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THE UNIVERSITY OF ALBERTA

UNDISTURBED OIL SAND SAMPLING AND SAMPLE QUALITY EVALUATION

by

JOHN GILBERT McKAY

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

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Abstract

Athabasca oil sand sample disturbance which occurs before, during and after coring, in storage, and preparation for testing is investigated. Athabasca oil sands are a four phase system of solid grains (predominantly quartz), bitumen, water and dissolved gas. After sampling, pore pressure relief allows gas evolution causing expansion of the core without imbibition. Tests on disturbed core can lead to inaccurate petrophysical and geotechnical data.

Modifications to two sizes of triple tube wireline core barrels were made in an effort to reduce sample disturbance. The modifications included reduced clearances between the core and liner, thicker liners with end restraints and a built in liner core catcher. A comparative field testing program was undertaken to evaluate whether the modifications made to the core barrels were effective.

Sample densities and extraction results allowed calculation of I_{DD}. I_{DD} is the nondimensionalized difference between the no gas sample density and the actual sample density. I_{DD} is the recommended indicator of disturbance. The low dissolved gas content in the samples taken led to overall high quality samples and prevented a conclusive evaluation on the success of the modifications.

The no gas density is calculated assuming the undissolved gas volume in a sample is zero. The no gas density provides a good estimate of the in situ density of oil sand. The core-log discrepancy is that the no gas or

maximum sample density values derived from core are lower than the geophysical density log values. Since water imbibition of oil sand cores is doubtful, it is recommended that the no gas sample density parameter be used to estimate in situ densities for evaluation of oil sand sample disturbance instead of geophysical density logs.

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Symbols and Abbreviations

AOSTRA	Alberta Oil Sands Technology and Research Authority
API	American Petroleum Institute
ARC	Alberta Research Council
B	pore pressure coefficient
bc	back calculated
CI	Chevron injector
c'	effective cohesion
HCTD	hollow cylinder triaxial test
id	inner diameter
I_D	index of disturbance based on porosity
I_{DD}	index of disturbance based on density
n_i	in situ porosity
n	porosity
n_{ng}	no gas porosity
od	outer diameter
p'	$\frac{\sigma'_1+\sigma'_3}{2}$
PDC	polycrystalline diamond compact
PL	plastic liner
PVC	polyvinyl chloride
q	$\frac{\sigma_1-\sigma_3}{2}$
rpm	revolutions per minute
S	solid content by mass

SAE	Society of Automotive Engineers
SATAC	Shaft and Tunnel Access Concept
SEM	scanning electron microscope
UTF	Underground Test Facility
V_g	volume of gas
Z	atomic number
ρ	density
ρ_e	electron density index
ρ_f	density of fluid
ρ_{ng}	no gas density
ρ_s	density of solid
ρ_{mnl}	average minimum liner density
ρ_{mxl}	average maximum liner density
σ_n	normal stress
$\sigma_1, \sigma_2, \sigma_3$	total principle stresses
$\sigma'_1, \sigma'_2, \sigma'_3$	effective principle stresses
τ_f	shear stress at failure
ϕ	diameter
ϕ'	effective friction angle
^0C	degrees Celcius
^{0}	degrees
"	inches

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1. Introduction

1.1 Statement of the Problem

Soil properties required for engineering design can be derived from estimations based on index tests, observations of field behavior, in situ tests or tests on soil samples. Estimations are based on previous experience and can be inaccurate. Simulating field behavior is expensive and the properties of oil sands can vary greatly over small distances preventing extrapolation of the observed properties. Oil sand formations, due to their high strength, present difficulties in addition to those normally associated with standard soil in situ testing. Of all four approaches, sample tests provide a direct method for determining the greatest variety of properties.

