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Proceedings of

The Wellbore Sampling Workshop

Richard K. Traeger, Barry W. Harding

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PROCEEDINGS OF

THE WELLBORE SAMPLING WORKSHOP

Sponsored By:

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May 27-28, 1987

Houston, Texas

Conveners

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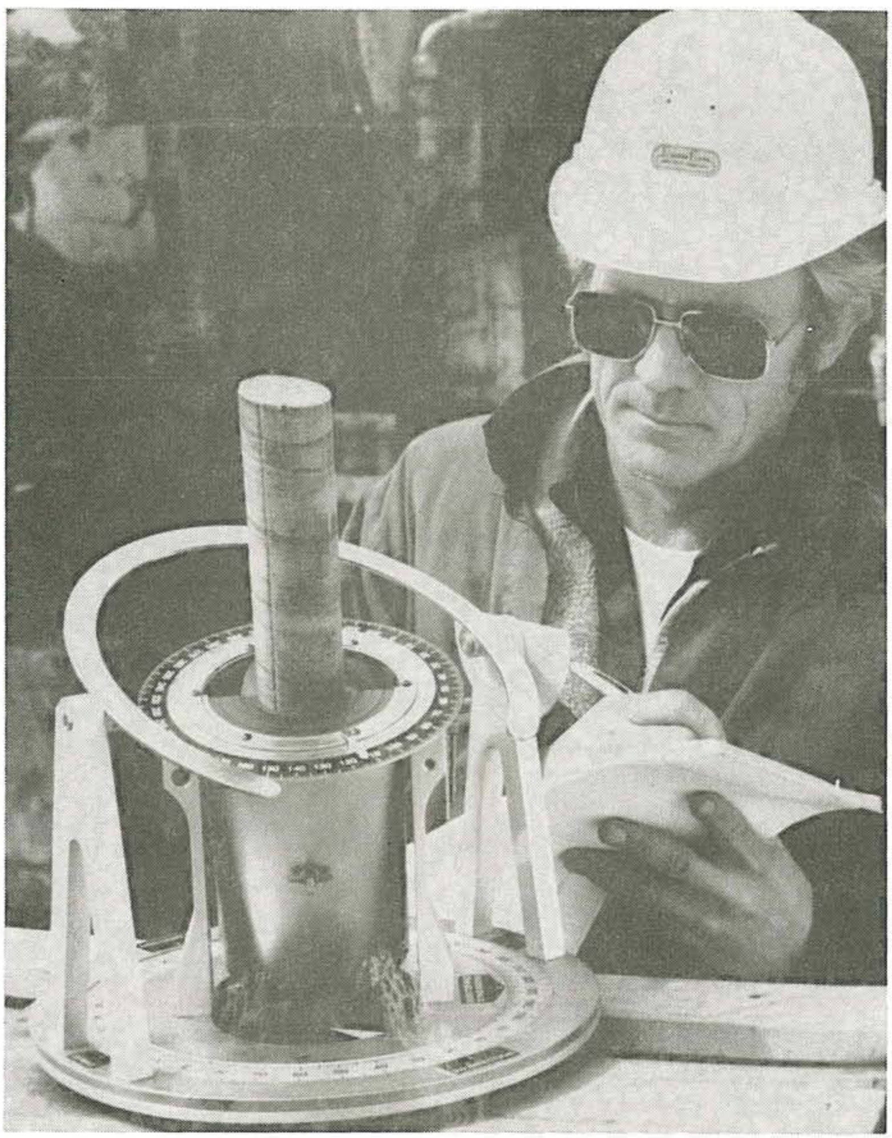

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Editor
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ABSTRACT

Representatives from academia, industry and research laboratories participated in an intensive two-day review to identify major technological limitations in obtaining solid and fluid samples from wellbores. Top priorities identified for further development include: coring of hard and unconsolidated materials; flow through fluid samplers with borehole measurements T, P and pH; and nonintrusive interrogation of pressure cores.

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*Paper not available.

*Paper not available.

SYNOPSIS

The Workshop considered scientific limitations and technology needs in two days of intensive discussion by 72 participants. Academia, industry and research labs were about equally represented. Issues, recommendations, abstracts of presentations, a sampling bibliography and other relevant workshop information follows.

The fact that any drilling or intrusion immediately alters the formation being sampled needs to be considered in all new technology or scientific experiment plans. Given that limitation, the coring of soft sediments by piston systems and competent hard sediments by standard coring appears satisfactory. Gas and liquid sampling from nonpermeable formations is a priority, but no potential solution came out of this meeting. Development activities that could provide needed sampling improvements focussed on: (1) sampling unconsolidated sediments, (2) improved flow-through samplers with capabilities for measuring in situ temperature, pressure, pH, and other chemical constituents during sampling, and (3) pressure coring systems that allow nonintrusive interrogation of the core prior to releasing it from the confining liner. Future directions should be to do the scientific measurements in the borehole itself. Such measurements should be research developments and not dependent on commercial logging developments.

WELLBORE SAMPLING WORKSHOP

RECOMMENDATIONS

RECOMMENDATIONS

Workshop participants identified five general areas of needed improvements in sampling technology:

Core/Sample Preservation and Handling
Pressure Coring
Contamination/Decontamination of Samples
Sampling Unconsolidated Formations
In Situ Chemical Analysis/Fluid Sampling

Working groups were then established (Appendix B) to identify the major issues in each area and the major improvements needed to address the issues. No attempt was made to prioritize the five working group areas nor to prioritize individual needs within each working group.

The following summary of issues and needs is the major output of this workshop. This list provides information and guidance to technologists and funding groups on the technology needs considered most important by participants at this workshop.

Core/Sample Preservation and Handling

Issues:

Location of core in the borehole
Maximum recovery
Orientation
Integrity of core material in the liner
Core handling protocol and archiving
Preservation of plugs

Development Priorities:

Low z, core barrel-liner assembly
Measurement while coring (γ-ray)
Repository environment
Mobile unit to remove plugs from cores in the field
Protocol based on measurement priorities (science program dependent)

Pressure Coring

Issues:

Maintenance of in situ conditions
Retention of volatile components
Sample access
Cost
Scientific Limitations of existing systems not identified

Development Priorities:

Maintenance of borehole pressure (and temperature) in the sample during and after coring
Ability to interrogate the core while in the pressurized core barrel (Cat Scan, electrical...)
Ability to transfer the core while maintaining pressure, temperature and structure
Means to identify hydrates before opening

Contamination/Decontamination of Samples

Issues:

- Uncertainty of chemicals added during operations
- Representative samples
- Trace contaminants
- Understanding what is tolerable
- Corrosion/erosion during drilling
- Increasing importance of identifying organics and biosystems

Development Priorities:

- Complete drilling logs including all additives available with samples
- Identify contaminants intentionally and unintentionally added during drilling and sampling
- Sample ahead of the bit out of drilling fluid invasion zone
- Independent, in situ measurements to verify sample analyses
- Equipment and procedures for biological sampling

Sampling Unconsolidated Formations

Issues:

Good core sample
- no deformation
- maintain in situ conditions
- limit contamination
- high recovery

Orientation

Handling

Development Priorities:

Improved heave compensation (ODP)

Technique to obtain 100% oriented core

Redesign core catchers and liners; consider using the liners for storage

High rotary coring speeds to improve recovery

Measurement-while-coring technology for barrel speed, flush flow, rate of penetration, entry of core into barrel, scientific measurements

Invent new coring/sampling concepts as freezing or encapsulating the formation before coring, just kerfing with laser or water jet followed by liner, making critical in situ measurements ahead of the bit before coring, etc.

In Situ Chemical Analysis/Fluid Sampling

Issues:

Enhanced fluid transport in the oceanic and continental crust
Representative samples allowing thermodynamic modelling
Contamination sources and amounts
In situ chemical and physical conditions
Temperature limitations

Development Priorities:

Reliable seals for retrieving samples
Chemically inert flow-through or syringe-type samplers
High temperature (400-450C) samplers
In situ T, P and pH measurements at sampling point; eH, conductivity, turbidity also of interest
Improved gas sampling and on site analysis

WELLBORE SAMPLING WORKSHOP

ABSTRACTS

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Sampling Priorities for Scientific Drilling/The Past

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Sampling for scientific purposes has been carried out differently than that done strictly for exploration purposes. Typically, in both ocean and continental drilling programs, such as the ocean drilling program (ODP) and the deep observation and sampling of the earth's continental crust (DOSECC), major emphasis has been placed on obtaining continuous undisturbed cores, whenever possible. Within ODP, this is now technically possible for many types of sediments. However, participants at this workshop noted the technical difficulties that still exist in obtaining good samples from harder formations. Fractured and heterogeneous rocks, particularly those with interbedded hard and soft intervals, present particularly difficult problems. Many scientists put a high priority on the ability to recover these intervals intact because they often represent important geological contacts which should be examined in detail.

The "first priority" generally given by drilling programs to detailed continuous core recovery and description is exemplified by ODP where scientific programs requiring whole round (rather than split) cores generally receive a lower priority. Therefore, only "spot" samples are generally available for scientific programs where "whole-round" cores are required, e.g., for programs requiring pore water analyses, organic geochemistry, microbiological studies, or geotechnical measurements.

The reason for this primary emphasis on core description is that this information is almost always needed to interpret other data from the drillhole. For example, in the El Cajon DOSECC program, the idea of

For example, in the El Cajon DOSECC program, the idea of continuous coring was considered and then abandoned for financial reasons. The alternative procedure of using well logs extensively and then taking only spot cores and pore water samples has not been entirely satisfactory - important geological contacts have been missed. Also, in the early stages of the deep sea drilling project (DSDP), the predecessor to ODP, continuous coring was not carried out routinely. The result was a loss of much important information to the scientific community as a whole. For example, the geological history of many of the early DSDP sites could only be reconstructed at a later date when sites were redrilled using continuous coring.

Sampling of pore fluids and gases has also had strong priority within various drilling programs. Traditionally, however, these samples have been given secondary priority to whole rock or sediment sampling. For example, within ODP, increased emphasis is currently being placed on developing and using in situ pore water and gas samplers. For technical reasons, all of the devices currently being considered or developed appear to be capable of taking samples only at discrete intervals rather than doing measurements continuously downhole.

