERSONNEL

A number of scientists with expertise in various aspects of the Geoprops Probe have been contacted or identified. These people have, when contacted, agreed to provide analyses of the conditions presented by the Navidrill-Geoprops Probe system, and to provide information concerning similar systems that they have designed. A short list is as follows:

Permeability & Pore Pressure:	Richard Bennett, Bobb Carson, Steve Hickman
Temperature:	Richard von Herzen, Seiya Uyeda
Fluid Sampling:	Ross Barnes
Pressuremeter:	Kate Moran, John Hughes
Packer design:	Keir Becker

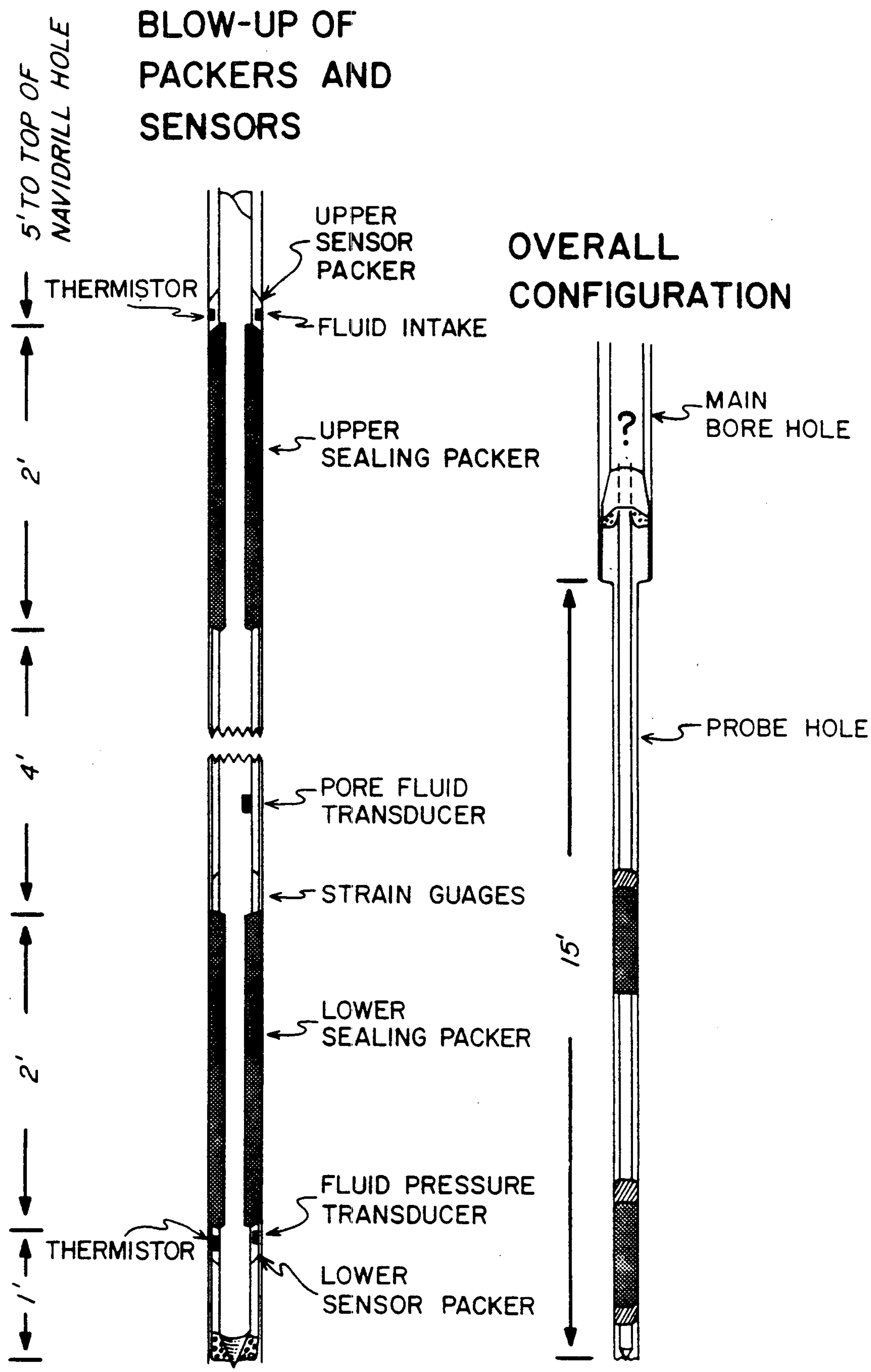
BLOW-UP OF PACKERS AND SENSORS
5' TO TOP OF NAVIDRILL HOLE
UPPER SENSOR PACKER
THERMISTOR
FLUID INTAKE
UPPER SEALING PACKER
2'
4'
PORE FLUID TRANSDUCER
STRAIN GUAGES
LOWER SEALING PACKER
2'
FLUID PRESSURE TRANSDUCER
THERMISTOR
LOWER SENSOR PACKER
1'
OVERALL CONFIGURATION
MAIN BORE HOLE
?
PROBE HOLE
15'

Figure 1