The deposit under consideration is the Athabasca oil sands of northeastern Alberta. The Athabasca oil sands are an unconsolidated, water-wet (predominantly quartz) sand, bitumen and gas system. The bitumen component is very viscous with an API gravity of 6 to 10^0 (density of 1.03 to 1.00 g/cm^3) (Dusseault and van Domselaar, 1982). The oil sands exhibit extreme lateral and vertical variability with interbedded zones, clean oil sand zones and zones of shale. The porosity is relatively high in comparison to a typical oil reservoir but conductivity is low due to the viscous bitumen phase. The oil sands are usually saturated with bitumen and water in situ and contain varying amounts of dissolved gases. The gas bubble pressure is typically equivalent to the in situ pore pressure. During coring and sampling the oil sand core experiences a decrease in effective stress and pore pressure. The drop in pore pressure causes gas evolution and expansion of the void space and is not restricted since the effective stress has been removed.

Reducing the magnitude of sample disturbance and understanding where sample disturbance occurs in the entire sampling and testing procedure is important for evaluation of core test results for petrophysical and geotechnical applications.

1.2 Objectives

The research program initially was concerned with developing a high quality oil sand sampler. The implementation of this work uncovered several more areas of focus.

With the presentation of the opportunity to take part in AOSTRA's extensive coring program at the UTF, two wireline core barrels were purchased and modifications made to improve the core barrels. After completion of the coring program, tests were performed on some of the core to provide an indication of the core quality. Throughout the whole process an attempt was made to evaluate the methods used.

The final objectives of this work are as follows:

1. Provide an effective and accurate quantitative method of

evaluating oil sand sample disturbance using volume change as the primary criteria.

2. To obtain better quality oil sand samples by developing a core barrel and sampling procedure. This included testing the prototype sampler in the field and, from core densities and extraction results, providing proof that oil sand samples of a quality heretofore not achieved under similar conditions of depth and dissolved gas volume had been taken.
3. Illustrate and discuss differences between geophysical density log values and in situ density estimates from core extraction results.
4. To evaluate Dusseault and van Domselaar's (1982) and Plewes's (1986) index of disturbance values of 10% and 14% respectively, given to define the boundary of undisturbed oil sand samples.
5. Discuss oil sand sample disturbance with reference to shearing dilation, gas evolution, sampling and sample handling techniques, core storage and test preparation.

1.3 Scope of the Thesis

The scope of the thesis involves high quality oil sand sampling and sample disturbance. This thesis also demonstrates and discusses the core-log discrepancy. A major finding of this work is a simple method to quantify oil sand core disturbance due to volume increase. This quantitative disturbance indicator uses core extraction results not geophysical density logs and is based on density not porosity. Previously, both geophysical density logs and porosity were the basis of oil sand disturbance quantification.

Detailed descriptions of soil and rock samplers, bit designs and core catcher configurations are beyond the scope of this thesis. Sample disturbance affects on specific geotechnical and petrophysical core tests are considered to be distinct from coring and sampling disturbance and hence are not included in this research.

1.3.1 Organization of the Thesis

The literature review is given in Chapter 2. Section 2.1 covers a brief history of oil sand sampling in the Athabasca deposit. This provides background for the present sampling program.

Hvorslev's 1949 work entitled "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes" is the classical work regarding sampling and sample disturbance. Section 2.2 reviews some of Hvorslev's thoughts regarding sample disturbance.

Maurice Dusseault authored and co-authored several papers dealing with oil sand sampling and sample disturbance. The relevant topics of Dusseault's work are summarized in section 2.3.

Section 2.4 details the University of Alberta's work in oil sand sampling and testing covering related works. Oil sand testing is affected by sampling and sample quality evaluation in turn requires testing.

Through the years, various sample quality classifications have been put forth. The most prevalent of these are detailed in section 2.5. Later on in section 7.1, the highest quality oil sand samples possible are graded according to the relevant quality designations.

The core-log controversy is not new. Core-log studies from some previous authors are summarized and in some cases discussed in section 2.6. Reasons for core solids content results from extraction being inaccurate are commonly given as imbibition or fluids loss. This is discounted in section 2.6.

Section 2.7 provides an introduction to the geology of the Athabasca area. Included is a brief description of the relevant litho-stratigraphic zones from the UTF coring site.

The geotechnical properties of Athabasca oil sands are summarized in section 2.8.

Chapter 3 explains the design process of the modifications to the core barrels undertaken in order to improve sample quality.

Chapter 4 reports the field work at Syncrude for a preliminary test of the modified core barrels and the later more extensive UTF coring program.