Several workshop participants emphasized the need for developing methods for sampling pore waters in consolidated sediments. Because of low water content, in situ samples from these intervals present particular problems both in continental and ocean drilling. In addition, within DOSECC program, some of the pore water constituents of particular scientific interest, such as trace metals and radionuclides, can only be measured in relatively large volume samples (in some cases, up to 20ℓ) which present enormous problems with respect to potential contaminants during collection.

In both DOSECC and ODP, pore water sampling for scientific purposes has had priority over gas sampling. For example, ODP now has an in situ downhole sampler which filters and traps a pore water sample together with associated gases at depth. The sample is brought to the surface for further analysis where shipboard procedures are used to analyze inorganic constituents. However, gaseous constituents from in situ samples can be analyzed currently only in shore-based laboratories. Thus, in spite of the emphasis placed on ODP shipboard core gas analysis procedures to prevent drilling into reservoired gas or oil, there are currently no shipboard procedures for routinely monitoring the quantities of gas present in situ in ODP core samples. Thus, there are always questions about gas samples taken after the cores arrive on board - how much gas was lost during core recovery and how much do these losses reflect changing lithologies rather than changing in situ concentrations? The one measurement which could eliminate all of these questions is a fast and routine shipboard method for measuring amounts and compositions of core gases from in situ samples to show how close these gases are to saturation values at depth. However, up until recently, ODP has had no practical means for making such measurements even though they would minimize the possibility of drilling into any type of pressured gas deposit and would also provide a reference data base of what constitute "normal" gas values for particular areas and sediment types.

Gas sampling has been given high priority in some specific scientific programs. For example, all deep drilling programs are interested in measuring and defining the possible contribution of deep mantle gas sources. Such deep gas sampling presents particular problems because of the possibility of producing drilling artifact gas, for example from well additives, drill string components or from the rock itself in contact with localized high temperatures from frictional heating produced during drilling.

In thinking about the future, it is interesting to speculate on how the above sampling priorities might change if various types of reliable continuous downhole measurements become available. For example, continuous coring is currently very time consuming and, therefore, expensive. In addition, it does not do well in recovering many types of lithologies, such as sands. To what extent could future downhole techniques, such as well logs, pictures, and other types of measurements be used to replace (or augment) coring? Could continuous in situ measurements of gases and pore water constituents be used to define sediment permeability and/or depositional conditions? To what extent could these methods be used in the future to pinpoint intervals where extensive coring of a specific type would be desirable? If such downhole methods become sophisticated enough and funds are available for adequate testing, then the priorities of future sampling and/or downhole measurement programs could be tailored to maximize the scientific return from each hole.

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Working Group on Contamination/Decontamination

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Drilling for scientific purposes often presents technical problems different from that done specifically for exploration purposes. It is generally crucial that specific procedures be followed to avoid contaminants or to decontaminate the samples if they are to be of any use for their stated purpose. Therefore, it is crucial for scientists and those responsible for drilling to discuss these problems before drilling begins, and preferably, at an early stage in the project planning.

Some general procedures which help in minimizing contamination, or at least allow a "reconstruction of the crime" after the fact are:

1. Keeping good records of drilling, including time and depth of everything added to the well. It is particularly important that the drill crew be encouraged to record the time and description of anything which strikes them as being unusual.

2. Good analyses should be obtained on all additives before addition. New batches of the same additive should be retested - experience has shown that commercial preparations vary significantly from batch to batch.

3. Additives should be well defined and traceable whenever possible.

In addition, it was suggested that samplers be designed, whenever possible to take redundant samples so that occasional "spurious" (as compared to the systematic) contaminant can be identified.

Specific types of contaminants which apply to rocks, pore water, and gases were then discussed separately. In addition, there was considerable scientific interest in obtaining various types of geological samples for microbiological purposes. These present unique contamination problems which are discussed in a separate section. However, it should also be recognized that inadvertently introducing organisms into a well can also cause problems with later sampling and/or analyses.

Rocks

All well samples must be invaded to some extent with drilling fluid during the drilling process. Therefore, the drilling fluid is the major potential source of contamination for all rock samples. If the primary research interests involve either trace or major element chemistry, then the barite/bentonite drilling mud must be considered as a potential major contaminant. If organic compounds are to be examined, then oil-based drilling muds can cause major problems. Many other organics additives, such as polymers, paint chips, walnut hulls, etc., can also cause problems. Surfactants, such as the lignosulfonates, are common drilling additives which give interference with both organic and some kinds of metal trace element analyses. Pipe dope, which generally contains both an organic and metal component, is generally easily recognized, but must be considered as a potential cause of later problems.

Because many of these additives are a necessity for the drilling process, scientists should give thought to how the effect of additives can be either minimized and/or traced through the sample analysis process. For example, if oil based drilling mud is necessary, then consideration should be given to use of a more expensive refined diesel oil, which has an easily recognizable and narrow compositional range, rather than a cheaper crude mineral oil which interferes with all hydrocarbon ranges. Alternatively, a silicone oil might be considered which is easily distinguishable from indigenous sediment hydrocarbons. The additional expense might be easily justifiable when the alternative is the expense of drilling for scientifically worthless samples.

Other contamination problems can arise during later storage of cores. For example, storage in wax causes interferences for organic constituents, while various kinds of metal and plastic storage containers can cause problems in trace metal analyses. With a little advance planning, this type of contamination is generally easier to eliminate or minimize than that caused by the drilling process itself.

Air drilling can cause problems such as oxidation of iron minerals.

Microorganisms

Several scientists expressed an interest in carrying out future research to better define the role of microorganisms in a variety of geological processes, such as alteration of sediment organic matter in ODP sediments and effects on groundwater flows and reservoirs. It was pointed out that special protocols would have to be worked out for this type of research in order to eliminate contamination by surface bacteria. Particular attention would have to be paid to drilling fluid contamination, accidental introduction of surfactants, and contamination of one well interval by another. In addition, potential pressure and/or temperature effects on the organisms to be recovered needs to be considered. In any planned studies of this type, a determination needs to be made on the environment from which the organisms are to be recovered (i.e. temperature, pressure, salinity, potential nutrients, etc.) prior to collection. This type of study might also require pressure coring/retrieval and sampler transfer to a second aseptic incubation chamber for further studies.

Water

Pore waters were considered to have the widest variety of potential sources of contamination. Most of these would be eliminated by in situ measurements, preferably carried out continuously downhole. The remaining problems would then be restricted to consolidated or unconsolidated sediments and rocks. Consolidated samples present particular problems because of low fluid content often requiring large sample collection times. Therefore, sources of contamination from the sampler or from drilling fluid invasion tend to be amplified. The opposite problem occurs in unconsolidated sections where rapid fluid flow either into or out of the section can cause problems.

Assuming that in situ measurement does not become available for most constituents of interest within the near future, then the following were also identified as potential problems:

1. drilling fluid contaminants,

2. core disturbance, which maximizes contamination from 1),

3. trace and major element contamination from diverse sources including the drill string itself and storage containers,

4. cross-contamination between drill hole zones,

5. surfactant contamination, which can be a serious unrecognized source of contamination in many inorganic analyses.

In addition, the few studies which have been carried out to date suggest that pore water organics could become an important area of study in the future. For example, anaerobic microorganisms living in deep geological samples might be easily recognizable from increased concentrations of low molecular weight organic acids. Potential additional interferences for these compounds would be adsorption by surfaces, potential outgassing of any plastics used in sampling or storage, and microbiological degradation subsequent to collection. The latter can be easily eliminated by freezing the sample before and after pore water squeezing.

Gases

It was pointed out that collection and storage of a good uncontaminated water sample often also means availability of a good uncontaminated gas sample. Some additional potential sources of contamination also need to be considered for gas samples.

"Reactive" gases, such as hydrogen, oxygen, and sulfur gases require particular care during sampling and storage to insure neither production via artifacts nor decomposition or diffusive losses.

If hydrocarbon gases are to be measured, then contamination by volatile fuels and fumes must be avoided. In addition, consideration must be given to the possibility of "cracking" light hydrocarbons either from the sediment or drilling components due to localized frictional heating affects caused by the drilling process itself.

Air drilling can cause significant problems for all gases by driving gases deep into various rock faces during the drilling process.

Potential purge gas contaminants must be considered for any gas sampler to be used.

Partitioning of a gas phase during and after sample collection can be a problem in some kinds of scientific investigations. In these cases, the effect of pressure and/or temperature "contamination" might have to be considered. Often, it is possible to reconstruct the initial gas composition and distribution if an exact pressure and temperature history of the sample is available from the time of collection up until the time of measurement.

Sediments containing clathrates present particular problems. In these cases, heat and pressure "contamination" become critical. Therefore, it is important to maintain such samples at in situ temperature and pressure conditions until they can be examined in detail. If in situ P/T conditions are not possible, then the sample must be frozen at liquid nitrogen temperatures so that further gas losses and partitioning are minimized until further examination is possible.

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Sampling of Solids in Deep-Sea Drill Holes

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Experience with DSDP and the early legs of the ODP highlight several present limitations to hole advancement and core recovery needed to make significant progress on a wide range of scientific questions addressed with scientific drilling in the deep sea. Several sorts of different materials pose a challenge to adequate core recovery, but most are characterized by: 1) rubbly aspect or 2) marked heterogeneity and contract of physical properties, or 3) being at interfaces or geologic contacts, or 4) lack of consolidation. For example, rubbly basalt (either rubbly deposits or rubble created in situ by drilling of pervasively cracked basalt) posed a difficulty during ODP legs 106 and 109. Alternating sequences of hard chert and softer chalk have also been notoriously difficult to core with good recovery. Flow and intrusive contacts within volcanic sections are in many cases systematically lost. Unconsolidated sands, sand-silt sequences and conglomerates are also difficult to core without disturbance and with good recovery. Improvements in core recovery are essential for progress on a wide variety of scientific questions ranging from the composition and structure of oceanic crust, sedimentation and tectonic processes at active margins, paleooceanography and others.

Improved core recovery in young basalts, gabbro and peridotite sequences, chert-chalk sequences and poorly consolidated clastic sediments are high priorities for the ODP thematic panels. Deep penetration into basement, with the goal of penetrating the oceanic crust is a high priority of the lithosphere thematic panel. It is vital that technological progress toward deeper drilling and better core recovery proceed at a reasonable pace in order that the present phase of drilling can accomplish a significant number of the scientific objectives laid out in the COSOD I and forthcoming COSOD II reports. Excellent progress on the problems of core recovery and deeper drilling may be expected from a variety of new developments being explored and tested by ODP including down-hole drilling motors, hybrid, smaller diameter and narrow-kerf drilling bits and high speed small-diameter diamond drilling within a "riser" of standard diameter drill pipe. New developments of this sort will probably require additional support and adequate testing on the drill ship if they are to be available for use in a timely manner.