Once the core was taken, the success of the core barrels was determined by reviewing field performance and by performing core tests. Sample densities and solvent extractions were performed on some of the core. The test procedures are covered in chapter 5.

Chapter 6 discusses and draws conclusions from the test results of the samples taken from Syncrude and AOSTRA's Underground Test Facility as well as some previous data from Branco's Syncrude samples. Sample disturbance and evaluation of disturbance are key topics. The core-log discrepancy is illustrated by comparison of geophysical density logs and core derived in situ density estimations. The discrepancy is discussed and recommendations provided regarding the use of core or geophysical logs to evaluate sample disturbance.

Chapter 7 discusses in detail oil sand sample disturbance and gives some recommendations for oil sand sampling.

Dusseault and van Domselaar (1982) and Plewes (1986) chose quantitative values to classify undisturbed samples of oil sand. Their findings are discussed in chapter 8.

Finally, the main conclusions are summarized in chapter 9. Chapter 9 also includes recommendations for future research and an epilogue.

2. Literature Review

2.1 A Brief History of Oil Sand Sampling in Alberta's Athabasca Deposit

The following gives some examples of how oil sand sampling was carried out in the Athabasca deposit throughout the years. The reason for sampling was two fold:

1. To improve the understanding of the geology of the Athabasca oil sands deposit.
2. To provide samples for testing to understand the various petrophysical and geotechnical properties of Athabasca oil sand.

Sampling methods varied from outcrop investigation, shallow and deep borehole sampling to pit excavation.

From 1897 to 1925 the Geological Survey of Canada drilled 40 holes in the Athabasca area of which half penetrated oil sands strata. Bitumen contents were not measured but the thickness of the oil sand zone was noted. Before 1925 samples were hand augered to a maximum depth of 1.2 m along river outcrops.

From 1925 to 1928 eight deep holes were drilled into the McMurray Formation. The deepest hole went to 72 m and four other boreholes were deeper than 30 m. The boreholes were advanced by machine and sampling was by hand augering. Sample logs by the Canadian Department of Mines included test results of percentage moisture, bitumen content, sulphur content and sieve analyses of dry extracted sand.

Cores were taken at varying intervals, particularly when the strata changed (Ells, 1928, 1962, Galovich and Weaving, 1983).

Clark and Blair (1927) trenched outcrops of oil sands to investigate oil sands variability in the Athabasca area. The exposures of oil sands were trenched from top to bottom in unweathered strata. A channel sample was taken in each distinguishable division of the oil sands strata. Each sample weighed 23-45 kg of which 1.8 kg was sealed in a quart sample tin. The samples were sent to Edmonton for testing. Thirty-five trenches were dug in exposures and about 225 bituminous samples were sent to the laboratory.

A 13.7 m deep shaft, 1.2 m by 1.2 m was dug through overburden and oil sands in the valley of the Horse River. Clark and Blair (1927) took samples in the shaft to determine the oil, water and solids content, specific gravity of bitumen, sulphur content and grain size. Distillation tests were also done on large (greater than 50 kg) samples to determine distillation products and their properties.

From 1942-43 cable and rotary rigs were used but samples were still taken by hand augering and the entire hole length was cased.

In 1943 the Boyles Brothers Drilling Company Limited under the Mines and Geology Branch of Canada drilled over 900 m in the Steepbank area. They tried a single tube core barrel but experienced poor recovery and core flushing. The augering method of sampling was still superior and it was used until a 1.5 m swivel double-tube core barrel was tried. This barrel had a non-rotating inner tube as was used for coal drilling. Collodial mud was introduced to prevent leaching the bitumen from the core and eliminating the need for casing the holes.

The bits were face ejection NX size and small clearances caused difficulties. The bit outer diameter was increased from 75 mm to 81 mm (the core diameter was 54 mm) and water courses were cut across the face of the bit. The recovery increased to 90%. The working pressure of the pump was 3450-4150 kpa at 68 litres/minute. The mud used was very light because there was little clearance between the inner and outer tubes. They decreased the outer diameter of the inner tube from 62 mm to 59 mm and core size to 51 mm from 54 mm. This reduced pump pressures to less than 1035 kpa and increased the recovery to an average of 95% in the oil sands. This barrel was designated N.F. and was too big for the NX casing so an NM size barrel was designed giving a 47 mm diameter core and 96% recovery. The fluid volume was kept to a minimum, rpm slow, and feed fast to give good recoveries. This barrel could pass through NX casing which was put through the overburden to the oil sands. The drilling parameters that gave the best results were 80 rpm and 8-16 revolutions per cm. A 3.0 m barrel was tried but the core appeared to crush under its own weight.

A diamond bit required resetting after about 9 m of drilling. Carbide insert bits could run 18-24 m with resharpening at 12 m intervals. The drill used was a Boyles Brothers Model BBS-2 diamond drill. The pump was a Boyles Brothers Model BB5-12 M with a maximum capacity of 91 liters/minute and a maximum working pressure of 3450 kpa. Small mud pits were used and the mud was changed frequently. Mud viscosity was 40-55 seconds and the circulating volume was 68 liters per minute. The core was put in bottles when removed from the barrel (Hall, 1951).

From 1943-47, 291 holes were drilled and 16434 m cored (Ells, 1962). Using the non-rotating core barrel and drilling mud, casing was not necessary, the maximum depth was now 91 m and core recoveries were 93-98%. However the historical data determined from this sampling is inaccurate due mainly to water loss of the unfrozen core and bitumen extraction by the retort method which is not as accurate as the Dean Stark method (Galovich and Weaving, 1983).

Hume (1947) described the results of drilling 70 holes in the Mildred-Ruth Lakes area. The cores were covered with a film of drilling mud. The bitumen flowed as a liquid and was stored separately from the cores. The cores showed distinct layers of bitumen, free of sand. Hume hypothesized the presence of bitumen beds capable of supporting the overburden. This led R.C. Fitzsimmons to drill in search of a pool of liquid bitumen in the Bitumont area. Clark (1957) notes that these layers of bitumen were merely an artifact of sampling.

Scotland and Benthin (1954) describe the coring techniques used by the Calvin Consolidated Oil Sand Gas Company in the Athabasca oil sands from 1952-54. The entire McMurray Formation was cored in each hole. Core lengths were 1.52 m. The equipment and procedures used were similar to that used in 1943-47 by the Boyles Brothers. There were no core catchers used and the barrels were just packed full. The core was removed from the barrel, placed on a steel trough and washed off. The core was placed in boxes then logged, and the 1.52 m lengths quartered longitudinally and sealed in tin cans. Each can had about 1 kg of core. Percentages of bitumen, water and solids were determined by solvent extraction.

The exploratory techniques to 1960 used in the Athabasca oil sands area were given by Gallup (1960). Up to May of 1959 about 1000 holes were drilled in the area. A typical drilling outfit consisted of one drill of the Failing 1500 type, two bulldozers, a logging unit (electric and radioactive), a geologist and a survey crew. Coring was started as soon as bitumen was noticed in the drilling mud. Coring was continuous from this point to the Devonian Formation. The bituminous section was up to 53.3 m thick. The core recovery was 70-80%. Cores were cut longitudinally with a hunting knife and manually sampled in the center where the drilling mud had not invaded. The cores were described and lengths of about 1.5 m containing only one type of lithology labelled, sealed in a can, and stored in a shack. The remainder of the core was discarded. Analysis of the cores included bitumen by weight and percentage of connate water. This information was used to calibrate the logs. As an example of a fast section of coring and logging, 50 m was completed in about seven hours. All holes were geophysically logged but not necessarily cored.

Samples of oil sand core were taken with a VTM-3 and a Christensen core barrel for the Saline Creek diversion tunnel (Smith et al, 1978, Thurber Consultants, 1977). Gas concentrations were relatively low due to gradual stress release during valley formation. The seepage conditions influenced by the valley wall and adjacent creek may have provided a release for the gas in the oil sand. The densities of 20 cores usually did not change after sampling. Gas monitoring showed low concentrations of gas. Core densities were 2.04 g/cm^3 and the geophysical log densities were 2.17 g/cm^3 on average. Differences were attributed to swelling or calibration error of the geophysical densometer. Also there were greater overburden depths in test holes where the density logs were taken than where the cores were taken. The average porosity based on geophysical logs was 33%.