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Scientific Aspects of Wellbore Pore Fluid Sampling: Issues and Prospects

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Pore or formation fluids are collected from wellbores to provide a sample of fluid for chemical or physical analysis, or to measure formation fluid pressures and permeabilities by monitoring fluid pressures before, during and after fluids are extracted from the formation. The latter technique is a standard practice of the commercial exploration industry, but, to date, it has found limited utility in most holes drilled primarily for scientific exploration. Pore fluid sampling and analysis is required for studies of (1) fluid-solid reactions and chemical exchange, (2) biogeochemical reactions and processes and (3) diagenesis of organic materials. (4) Fluids also contain tracers useful for studying fluid migration, including origin of fluid and dissolved constituents, migration pathway, and fluid "age" or residence time in the rocks. (5) Various combinations of items 1 to 4 also provide the information needed to calculate hydrological or hydrothermal chemical fluxes on local to global scales.

The mainstay of pore fluid sampling from holes drilled for scientific purposes in unconsolidated and semiconsolidated sediments has been extraction of fluids from recovered drill cores. The fluids are usually extracted by squeezing core samples in specially designed presses, but centrifugation and immiscible fluid displacement have also been utilized. Extracting fluids from cores utilizes relatively simple and inexpensive technology, does not interrupt drilling operations, and provides a sampling density limited only by core handling and archiving protocols. However, contamination by drilling fluid limits the accuracy of fluid analysis and can be severe when the core is disturbed or highly permeable. The core is also subject to temperature and pressure changes and other disturbances to the in situ state (i.e., redox changes) that can alter the composition of fluids before they are isolated from the solid phase. Core sampling is also very unsatisfactory for quantitative analysis of dissolved gases, because of gas loss and contamination that occur during core recovery and handling.

It is clear that filtration and encapsulation of fluids in situ, from sediments undisturbed by the drilling process, can potentially eliminate or minimize the sampling disturbances associated with fluid sampling from cores. However, in situ filtration techniques for use in wellbores are still primarily experimental and will require further development to realize their maximum potential for quantitative fluid sampling. In situ filters usually push a filter containing probe into undrilled sediments ahead of the drilling bit and are thus limited to unconsolidated or mildly consolidated sediments. It is often difficult to extract adequate fluid volumes from low porosity, low permeability formations. In situ sampling usually interrupts the drilling process, because a special sampling tool is lowered on a wireline. Thus, sampling density is usually limited from considerations of available downhole time.

In situ filtration from harder rocks is beyond the capabilities of current instrumentation except for the special case of formation testing of permeable sands in the commercial exploration industry. The commercial Repeat Formation Tester® is not generally suitable for the conditions found in many scientific drilling operations. Several combination packer-water sampler tools, currently under development, may also prove useful in permeable formations. Thus, in situ sampling from hard rocks generally means open wellbore sampling. Open wellbore sampling suffers from severe drilling fluid contamination unless permeable "producing" horizons flush drilling fluids from the well, in which case information on in situ vertical gradients is lost because the producing horizons control wellbore fluid composition.

Inflatable packers can be used to isolate single or multiple zones of a wellbore and the isolated zones can be purged of drilling fluid and sampled to provide various approximations to undisturbed in situ conditions. The packers are left in the wellbore for extended time periods. To be effective, the packer approach requires continued accessibility to the wellbore for significant time periods beyond the initial drilling effort. Such access is often limited by budgetary constraints, but may be available for continental holes of high scientific or experimental priority. On the other hand, post drilling access to scientific holes drilled on the sea floor is severely limited until tools and techniques are available for wireline re-entry of the hole independent of the drilling ship. The high costs of multiple zone packers would limit their deployment in seafloor holes to a few very high priority sites. However, these same sites would also be likely targets for continued drilling or re-entry experiments that are incompatible with an in-place packer array.

Ideally, in hard rocks, the disturbing and intrusive influence of the drilled hole should be removed as soon as possible after drilling, so that local hydrological conditions can approach the undisturbed state before detailed in situ fluid sampling is attempted. The ideal technique would be simple, inexpensive, of broad applicability, and would not interfere with hole re-entry by a variety of non-water sampling instrumentation. Filling the wellbore with a special "mud" that would be relatively chemically inert and stable, would suppress vertical advection and inflow from permeable producing horizons, and through which instrumentation could be lowered seems to satisfy the above requirements. It would also help to stabilize uncased bores. In situ sampling from hard rock would then consist of using the soft sediment in situ filtration instruments to filter equilibrated fluids from the borehole mud and collecting associated samples of the mud for chemical analysis. Such re-entry sampling could be associated with or independent of the re-entry of a drill string, depending on hole conditions and the availability of wireline hole conditioning tools. The technique would appear to be applicable to most wellbores in non-thermal areas; high temperatures and their accompanying high reactivity fluids would pose special problems. Surprisingly, this technique does not appear to have been explored for possible use in scientific wellbore drilling and sampling.

Data from Deep Seal Drilling Project drill sites show the improvements in quantitative gas analysis that are possible with in situ sampling in soft sediments. However, much of the drilled interval is not suitable for in situ filtration techniques (too hard, too low permeability).

In situ pore fluid filters, open wellbore fluid samplers and packer associated fluid samplers continue to be developed and improved. I suggest that two other aspects of wellbore pore fluid sampling also need immediate attention. (1) New methods of core handling and processing, that can be used on a routine basis, must be developed to improve the quantitative recovery of dissolved gases from core materials. (2) As mentioned above, simple, inexpensive techniques for sealing and then re-entering and sampling wellbores in hard rocks need to be developed.

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SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

In Situ Borehole Fluid and Gas Sampling in High Temperature Environments

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Acquisition of unflashed and uncontaminated fluid samples under in situ conditions is desirable in order to obtain reliable chemical and isotopic analyses that are used to evaluate the temperature, chemical characteristics, and properties of specific fluid horizons in geothermal reservoirs or to obtain data on non-flowing wells. Los Alamos National Laboratory (LANL) has obtained in situ fluid samples with three different sampling tools: the LANL-Sandia National Laboratories (Sandia) sampler, the Lawrence Berkeley Laboratory (LBL) sampler, and the Leutert Instruments, Inc. (Houston, Texas) sampler. The LANL fluid sampler (Archuleta, et al., 1978) is a stainless steel tool, with a preevacuated 2-liter chamber, designed to run on a standard wireline cable or with the use of a battery pack/controller (Sandia). At the desired depth, a 0.40 amp current activates the DC permanent magnet motor and planetary gearing system, which rotates a shaft to open and close the valve. The LANL tool with wireline cable has been used successfully in the Hot Dry Rock program (300°C)and Valles caldera (232°C) in New Mexico, Maravalles, Costa Rica (240°C in an acid environment), and the East Pacific Rise (160-290°C). However, at temperatures in excess of 300°C in hypersaline environments, a standard wireline cable is not capable of delivering sufficient power to activate the motor and open the valve. Therefore, Sandia design a battery pack/controller housed in a dewar to be used to activate the LANL sampler at temperatures up to 400°C (Wolfenbarger, 1986). The battery pack/controller consists of a timer that activates the flow of current from eighty-four 1.2 V NiCad cells. This battery pack assembly allows the LANL tool to be run on a slickline thus eliminating

the problem of break down of insulation and damaging expensive wireline cables. The battery pack/LANL sampler combination successfully retrieved fluid and gas samples from a well at 350°C in the Salton Sea field, California.

The LBL downhole fluid sampler is a flow-through sampler constructed of MP35N alloy (Solbau, et al., 1986). Both valves of this sampler are held open by a magnet coil energized with 40 milliamps of current delivered by a single conductor cable. At the depth of sample collection, the valves are closed by removing the current supplied to the magnet coil. The LBL sampler has been successfully used in The Geysers geothermal field (260°C) and in the Salton Sea field (350°C).

The Leutert downhole sampler is a flow-through tool whose valves are mechanically opened at the surface and are closed at the desired depth using a timer-clock or are jerked closed using a jarhead mechanism. The Leutert tool is designed to sample fluids at temperatures ≤150°C, but successfully retrieved samples in Long Valley caldera (202°C) with the use of teflon seals and o'rings.

In situ fluid samples can be obtained with several available samplers, which are operable in different temperature ranges. However, in order to obtain useful information from the samples, quantitative recovery of gas samples and proper sampling and preservation of fluids must be accomplished. After a successful, gas-tight, sample has been retrieved from the borehole, the gas/liquid ratio as well as the gas and liquid compositions must be known in order to reconstruct the downhole fluid composition (Grigsby, et al., 1987). Therefore a gas extraction system has been designed and constructed by LANL to remove the gas for analysis and to measure the volume of gas collected by the downhole sampler. Before gas sampling begins, the sample bottle must be cooled below 70°C to lower the water vapor pressure and prevent loss of steam during gas collection. Gas is then collected according to the procedures of Goff, et al. (1987), with information on bulk gas, noble gases, and isotopic chemistry being obtained from the acquired samples.

Because high-temperature geothermal fluids are unstable at surface conditions, sample preservation and some field measurements are performed on site. Following gas collection, the geothermal fluid in the sampler is poured into a tared beaker and weighed. Density, pH, Eh, dissolved H_2S, NH_4^+ and HCO_3^- are next determined. Major and trace element chemistry and isotope samples are then collected and preserved according to procedures in Goff, et al., (1987) for brine samples or Trujillo et al. (1987) for dilute samples (<15,000 mg/kg total dissolved solids).

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SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Sampling for Light Hydrocarbon Analysis

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Low molecular weight hydrocarbons in deep sea sediments comprise a suite dominated by methane, generally at ppb levels, except where clathrates are found. These hydrocarbons are both of scientific interest and of major significance in the ODP safety program. Continuous coring is carried out to facilitate light hydrocarbon monitoring, in order to avoid chance encounter with reservoired oil or gas.

Available criteria for the detection of reservoir proximity rely upon the interpretation of methane/ethane concentration ratios. Reservoir gases possess a ratio value of less than 20, rarely rising to sediments lacking biogenic methane, and those in which in situ generation of light hydrocarbons is taking place. In these instances, resort to the evaluation of concentration gradients must be made. Recent experience on Leg 113 (Site 696) shows that this is a judgement fraught with uncertainty.

Present-day shipboard quantification relies upon headspace gas analysis. Vapor pressure considerations indicate that this technique seriously underestimates C_3-plus species. Data are presented showing that clearly recognizable compositional anomalies are observable at least 100 m above long-established accumulations of oil and gas, detectable in molecular concentration ratios such as propane/n-heptane and benzene/n-hexane. These ratios contrast diffusively mobile species to those having lower aqueous solubilities and diffusion coefficients in sediments. Analysis for

C_4-plus light hydrocarbon employing readily prepared ultrapure helium in stripping and concentration procedures is strongly recommended as a routine ODP shipboard procedure. The provision of liquid nitrogen as a refrigerant in this analysis would be required and appears to be feasible.

It is suggested that the methane/ethane ratio criterion might fail to provide forewarning of reservoir proximity. Shipboard monitoring of methane relies upon the retention of this and other permanent gases during core recovery by the intrinsically low permeabilities of oceanic sediments. Undoubtedly, there is substantial loss of these compounds during recovery, indicating the need for other means of preservation. Possibilities include in situ pore water sampling or pressure-retaining cores. Conceivably a Barnes water sampler could be routinely operated within the liner at the top of the core during ascent. An effective alternative would be to shift the reservoir proximity monitoring criteria to the C_4 to C_7 hydrocarbons which appear to be quantitatively retained during core recovery. To enhance available reservoir proximity criteria it is recommended that petroleum companies be approached with requests for fresh sidewall cores representing strata in vertical proximity to known reservoirs.

Hydrates of methane and natural gas are stable at low temperatures and high pressures. Y. F. Makogon suggests that 95% of the world's ocean floors present suitable conditions of pressure and temperature for their occurrence. Occurrence is evidently limited by the absence of sufficient biogenic methane or thermogenic natural gas in most areas. The shipboard recovery of encountered hydrates relies only upon their slow melting and visual recognition or the presence of gas partings in the core. Further retention for study would require the use of pressure vessels rated to some 500 psi, providing that they are maintained at 0°C, or simply the availability of liquid nitrogen which will reduce hydrate vapor pressure to a negligible level. Preservation during drilling and recovery would require substantial pressure core barrel capability or auxilliary cooling. Either or both approaches are recommended goals.

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Sampling for Physical Properties

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Physical properties measurements are undertaken to provide controlled information on the physical characteristics of rocks, to calibrate downhole measurements such as well logs, and to complement laboratory petrochemistry in establishing a physio-chemical database. These measurements include resistivity, porosity, acoustic velocity, radioactivity and permeability. Ideally, physical data are based on measurements of preserved, oriented core plugs, and are acquired non-destructively. Such a strategy requires preservation immediately after recovery in a mode which does not permit dehydration. These conditions are rarely satisfied in practice.

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Continental Scientific Drilling

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Deep Observation and Sampling of the Earth's Continental Crust, Inc. (DOSECC), is a nonprofit university consortium of 40 members established to implement a continental scientific drilling program for the National Science Foundation. The program is planned to investigate a broad range of geological processes such as thermal regimes, active faulting, mineral resources, and continental basements and basins, using the drill as a tool to collect samples and downhole measurements necessary to provide environmental constraints on and validation of models developed from surface geological, geochemical, and geophysical investigations. Planned is drilling from shallow to ultradeep (>6 km) holes designed for extensive coring, cuttings and fluid sampling, logging, and long-term monitoring (upon completion).

The Cajon Pass Project drill hole, presently at a depth of 6938 ft (2115 m), is investigating the heat flow/stress paradox associated with the active San Andreas fault in southern California. Thirty-three spot cores have been recovered, most in granodiorite and gneiss using diamond-impregnated mining core bits rotated by mud motors or turbines. One comprehensive wireline logging experiment was successfully conducted at 6000 ft (1800 m), along with fluid sampling. Temperature logging (about 90°C at present) and water-level monitoring (to determine permeability and pore pressure) is being conducted monthly during a furlough of about seven months before continuing drilling to a projected total depth of 16,000 ft (4900 m). Early results of hydrofracture experiments show maximum compressive stress oriented normal to the fault, indicating that the San Andreas fault is weak.

DOSECC also supports drilling experiments in the U.S. Mid Continent to investigate the Precambrian evolution of the North American craton, and predrilling surveys of the structure and geochemistry of the Creede, Colorado, precious metal mining district. The U.S. Department of Energy has recent completed a scientific drill hole to a depth of about 10,500 ft (3200 m) in the Salton Sea geothermal area of southern California, as well as a series of drill holes in the Valles caldera of northern New Mexico and in the area of the Long Valley caldera, east-central California. Communication with scientific drilling activities in the Soviet Union, Federal Republic of Germany, Sweden, France, Great Britain, Canada, Iceland, and South Africa provide valuable insight to new scientific results and engineering advances in drilling, logging, and sampling tools and techniques.

A constant problem in sampling is avoiding and/or monitoring the many sources of contamination to samples introduced by standard drilling chemicals, lubricants, and other materials. Representative fluid sampling from isolated formations and zones in low permeability crystalline rocks represents another issue receiving continuing attention.

SCIENTIFIC SAMPLING ISSUES - ABSTRACTS

Drilling to Observe Processes at the Glacier Bed

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Drilling in glacier ice has received a moderate amount of attention since World War II. There are two main and rather different scientific goals. The first is to extract paleoclimatic and paleoenvironmental information, and requires continuous core, sometimes to 2 km or more. This technology is well developed particularly in Europe. The second goal is to study the mechanisms of glacier flow, particularly processes at the glacier bed, and requires access holes and the means to sample the underlying substrate. While access is relatively straightforward via hot water drilling, the substrate has yet to be sampled successfully. This is a serious deficiency for several reasons, one of which is that motion at the bases of many glaciers, as opposed to deformation of the ice itself, often accounts for much and sometimes all of the motion observed at the glacier surface. Also, instabilities in basal motion, which are related to the hydraulics of liquid water there, are known to be the source of catastrophic glacier advances, or surges, during which speed may increase from 0.1 to 50 meters per day, or more. In addition, the understanding of processes at the glacier bed would provide the link between glaciology (the study of existing glaciers) and glacial geology (the study defositional and erosional features of retreated or vanished glaciers).

Whatever the morphology of the glacier bed, it is probably highly variable, varying from a relatively clean ice-bedrock contact, on the one hand, to an ice-till contact on to no well-refined contact at all, on the other. Basal sliding motion along an ice rock contact, or deformation of an underlying till layer (and perhaps sliding along its tip) probably commonly account for a few centimeters to a few meters of motion per day, or in the case of surges, 50 or more meters per day. Sampling the basal material, particularly when the porewater pressure is high and motion is occurring, is a difficult challenge, and probably requires the development of new techniques. Monitoring systems for basal motion and water pressure are also needed.

Existing information about glacier beds comes from glacier geology, tunnels, downhole photography, geophysics, and mineral and hydroelectric developments.

SAMPLING TECHNOLOGIES - ABSTRACTS

Scientific Sampling Program, Gravberg 1-Well, Sweden; Integration of Well Site and External Laboratory Analyses

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The Gravberg 1-well is situated in an area of central Sweden known as the Siljan Ring structure, which was formed as the result of a meteorite impact 360 million years ago. The well is being drilled as a commercial venture by Vattenfall, the Swedish State Power Board. The objective is to explore for abiogenic deep mantle gas in the crushed granite bedrock in the crater. The only rock types encountered thus far are granotoids and dolerites of pre-Cambrian age. At present (mid-May 1987) we are at 6,000 meters, drilling down to a programmed total depth of 7,500 meters.

The scientific sampling program in the deep borehole at Gravberg incorporates a close cooperation of sophisticated measurements made at the well site in close coordination with a group of eight laboratories performing various analyses. At the well site, hydrocarbon gases are monitored by three different systems, each one of which offers particular advantages. Inorganic gases, H_2, CO_2, N_2 and He are also measured at the well. Because of the nature of the project, many devices were redesigned in order to provide the precise data required.

Study of the cuttings at the well site includes a lithologic description with special emphasis on the rock characteristics which affect porosity and permeability and that can indicate the potential presence of a fractured reservoir. The lithologic study is also geared to describe those elements which can affect a tie to wireline logs. A mineralogical point count analysis is carried out which helps in the identification of changes in rock type.

Cuttings study is a crucial part of the evaluation, as relatively few cores have been taken, and for the most part, recovery has been poor. The Gearhart sidewall coring tool appears to have significant potential, for we obtained good results as deep as 5,400 meters, under extreme weather conditions (-30°C).

The off-site laboratories analyze gas samples, mud samples, canned cuttings (for headspace and desorbed gas analysis), and dried cuttings. These analyses parallel the ones done at the well, but also include isotopic compositions of methane, ethane, propane, deuterium and helium.

Inorganic rock analyses include the typical petrographic and X-ray study, plus major and trace element analysis. These data have permitted us to make a subdivision of the granites into several major types. Fluid inclusion studies underway are aimed at understanding the properties of the fluids that have migrated through the granites. Also in progress are radiometric age dating studies that are planned to help obtain the age of the granites, the dolerites, the melts associated with the meteorite impact, and the age of the alterations (fracture zones and hydrothermal effects).

Two types of methane are present: a fairly dry gas, rich in methane is found in the dolerites. These are the major gas shows. The second type is found in smaller amounts, and it includes a fairly high concentration of ethane and propane. We seem to be dealing with at least a dual origin for the gases; it is not clear what the origins of the gases are at this point in our study.

Hydrogen gas is a prominent part of the gas mix, it is usually found in concentrations greatly exceeding the C_1 concentration by about an order of magnitude. Radon occurs in fairly low levels throughout the well, while helium is found only at greater depths.

The character of the mud system, varying from fresh water (around 8.5 ppg mud weight) to a bentonite-barite mud (up to 13.5 ppg), and at times contaminated with diesel, has a major impact on the quality and quantity of hydrocarbon shows.