Recent summaries of Athabasca coring programs include Galovich and Weaving (1983). They describe a joint venture between Petro-Canada and Nova, an Alberta Corporation where 260 holes were drilled through the McMurray Formation to investigate an oil sands lease. They used a standard diamond or rotary drill with a wireline core barrel. Core size was H. or H.Q. and core lengths were 1.5 or 3.0 m. The mud was bentonitic with polymers. The overburden was cased. Coring began when oil was noticed in the drilling fluid and continued through the entire McMurray Formation and at least 3 m into the Devonian limestone. The core barrels had a PVC liner which only allows visual examination of a grab sample. The full liners were labelled and frozen to prevent core expansion and water loss. All the holes were geophysically logged. The frozen core was shipped to the lab where it was slabbed in half for geologic logging and core analysis. To account for the nonhomogeneous core, the central rectangular sections, about 3/4 m long, were homogenized before Dean Stark procedures were followed to determine percentages of bitumen, water and solids. Centrifuging was used to separate bitumen-solvent and nonfiltered solids in a complete mass balance analysis. Grain size, x-ray diffraction, SEM to determine clay mineralogy, and palynological and micro-palynological studies were done.

2.2 Hvorslev's Views on Sample Disturbance

The following is a brief summary of the main points on sampling and undisturbed sampling requirements which Hvorslev (1949) stressed.

The basic types of soil sample disturbance are:

"A. Change in stress conditions.

B. Change in water content or void ratio.

C. Disturbance of soil structure.

D. Chemical changes.

E. Mixing and segregation of soil constituents."

Gaseous soils experience an increase in void ratio without an increase in water content on stress relief. Gaseous soil will decrease in density without imbibing fluid. Gaseous soil will expand not swell. Swelling is a term associated with an increase in water content, while expand implies no change in water content.

Chemical changes during storage of quartz grained samples may include bond formation. Base or cation exchange may occur in clays.

Hvorslev's basic requirements for undisturbed samples are:

"1. No disturbance of the soil structure

2. No change in water content or void ratio

3. No change in constituents or chemical composition"

Hvorslev recommended for the design of a core barrel that the core diameter be 100 to 150 mm. Considerations involved in chosing core diameter include resistance to torsion induced by the bit cutting the core.

2.3 Dusseault's Investigations into Oil Sand Sampling and Disturbance

In 1977 Dusseault finished his Ph.D. thesis on the geotechnical characteristics of oil sands (Dusseault, 1977). Dusseault has authored and co-authored many papers since then regarding oil sand sampling and sample disturbance. Areas of Dusseault's work pertaining to this thesis include:

1. Reasons for obtaining high quality oil sand samples.
2. The nature of oil sand sample disturbance.
3. Quantitative evaluation of oil sand sample expansion.
4. Oil sand sampling and sample handling field work.
5. Recommendations for oil sand sampling and sample handling.

2.3.1 Reasons for Obtaining High Quality Oil Sand Samples

Oil sand samples are taken for geological, petrophysical and geotechnical purposes. Laboratory test results from each of these disciplines are influenced by sample disturbance. Reduction of sample disturbance increases the accuracy and improves the interpretation of test results.

Most early investigators did not have an appreciation for oil sand sample disturbance and its effect on laboratory results. Dusseault (1977) concluded that all published data from laboratory tests on oil sand samples to that date were unreliable.

Sample disturbance affects oil sand properties to varying degrees as follows:
nonsensitive- oil content,
sensitive- porosity, saturation,
more sensitive- shear strength,
and very sensitive- elastic modulus, compressibility and permeability (Dusseault, 1980).

High quality oil sand samples further the design and development of:
-enhanced oil recovery techniques
-numerical simulation
-hydraulic fracturing design
-settlement analysis
-tunnels, shafts
-determination of temperature and pressure affects on in situ oil sand
-and oil reserves estimates.

2.3.2 The Nature of Oil Sand Sample Disturbance

Under natural conditions oil sand formations are, as a rule, saturated with bitumen and water. Gas is dissolved in the bitumen and water phase. On sampling the gas evolves overpressurizing the fluid phase in relation to the total stress relief. Oil sands are unconsolidated and this effective stress reduction causes volume change. Dusseault and Scott (1984) provide the mathematical theory of expansion potential due to stress release for oil sand cores. Recovery ratios of greater than 100% can occur due to expansion even with core loss. Axial extrusion of up to 400 mm over a 9.15 m unchilled core length has been observed (Dusseault, 1980).

Qualitatively, core damage falls under two categories; gross and expansion damage. Gross damage to cores includes missing intervals, total remolding, torsion features, and cone-in-cone or cross-cone faulting. Damage due to expansion is evidenced by fracture features, radial expansion in the liner, axial extrusion, and bedding plane separation (Dusseault and van Domselaar, 1982).

2.3.3 Quantitative Evaluation of Oil Sand Sample Expansion

Dusseault uses the index of disturbance to quantify oil sand sample expansion (Dusseault and van Domselaar, 1982). The index of disturbance is the percentage difference between the sample porosity and the estimated in situ porosity. Dusseault recommended that the in situ porosity be obtained from geophysical density logs. The equation for the index of disturbance is as follows:

$$I_D = 100\ (n - n_i)/n_i\ (\%) \qquad (2.1)$$

where n = laboratory porosity from samples

n_i = estimated in situ porosity from gamma-ray density logs

The use of cores or logs for sample disturbance evaluation is discussed in section 6.6.3.

2.3.4 Oil Sand Sampling and Sample Handling Field Work

In an attempt to reduce oil sand sample disturbance, borehole freezing and diamond coring was used by Dusseault (1977). A rotary rig with a depth capacity of 750 m was used. The drilling fluid was a bentonite-water slurry. The refrigerant was diesel fuel cooled in an open pit with ambient temperatures ranging from -14 to -22°C. The sampler was a Christensen diamond triple-tube core barrel with core catcher. The core length was 6.1 m, the PVC liner had a 95 mm inner diameter and 107 mm outer diameter. The inner diameter of the bit was 88.9 mm, the outer diameter of bit was 158.7 mm. Continuous coring was used from depths of 30 to 70 m.

Typically a full barrel was cored, brought to the 35 m level and gently rotated and spudded (vertically agitated up and down) while the drilling fluid was replaced with the refrigerant. Circulation of the refrigerant continued for up to 3 hours until the difference in temperature between effluent and influent diesel fuel was 4°C. The oil sand core was thus cooled from a formation temperature of 5 to -15°C.

The sample was brought to the surface and removed from the core barrel. The core and liner were cut into four 1.5 m long sections, rubber end caps were stapled on and then the sample was placed in 152 mm outer diameter, 1.52 m long pressure vessels. These 'bombs' were pressurized with nitogen gas to the approximate in situ hydrostatic pressure. Many of the vessels experienced pressure loss due to poor gaskets. The bombs and dry ice were stored in containers and transported to Edmonton for testing.

Sample handling disturbance involved core extrusion, radial expansion and liner flexure. Extrusion of oil sand core from the sectioned liners of up to 10 mm occurred in -15^{0}C core and for unchilled cores extrusion of up to 80 mm occurred. The inside clearance of 6.1 mm allowed radial expansion of the oil sand core, however this clearance was necessary to prevent jamming in the 6.1 m long sample tube. Flexure of the plastic liner was also a source of disturbance. Results from core tests and visual examination indicated the down hole cooling technique of sampling oil sands had some success.

Hand cut specimens from oil free outcrops were used to estimate saturated bulk densities. The saturated bulk densities of the hand cut specimens were less than those indicated by geophysical logs but higher than those determined from oil rich samples. Coarse grained rich oil sand cores expanded more than medium or fine grained rich oil sand cores. The difference between the estimated saturated bulk density of the hand cut specimens and the geophysical density logs is an example of the core log discrepancy and is discussed later in this thesis.

A triple-tube core barrel was used at a depth of 425 m in the Clearwater Formation at Cold Lake, Alberta (Dusseault and Scott, 1984). Surface freezing and cold room storage and test preparation techniques were used. Geophysical logs showed porosities of 28-31%, sample porosities were 35-42%. Back calculated no gas in situ sample porosities gave I_D values of 20-40%.