SAMPLING TECHNOLOGIES - ABSTRACTS

Porefluid Sampling at Cajon Pass

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Previous studies to determine the state of stress along the plate boundary defined by the San Andreas Fault in the locked section near Cajon Pass, lead to an apparent paradox; limited-depth stress measurements suggest a high stress fault whereas heat flow measurements suggest a low stress fault. Several possibilities have been suggested to resolve this problem: (1) the fault is predominantly weak, (2) high stress is distributed over subhorizontal detachments, (3) the heat flow requires additional erosion and structure corrections, and (4) the heat from a high stress fault is widely distributed by hydrologic flow.

DOSECC-sponsored scientific drilling at the Cajon Pass Site was initiated in 1986 and is directed primarily towards the resolution of this paradox. The program encompasses a broad range of geological, petrological and hydrological sampling and extensive geochemical and geophysical logging programs.

Hydrologic and porefluid sampling for major and minor element chemistry and stable isotopes are being conducted to characterize the porefluid chemistry with respect to sources, interaction with the major rock types and fracture-plane rock-types, and to assess mixing. Dissolved gases are being sampled for hydrocarbons, major gases and a suite of rare gases to assess hydrocarbon sources, gas phase separation and mixing, residence times and flow paths. Radio-isotopic studies are directed towards a determination of fluid residence times and fracture geometry, some of which require large volume samples.

Porefluid sampling was undertaken in a ~250' interval below the casing at ~6000'. The hole was flushed with fluorscene-tagged freshwater to provide freshwater to provide an indicator of drilling fluid and was repeatedly sampled using the LBL sampler and a Kuster Co. sampler during a four-day drill stem test monitoring the pressure build-up. Large volume samples were taken by pulling a "wet string." Low permeabilities (<1 microdarcies) limited the amount of porefluid entering the hole and sampling was later conducted directly within the open hole. The preliminary results indicate at least two water types as might be suggested by the low permeability.

SAMPLING TECHNOLOGIES - ABSTRACTS

On Fluids in the Earth's Crust

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Over the past 35 years, the measurement of geologic time scales and the quantification of geologic rates and reactions has dramatically altered our concept of the processes controlling the evolution of the Earth. While the traditional earth sciences might have been largely descriptive and categorizing, the Earth is now examined as a dynamic set of systems which respond along fluid dynamically and kinetically determined pathways which include both reversible and irreversible thermodynamic reactions and exhibit both transient and steadystate conditions.

Recent research has shown that crustal fluids play an essential (and possibly dominant) role in metamorphic reactions and mineralogic transformations in the crust (Etheridge, et al., 1983; Etheridge, et al., 1984; Mottl, 1983; and others). These studies have also shown that the quantities and fluxes of fluids required to complete these solid phase reactions cannot be supplied in situ or by diffusive transport. Such studies provide substantial indications for the existence and pervasive nature of enhanced fluid and mass transport in oceanic and continental crust.

In the continental crust, obvious systems like Yellowstone and The Geysers clearly illustrate the role of fluid convection in high temperature geothermal fields. However, Blanchard and Sharp (1985) have calculated not only the distinct possibility of free convection in low-temperature Gulf Coast sediments, $Ra \gtrsim 40$, but have also shown that porefluid chemistry and temperature distributions are consistent with Bernard-type convection cells. Wood and Hewett (1982) stress that "it is virtually impossible to maintain a static fluid in a porous body," and that "eddy currents will arise and persist in bodies of (kilometer) size, simply due to the difficulty in establishing equilibrium conditions." They calculate typical circulation velocities of ca. 1m yr^{-1}. Etheridge and others (Etheridge, et al., 1983; Etheridge, et al., 1984) have concluded that "advective mass transport is likely to dominate at all but the very smallest scales during regional metamorphism" (my emphasis; see also Fletcher and Hoffman, 1974; Wood and Hewett, 1982). His evidence clearly shows the necessity of a mobile, high pressure fluid and large fluid/rock ratios (10^2-10^3). Thus, the question is not whether crustal fluids will convect/advect and affect large-scale mass transport under normal geothermal and porefluid pressure gradients, but whether these processes are sufficiently pervasive to generate regional and global effects.

The measurement of a crustal degassing flux of ^4He (Torgersen and Clarke, 1985, Torgersen and Ivey, 1985) equivalent to the whole crustal production and its corroboration with the atmospheric helium balance quantitatively supports this concept; large-scale fluid-driven mass transport in the Earth's crust is both geologically rapid and ubiquitous.

Etheridge's view (Etheridge, et al., 1983) of fluid transport processes in the whole continental crust depict numerous mechanisms at various depths for variable time intervals. Generally, fluid transport in the crust arises from enhanced porosity and permeability induced by tectonic/seismic fracturing, high porefluid pressure gradients (short-range migration) and normal geothermal gradients (long-range migration). Etheridge, et al., (1984) have proposed a crack-seal fluid pumping mechanism analogous in some ways to dilatancy theory (Scholz, et al., 1973) and seismic pumping mechanisms (Sibson, et al., 1975) to explain this transport in part. Rayleigh/Darcy calculations indicate that the continental crust is capable of sustaining free convection ($Ra > 40$) at permeabilities $> 10^{-17}m^2$ where in situ permeabilities of 10^{-15}-$10^{-18}m^2$ are indicated (Etheridge, et al., 1983). However, the time scales of such convective/advective processes are not adequately determined and it is presently unclear whether convection/advection is a continuous or semi-continuous long-term process in the crust; or whether the mass transport mechanism is a highly episodic, but very effective short-term process. Thus, (i) the observed mineralogic, geologic and economic importance of fluid-driven mass transport in the Earth's crust, (ii) the substantial evidence for large scale convection/advection and (iii) the potential for fluid transport interaction with tectonically controlled (a) seismic, (b) thermal stresses and (c) heat transfer mechanisms in the Earth's crust make it clear that physical measurements of the geologic rate of fluid and mass transport need to be determined and the forcing functions (thermal buoyancy, chemical buoyancy, porepressure gradients, etc.) for such transport need to be established. Only within such a framework can the current models of fluid-driven mass transport be evaluated and tested for application to problems of hydrothermal ore emplacement, crustal metamorphism, fault zone heat and stress balances, radwaste disposal, gas and oil accumulation, crustal degassing and the evolution of the oceans and atmosphere.

The implementation of any such program requires the development of borehole sampling techniques from multiple horizons with minimal surface contamination and minimal zone-to-zone contamination. It must be operable in both fracture-dominated systems and porous media. Such techniques must be able to provide representative samples for major elements, trace elements, trace metals, stable isotopes, radioisotopes and dissolved gases. Such a sampling scheme must also provide at least limited downhole real-time measurement of pH, T°, Press., conductivity and selected specific species. It must operate at high temperature, high salinity and high pressures. The development of this fluid sampling capability together with the physical properties needed to define fluid flow and fluid-driven mass transport represents a major step in our understanding of the dynamics of the Earth's crust. It is a challenge that can and must be addressed.

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SAMPLING TECHNOLOGIES - ABSTRACTS

Pressurized Sampling Needs for the Ocean Drilling Program

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During a workshop on "Development of a New Pressure Core Barrel," held in College Station on October 1, 1986, ODP explored the needs and design concepts of scientists interested in pressurized sampling. Attending were organic and inorganic geochemists and physical properties scientists. Three basic concepts were advocated during the presentation of ideas on the new tool:

(1) As long as we are able to maintain a material balance of sediment and gas, we do not need a truly pressurized sample (harmonica-design). Reason: This approach seeks to establish quantitative relations of sediment, interstitial water, and gas calculations concerning the abundance of biogenic and thermogenic hydrocarbon gas. Status: With the development of the in situ filtering device (Barnes-tool), we have a sample to establish this mass-balance.

(2) We need a pressurized sample, we want to be able to look at it, and we want to take pressure measurements and sample without having to dismantle the core barrel (Advanced Pressure Core Barrel design). Reason: The physical appearance of the sediment and/or fluid components in the pressurized sample should be tested in a manner non-destructive to the bulk sample. Status: Advanced design of the DSDP Pressure Core Barrel, which was not designed to take controlled samples.

(3) We need a combination of Pressure Core Barrel and shipboard hyperbaric chamber in order to retrieve, handle, split (and analyze) pressurized sediment under in situ conditions for physical properties. Reason: In order to maintain the conditions prevailing in the hole and to maintain the physical properties, the sediment has to be pressurized at any stage in the data-gathering process. Status: Entirely new concept and probably not feasible for deep-sea operations. As an alternative, in situ measurements were discussed and generally favored over the costly and complicated equipment needed for pressurized measurements.

SAMPLING TECHNOLOGIES - ABSTRACTS

Update Report: Pressure Core Barrel Development for the Ocean Drilling Program

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The Ocean Drilling Program is currently undertaking to develop a capability to obtain deep sea cores at in situ pressures. This program is in response to an oft repeated desire by the scientific community for analyses of core samples which cannot be conducted on cores which have been allowed to depressurize upon retrieval as is normally the case.

As the successor to the Deep Sea Drilling Program, ODP has a Pressure Core Barrel (PCB) which was designed in the early 1970's. This tool has been obsoleted due to its numerous shortcomings. It was originally designed to sample, recover and verify the existence of methane hydrates in the deep ocean. The on deck analysis was limited to extraction of gases from within the pressurized section of the core barrel. The barrel was over thirty feet long and thus difficult to handle on deck. Temperature control of the enclosed sample required cooling or heating the entire core barrel mechanism. There was no provision for physical access to the core sample itself without first depressurizing the container. A final drawback was that the PCB was not compatible in the same bottomhole assembly as ODP's Hydraulic Piston Corer and Extended Core Barrel Tools which were developed later in the course of DSDP.

To remedy the restrictions of the existing PCB an all-new tool is currently under development although progress to date has been limited to identification of the scientific needs and establishing the technological goals. The first goal is to limit the pressure sample size to something small enough to be easily handled, thermally controlled, transported and inserted in pressure chamber testing equipment. A two-foot long sample chamber will produce a sample volume of about 1200 cc. The new tool will ideally be designed to run as a piggyback addition to the existing XCB system. In whatever form it takes it will be fully compatible with APC/XCB coring operations and be as non-intrusive as possible to normal coring so that utilization will be more common. Ideally, a piggyback Pressure Barrel cartridge would actually take two core sections retained at in situ pressure. One would be the larger portion for scientific analysis while a smaller section would be separated for immediate hydrocarbon safety analysis.

Sample accessibility within the pressurized chamber will be accommodated in three stages as successive models of the tool are developed as follows:

Stage I: Amount (mass and length) of sample under pressure will be determinable. Gases will be extractable via a gas sampling manifold.

Stage II: Access to the sample while under in situ pressure will be possible for visual observation, photographing and some remote measurements (e.g., CATSCAN).

Stage III: Access to sample under in situ pressure will include the ability to subsample and perform physical property measurements. These steps will require inserting the sample into a hyperbaric chamber. Subsamples will be removed under pressure into suitable vessels for transport to other test equipment onboard or in other labs.

In addition to the above, the development of the new PCB will be staged according to pressure capability. At first a tool capable of taking samples at in situ pressures from water depths up to 3000 meters will be designed. As the development progresses pressure capabilities will be stepped up to 6000 and possible 9000 meters.

SUMMARY OF WORKING GROUP DISCUSSIONS

Pressure Coring Group

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I. SCIENTIFIC PRIORITIES

During the course of the discussions it became clear that the members of this particular working group would not be able to accurately identify the scientific priorities attendant to a near-term future development of a coring or sampling system designed to sample materials in the wellbore and retrieve them at in situ pressures. In part this may have been due to the fact that the members tended to be technological rather than scientific in their backgrounds and expertise. In another respect the group's inability to identify specific scientific goals and requirements for the hardware in question was symptomatic of the general difficulty that has been faced for many years in the development of sampling equipment for acquiring pressurized downhole samples.

Virtually all breeds of scientific investigators who examine wellbore samples would, at one time or another, like to have samples which were not allowed to depressurize from their in situ condition during retrieval. This general desire is a common denominator among geotechnical investigators, geochemists, structural sedimentologists, paleomagnetists, etc. The overall purpose of achieving an un-depressurized core is to allow the investigator to perform studies on the sample under conditions as close as possible to absolute in situ replication. The big difference between the desires of these investigators is what they would attempt to do experimentally with a pressurized sample. There has not emerged a focused description of the experimental methodology which would be associated with pressurized samples if they were brought to the laboratory. With unpressurized samples this is not necessarily a problem--the samples must only be curated in some appropriate manner (i.e., refrigerated, sealed in wax, etc.) and made available when a specific investigator has decided on a specific course of action. In the case of pressurized samples the most direct approach would be to include at least some degree of capability for a given experimental method by building measuring devices into the pressure container in which the sample is recovered. Since so many different types of investigations are probable the logical alternative approach is to attempt to build a simple pressure chamber cartridge which would recover the sample at in situ pressures and allow the sample to be transferred without disturbance or loss of pressure to any of a variety of containers/chambers where subsampling and experimental measurements would be performed.

Statement of the scientific priorities was not forthcoming from the working group, but certain scientific desires were identified which help in the process of identifying the technological goals. The wish list can be divided into two basic categories: 1) samples recovered with all in situ conditions maintained, including pressure, and 2) samples recovered in which all volatile constituents are contained while other in situ conditions are allowed to change. In reality, all visions of a pressurized sampler fall into category 2 because even the most optimistic investigators do not expect samples to be maintained at in situ temperature along with pressure and all other in situ conditions. It is, however, important that any pressurized sampler take a local temperature measurement at the time the sample is acquired. Another important approach which falls into the second category is a sampler which would allow gases to evolve from the solid sample or interstitial fluids while being retained in the sampler as the enclosed volume of the sampler is allowed to enlarge as it is retrieved. In this way very high hydrostatic pressures downhole can be reduced to make on deck handling safer as well as allow the use of vessels with lower pressure capabilities. This approach would be adequate for investigators interested in determining amounts and types of gases present in samples under in situ conditions.

One member of the group pointed out, quite rightly, that some investigators who have expressed a desire for samples retrieved at in situ pressure could actually perform their subsequent analyses as well or even better if a controlled temperature or "frozen" sample were acquired instead, e.g., investigators seeking samples of micro-organisms. (The use of the word "frozen" is used here cautiously understanding that freezing is normally used in the context of solidified water, but actually applies to the general case of solidifying many other compounds each of which has its own temperature/pressure freezing characteristics.) In any case, the nature of subsequent on-deck examinations should drive the specifications for a pressurized sampler. It is unlikely that any set of generic specifications will satisfy the needs of an adequate number of investigators to justify the expense of development or the difficulty of deployment of a pressurized sampling system.

It should be pointed out that pressure coring devices have been commercially available for some years, but have failed to fulfill the scientific sampling mission because of a number of shortcomings which any new pressure sampling system should attempt to improve upon: compatibility with drilling systems in use, price, pressure limitations, sample disturbance and sample access while under pressure in the lab. The following is a list of the types of investigations which might be of immediate interest if a usable pressurized sampling system were more routinely available for retrieving scientific samples in boreholes.

- Evaluation of gas hydrates
- Geotechnical/physical properties studies
- Dissolved gas studies, chemical fractionation analyses
- Paleomagnetics on undisturbed samples
- Depressurization effects on physical properties for comparison with samples retrieved by routine methods
- CATSCAN imaging of samples under pressure
- NMR imaging of samples under pressure
- Evaluations of microorganisms
- Gas isotope studies

There are inherent difficulties in retrieving downhole samples which are undisturbed either by sampling mechanisms or depressurization effects. Because of this there is a strong argument for achieving scientific objectives via in situ measuring (i.e., logging) rather than sample retrieval. Investigators interested in pursuing means to acquire pressurized samples should consider the logging alternative even to the point of developing new and better logging tools which have the potential to produce the closest approximation to true in situ property measurements.

II. TECHNOLOGICAL PRIORITIES

Having established the scientific goals of recovering wellbore samples at in situ pressures a myriad of technological hurdles can be foreseen. Many of these are compounded by the lack of concensus scientific direction as discussed above. Some of these problem areas were discussed by the members of the working group and summarized here.

1. Sidewall coring has been suggested as a means of more simply integrating pressure sampling into a conventional drilling/coring program. The group considered this a weak approach to the problem. It would require a sidewall coring tool which would likely be as complex or more complex than in-line coring tools. Secondly,

sidewall corers can only be deployed after the borehole is established by other drilling means which allows for predisturbance and contamination of the in situ pressure sample sought.

2. The three primary technological issues are pressure capability, reliable downhole closure mechanisms, and access to the pressurized sample in the lab or on deck after recovery.

3. Pressure ratings for envisioned sampling tools run the gamut from a few hundred psi for shallow land holes up to 12,000 psi for samples recovered from the depth limits of deep ocean coring systems. No single design will be appropriate for this range of potential applications. The implication is that sampler ratings will have to be custom-adapted for given missions. The same applies to the laboratory equipment required to gain access to the pressurized sample for measurements or subsampling as well as containers used to store and transport samples under pressure.

   Investigators should be encouraged to consider the alternative of retrieving samples at pressures higher than hydrostatic or in situ but lower than ambient. For analyses where this option is acceptable the pressure container can be designed with a lower pressure rating thus allowing for thinner walls, less expensive materials or metal processing, and/or greater safety factors.

4. A first priority for any functional sampler is the ability to readily control temperature of the sample container in the lab. This implies that an ideal sample container should be small enough to place in a controlled-temperature bath. Another feature of the sampler that is considered mandatory is a facility to record local temperature at the time that the sample is taken.

5. Pressure control ability while recovering the sample and while examining it in the lab must be a part of the sample container design. This problem is especially compounded by the possible presence of gas hydrates in solid form in the sample. Since temperature control systems breakdown or human error can always occur overheating of the sample container must always be considered a possibility. A solid hydrate sample under in situ pressure which was allowed to warm would experience pressure increases far greater than ideal gas laws would imply. Thus a safety pressure relief system would be required which would operate automatically whenever the container internal pressure exceeded the exterior pressure by a selected amount. At first pressure should be reduced by enlarging the internal volume or dumping inert gases from an artificial head. If this does not result in safe pressure levels in the container, actual gases coming off the sample must be vented. The vent system must not be susceptible to failure by clogging by particles entrained in the escaping gases. An ultimate safety rupture disc is probably a mandatory feature.

6. For studies in which only mass quantities present in situ are sought an enclosed sample can be recovered in a chamber with the ability to expand without loss of material. Thus it is conceivable to design a container in which the sample is brought back at low or near-atmospheric pressures which would still constitute a useful "in situ" sample.

7. Those analyses which require visual access to the sample (for observation of physical changes or scintillation counters) should be separated from other requirements where visual access is not necessary since windows would present significant design compromises.

8. To best satisfy the variety of followup studies which might be applied to pressurized samples the best container would be one which would have only the ability to transfer the sample under pressure to any other compatible container. The receiving container would be customized for the measurement or procedures to be performed (e.g., an all-aluminum container for CATSCAN examination, a Monel container for magnetic analyses, a hyperbaric chamber with remote manipulators to allow for physical property tests or subsampling, etc.).

III. CONCLUSIONS

Even with limited representation by scientific investigators with actual plans/desires to do work on samples recovered at in situ pressures it was apparent to the working group that a scientific demand exists for pressurized solid wellbore smaples. This demand appears at present to be unfocused. It also appears that the demand has not been met by currently existing pressure coring tools including those which are commercially available. Scientific investigators would be better served in this regard by defining the experimental methodology and goals that would be pursued if pressurized samples were available so that technologists can begin to fashion specific solutions to satisfy defined needs.

The technological demands are great for tooling to recover pressurized solid samples, but not unprecedented. Both scientific programs (DSDP) and commercial interests have designed and deployed successful pressure coring tools. As the cliche goes, "we have the technology," the question is one of application of the technology to the specific problems. It is highly unlikely that a generic pressure coring tool will ever be available for scientific sampling. Like wellbore fluid samplers and high temperature logging tools this technology will remain somewhat esoteric for the foreseeable future.

POSTER SESSION - ABSTRACTS

Description of a Flow-Through Downhole Fluid Sampler

R. D. Solbau, O. Weres, L. Hansen, and B. Dudak
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University of California
Berkeley, California 94720

Under the joint sponsorship of the Gas Research Institute (GRI) and the U.S. Department of Energy, engineers and researchers at the Lawrence Berkeley Laboratory designed and fabricated a downhole fluid sampler. The sampler is constructed of MP35N alloy, which is chemically inert to wellbore fluid. It is capable of retrieving a 1000 ml downhole sample at a maximum operating temperature of 350°C and pressures of up to 20,000 psi (Michel, et al., 1982; Weres, et al., 1984a).

The sampler is of the flow-through type; while the instrument is lowered down the wellbore, the upper and lower valves are in the open position. When the valves are open, fluid is free to enter at the bottom and exit at the top of the sample chamber.

The unique mechanism for holding the sampler valves open until closure is required consists of two primary components: an electromagnet assembly and a lock-ball arrangement. When the magnet is energized, the lock-balls hold the valves open. After the appropriate sampling depth is reached, current supplied to the magnet is decreased, the lock-balls disengage and the valves close. The 40-mA current required to maintain a magnetic field sufficient to keep the valves open can be supplied from the surface through a logging cable or with a dewared downhole battery pack.

After retrieving the sampler from the well, piercing valves are attached to rupture disks located in the sampler's valve bodies. A custom-designed sampler-extraction system (Weres, et al., 1984b) may be used to remove the brine and gas from the sampler without exposing them to air.

Acknowledgements

The design and fabrication of this sampler was funded by the Gas Research Institute under Contract No. 55081-212-0552. This work was also supported in part by the U.S. Department of Energy, Office of Basic Energy Sciences and the Assistant Secretary for Conservation and Renewable Energy, Division of Geothermal Technology, under Contract No. DE-AC03-76SF00098.

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POSTER SESSION - ABSTRACTS

Workshop Displays from the Department of Energy's Multiwell Experiment

A. R. Sattler, J. C. Lorenz, and S. J. Finley
Sandia National Laboratories
Albuquerque, NM 87185

The objective of the Multiwell Experiment is to characterize the tight lenticular gas reservoirs in the Western United States and to develop technology for their production. An overview of the project was provided. The displays at the workshop concentrated on equipment that has been developed in the course of the Multiwell Experiment core program and on a study of drilling-induced fractures. Over 4100 feet of core were taken, about one-third of it oriented during the course of the program.

The first display outlined the core program. This display included:

- An outline of the core program and the more than 20 participating laboratories.

- A complete description of the thorough, comprehensive field processing utilized on the core.

- The core gamma assembly developed to provide core log correlation. It was also useful for well control and special studies requiring better spatial resolution than provided from downhole gamma ray logs.

- Simple goniometer-like devices for quick, accurate measurements of dip, strike, and other linear features on oriented core.

- A summary of a pressure coring operation in tight sandstones that provided unambiguous water saturation analyses, analyses of gas species on a foot-by-foot basis, and implications for optimizing "routine" water saturation measurements of tight rocks.

- Descriptions of hardware for measuring anelastic strain relaxation in oriented core. These data are used to predict hydraulic fracture azimuth and as inputs to models which provide an estimate of in situ stress magnitudes.

The second display provided a summary of a study on drilling/coring-induced fractures including the types of induced fractures, their characteristics and their significance.

- Types

  - Petal fractures that form ahead of the bit.
  - Scribe-line fractures that are initiated by the scribe knives.

- Characteristics

  - Each of these fractures has a distinct morphology.

  - The upper termination of a petal fracture is outside the core, whereas the bottom of the fracture terminates within the core.

  - Scribe-line fractures are confined to the scribe groove on the outside of the core and terminate 1" to 2" into the core. The scribe groove is often irregular where these fractures occur.

  - The surface of both types of fracture is fresh, characterized by distinct conchoidal fracture of quartz grains and other angular broken grains.

The fracture surfaces may be coated with rock powder and/or drilling mud.

- Both petal and scribe-line fractures are generally aligned parallel to the horizontal maximum compressive stress. However, petal fractures may be rotated in the direction of bit rotation by additional shear stress created by the torque of the bit.

- Significance

  - These drilling/coring-induced fractures can be used to determine the actual and/or relative orientation of the principal horizontal stress field.

POSTER SESSION - ABSTRACTS

Advanced Downhole Sampler Prototype

R.Charles, C. Navarro, and D. Janecky
Los Alamos National Laboratory
Los Alamos, NM

and

C. Wells
Lentert Instruments
Houston, TX

Investigation of the composition of hydrothermal fluids has important applications to resource evaluation, both in energy and materials development. Studying fluid compositions can lead to understanding of the source and pathway of fluids and indicate geothermal energy potential, hydrocarbon resources, and metal deposit formation. While many investigations of major component concentrations in such fluids have provided insights into the processes and products of these systems, it has become evident that understanding the behavior of minor and trace components is necessary to fully describe and differentiate these systems. However, many, if not most, hydrothermal solutions do not appear at the earth's surface for sampling and those that are accessible may be significantly modified by the venting process. Thus, sampling solutions from boreholes is a necessary part of hydrothermal research efforts. High quality samples of fluids from wells such as those drilled in the CSDP program help define the hydrologic regime, allow study or economic mineralization, allow temperatures of deeper reservoirs to be estimated, and help define the most productive aquifers.

Due to the inherent limitations of previous sampler designs, simultaneous collection of uncontaminated and unfractionated fluid and gas from discrete horizons under commonly encountered hydrothermal

conditions cannot be assured or even expected. Our objective is to develop a wireline-based tool for simultaneous collection of uncontaminated and unfractionated gases and fluid in the difficult environment encountered in boreholes drilled as part of the CSDP project and other projects of opportunity. This sampler will be designed to meet the following criteria:

-- function at temperatures up to 400°C
-- will be of flow-through design
-- will not fractionate gases and liquids during collection
-- will be helium leak tight following collection
-- will minimize contamination of the sample by reaction with the sampler
-- will operate without electrical connections to the surface
-- will be capable of collecting sample volumes of one liter

We have modified a commercially available slim-line, flow-through sampler which will be used to collect fluids from these extreme conditions. Different sealing mechanisms, and sampler metals are incorporated in the new design. A prototype is under construction at this time.

POSTER SESSION - ABSTRACTS

An Integrated Geophysical, Geological, and Geochemical Study of a Small Area South Hamilton, Massachusetts

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Riess Foundation
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Gene Simmons
Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts

and

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Salem, NH 03079

Three deep wells (3000 ft. maximum depth), have been drilled in igneous rock on the Totten farm in South Hamilton, Massachusetts. The site is located about 25 miles northeast of Boston in the southeastern corner of the Georgetown 7 1/2' quadrangle. The wells have yields of several hundred gallons per minute, extraordinarily high for wells in crystalline rock. They apparently intersect a shear zone with high permeability.

Twelve shallower boreholes (400 ft. or less) were drilled at a nominal radius of 600 feet around the deeper wells for use as shot holes for vertical seismic profiling in the deeper wells.

In order to understand the geologic setting of these wells, an extensive set of geophysical, geologic, and geochemical data has been collected, examined, and interpreted. We have used:

- New gravity data obtained at closely spaced, surveyed stations and new and existing data on a regional scale,
- New magnetic data at closely spaced, surveyed stations,
- Existing aeromagnetic data,
- Cuttings collected at intervals of 10 to 25 feet and several cores from selected depths,
- Borehole geophysical and television logs,
- Water samples collected at depth and at several times for geochemical analyses, and
- K/Ar dates on a set of felsite dikes.

In addition to the new data obtained during this study, we also used the existing gravity data available from NOAA, Joyner's (1963) interpretation of gravity, the aeromagnetic maps of the US Geological Survey Geophysical Investigations Map (GP-718,GP-719, GP-722, and GP-723) and the VSP results of Toksoz. We have drawn on the geological descriptions of Toulmin (1964), Bell (1977), Bell, et al. (1977), Zen (1981), and Dennen.

POSTER SESSION - ABSTRACTS

High Temperature Fluid Sampler

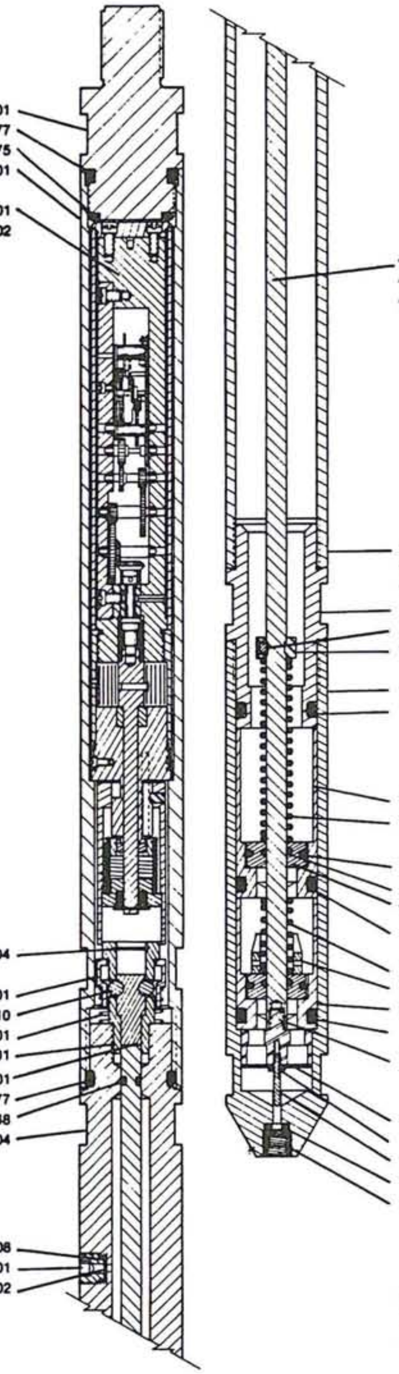
John Jacobson
Kuster Company
Long Beach, California 90809-0909

Temperature	300C max
Pressure	1400 kg/sq cm
pH	2.5 to 9.0
Salinity	0-300,000 ppm
Operating depth, water	50 m minimum
	5000 m maximum

Capacity, ml	250	500	1000
Dimensions			
Length cm	118	178	292
in	46.375	70.25	115

Material	Stainless Steel, copper-nickel alloy, copper, nitrile neoprene
Clocks	60 or 150 minutes, programmable

11500-100 SAMPLER



DIMENSIONS
LONG 250 CC 47. in.
500 CC 72. in.
1000 CC 112. in.
O.D. 1.25 in.

ACCESSORIES

11552-101 EXTRACTOR ASSEMBLY
11559-001 VALVE WRENCH

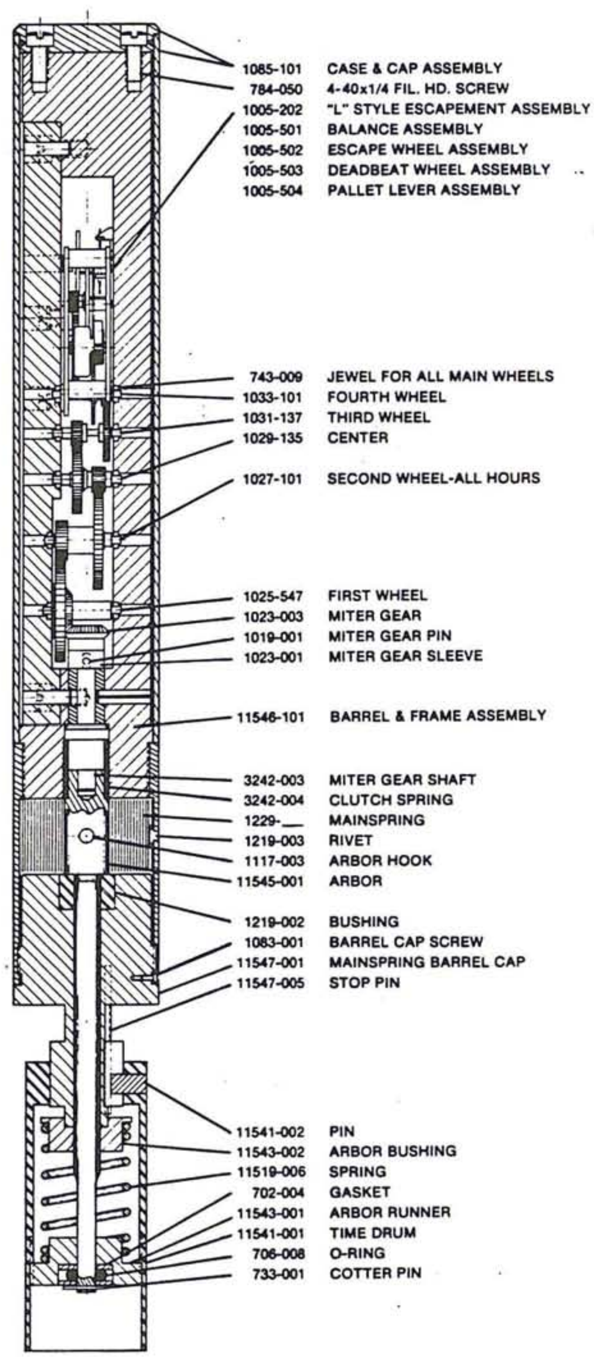
KUSTER COMPANY™
P.O. Box 90909 2900 E. 29th St.
Long Beach, California 90809-0909
(213) 595-0661 Telex: 65-6359

KUSTER COMPANY™

SAMPLER CLOCK 11540-900

IMPORTANT WHEN ORDERING PARTS-ALWAYS GIVE SERIAL NO. AND HOURLY RATE OF CLOCK

CLOCK 60 MIN	11540-101
CLOCK 150 MIN	11540-102
CLOCK 6 HOUR	11540-103



APPENDICIES

APPENDICES

A. Workshop Agenda

B. Working Groups

C. Poster Presenters

D. Reception Hosts

E. Sampling Bibliography

F Other Relevant Workshops

G. Attendees

H. Distribution

APPENDIX A

WORKSHOP AGENDA

WELLBORE SAMPLING WORKSHOP

MAY 27, 28 & 29, 1987

SPONSORS: JOINT OCEANOGRAPHIC INSTITUTIONS, INC.;
U.S. SCIENCE ADVISORY COMMITTEE
U.S. DEPARTMENT OF ENERGY;
BASIC ENERGY SCIENCES/GEOSCIENCES

AGENDA

MAY 27 -- SYMPOSIUM ON THE ISSUES

7:30 AM Registration
Continental breakfast

8:30 AM Scientific Sampling Issues
Jean Whelan, Chairperson
Woods Hole Oceanographic Institution
(617) 548-1400 X2819

Speakers

Bill Bryant - Texas A&M Univ.
Geotechnical Sampling Techniques
Rodey Batiza - Northwestern University
Sampling of Solids in Deep Sea Drill Holes
Paul Worthington, British Petroleum Co.
Sampling and Containimation Control
for Geochemical Studies
Ross Barnes - Rosario Geoscience Associates
In Situ Pore Water Sampling
Lisa Shevenell - Los Alamos National Lab
Borehole Fluid & Gas Sampling
Keith Thompson - Texas A&M University
Gas Sampling for Hydrocarbon Safety
Will Harrison, University Alaska
Sampling the Interface between bedrock
and Glaciers

LUNCH Hosted

1:00 PM <u>Technological Sampling Issues</u>

Dave Huey, Chairman
Ocean Drilling Program, Texas A&M
(409) 845-2112

Speakers

Scott Evans - Christensen Mining Products
  Mining Sampling Technology
John Castaño - Gas Research Inst. (Consultant)
  Vattelfall Deep Gas Project Sampling Program
Franklin Patton - Westbay Instruments, Ltd.
  "MP System" Fluid Samplers
Tom Torgersen - University of Connecticut
  Fluid Sampling at Cajon Pass
Bob Andrews - DOSECC
  DOSECC/DOE Scientific Drilling Update Report
Bob Blake - AMOCO Production Research Center
  AMOCO Borehole Fluid Sampler (Under Development)
Allan Sattler - Sandia National Laboratories
  Sandia Borehole Fluid Sampling Technology
Kay-Christian Emeis - Ocean Drilling Program, Texas A&M
  Scientific Requirements for Pressurized Sampling
Dave Huey - Ocean Drilling Program, Texas A&M
  Update Report on ODP Pressure Core Barrel Development

6:00 PM Industry Hosted Reception
Poster Session

MAY 28 -- CLARIFICATION OF ISSUES DEVELOPMENT OF PRIORITIES

7:30 AM Continental Breakfast
8:30 AM Identify Working Groups/Participants
9:30 AM Working Groups Meet Individually

Working Groups:

- Sampling Unconsolidated Formations
- Contamination/Decontamination of Samples
- Pressure Coring
- Core/Sample Preservation and Handling
- Organic Geochemical Sampling
- Inorganic Geochemical Sampling
- Sampling for Geotechnical Data
- Future Concepts
- Other groups as needs are identified

LUNCH Hosted

1:00 PM Working Groups Continue
3:00 PM Write Working Group Summaries

MAY 29 -- WORKING GROUP WRAP UPS

Sessions and attendees as needed

APPENDIX B

WORKING GROUPS

Working Groups

Name: Sampling Unconsolidated Formations
Chairman: Jean Kulla - Exxon Production Research
Barry Harding - ODP
Jacek Leznick - Stevens Institute of Technology
Jack Pheasant - British Geological Survey
Will Harrison - University of Alaska
Milton Craft - Core Laboratories

Name: Contamination/Decontamination of Samples
Chairman: Jean Whelan - Woods Hole
Wendy J. Harrison - Exxon Production Research
Peter Britton - The Riess Foundation
Ron Oliver - Los Alamos National Lab
Tom Garland - Battelle - Northwest
Ross Barnes - Rosario Geoscience Associates
John Castaño - Vattenfall Deep Gas Project

Name: Pressure Coring
Chairman: Dave Huey - ODP
Bill Livesay - Private Consultant
Bill Bryant - Texas A&M University
Bob Blake - AMOCO Production Research Center
Bryan Trimm - ODP

Name: Core/Sample Preservation & Handling
Chairman: Paul Worthington - British Petroleum Company
Tim Clawson - Illinois Geological Survey
Allan R. Sattler - Sandia National Labs
Louise Levien - Exxon Production Research
Dick Traeger - Sandia National Labs

Name: <u>In Situ Chemical Analysis/Fluid Sampling</u>
Chairman: Andy Campbell - M.I.T.
Bob Charles - Los Alamos National Lab
Philip Johnson - New Mexico Institute of Mining & Technology
Joe Moore - University of Utah Research Institute
Ed Wallick - Rockwell-Hanford Operations
Linda Wieczorek - Michigan Technological University
Chip Crocetti - Exxon Production Research
Lisa Shevenell - Los Alamos National Lab
Ray Solbau - Lawrence Berkeley Labs
John Jacobson - Kuster Company
Richard Wendlandt - Exxon Production Research
Tom Torgersen - University of Connecticut
Keith Thompson - Texas A&M University
Kay-Christian Emeis - ODP

APPENDIX C

POSTER PRESENTERS

WELLBORE POSTER SESSION

Bob Blake
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South Hamilton, MA 01982
617-468-2733

APPENDIX D

RECEPTION HOSTS

The following companies supported the evening reception which significantly enhanced the interactions and productivity of this workshop.

Eastman Christensen
Kuster Company
TAM International
Schlumberger

APPENDIX E

SAMPLING BIBLIOGRAPHY

The enclosed bibliography is the result of a literature search on borehole sampling technology for the approximate period of 1980-1985. Subnotes are R. K. Traeger's summary of report contents in a few of the citations. This bibliography indicates significant activity in the development of new or improved sampling hardware. The references should be of benefit in developing R&D plans and proposals.

BOREHOLE SAMPLING BIBLIOGRAPHY

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R. K. TRAEGER

SANDIA NATIONAL LABORATORIES

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APPENDIX F

OTHER RELEVANT WORKSHOPS

APPENDIX F

OTHER RELEVANT WORKSHOPS

A listing of other workshops that have relevance to sampling is attached. No attempt was made to do a literature search, so undoubtedly some will be missed. Any questions should be referred to the workshop conveners.

Development of a New Pressure Core Barrel
Convener:
Dave Huey, Ocean Drilling Program
Texas A&M University
(October 1986)

Measurements of Physical Properties and Mechanical State in the Ocean Drilling Project
Conveners:
Daniel E. Karig, Dept. of Geological Sciences, Cornell University, and
Matthew H. Salisbury, Centre for Marine Geology, Dalhousie University
(June 26-28, 1986)

Scientific Seamount Drilling
Conveners:
Rodey Batiza, Northwestern and
A. B. Watts, Lamont-Doherty
(June 4-5, 1986)

Ultra Deep Coring and Drilling
Cochairmen:
Matt Walton, Minnesota Geological Survey
Frank Schuh, ARCO and
John C. Rowley, Los Alamos National Laboratory
(April 20-25, 1986)

Borehole Measurements and Interpretation in Scientific Drilling: Identification of Problems and Proposals for Solutions

Editors:

Dana L. Cooper and Richard K. Traeger, Sandia National Laboratories

(March 1984)

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