Dusseault and Scott (1984) also used a triple-tube core barrel with gas release holes provided in the liner in the Athabasca deposit at depths of 125-160 m. The inner diameter of the diamond drill bit was 69 mm, the inner diameter of the plastic liner was 71 mm. The bit appeared to overcut the core by 1-1.5 mm resulting in initial core diameters of about 67.5-68 mm. On the surface samples were stored in -25^0C, 1.5 Mpa vessels. Slow depressurization at -18^0C was employed. I_D values ranged from about 10-30%. There were no noticeable benefits from repressurizing and providing gas release holes in the liner.

The Pitcher barrel sampler was used in less than 20 m of overburden (Dusseault and Scott, 1984). The inner barrel was a Shelby tube. Some tubes were repressurized and some of the tubes were supplied with gas release holes. All cores were frozen on the surface. I_D values ranged from 1-5%. Repressurization and gas holes showed no beneficial effects.

2.3.5 Recommendations for Oil Sand Sampling and Sample Handling

Dusseault (1977) had the following suggestions for improved oil sand sampling techniques. When using borehole freezing to obtain undisturbed oil sand samples, the core barrel should be continuously slowly rotated and gently spudded during the refrigerant circulation with the sample remaining at the bottom of the borehole. He also suggested the use of heavier refrigerant, rapid coring of 1-2 m long sections, and the use of rigid PVC liner with only 1-2 mm clearance. Core drilling should only be done in the winter and the refrigerant should be mechanically cooled. Dry ice packed vessels with internal pressures equal to the hydrostatic pressure at sample depth, should contain the core immediately following sampling. The pressure should be slowly released over a one month period. Specimen preparation should take place at temperatures of -25 to -30^0C.

An expensive, exotic and untried method of undisturbed oil sand sampling would be to freeze a column of oil sand by circulating refrigerant in a borehole for several weeks then coring a hole located about 1 m away in the frozen layer of sand with cooled compressed air as the drilling fluid.

Sampling oil sand zones free of dissolved gas such as outcrops and tunnels will reduce or eliminate core expansion due to gas evolution. For depths less than 100 m the Pitcher barrel and Denison samplers may be adequate, especially if a good core catcher can be designed. For deep coring triple-tube core barrels are recommended (Dusseault and Scott, 1984). The pressure core barrel remains a costly and, as yet, relatively unsuccessful tool for oil sand sampling.

2.4 University of Alberta Athabasca Oil Sand Sampling and Sample Disturbance

This section contains information related to oil sand sampling and sample disturbance from papers, and theses written over the years at the University of Alberta Civil Engineering Department. (Dusseault's work is covered in the previous section.) One of the first investigations into the geotechnical properties of oil sands was undertaken by Tustin in 1949.

Tustin (1949) took block and Shelby tube samples of rich oil sand from previously stripped areas in the Bitumont plant area. Consolidation tests and consolidated undrained triaxial tests were performed. The orientation of the bedding planes was varied, the oil sand was remolded for some tests and test temperatures were either 23 or -10^{0}C. Although not appreciated at the time, the strengths were low due to disturbance.

Hardy and Hemstock (1963) carried out a sampling program near the Mildred Lake area to determine the shearing strength of Athabasca oil sands. Conventional sampling and testing procedures caused gross disturbance of oil sand cores. Using freezing techniques it was determined that the oil sand behaved similarly to a dense sandstone. Cores were tested in undrained triaxial tests with different temperatures and confining pressures. Unconfined compression tests were taken in the field with specimens from 51 mm and 152 mm cores. Two hundred and twenty cores were taken altogether at 4-71 m depths. The drill rig was a truck mounted Failing 1500 rotary rig. A fish tail bit and double-tube swivel type core barrel were used. The drilling fluid was bentonitic. Results from the unconfined compression tests included strength, strain at failure and core temperature. Unit weights, solids, oil and water contents, and grain size sieve analysis were also done. It was noted that an ambient temperature of -29^0C was necessary to keep the drilling mud chilled and the core temperature low to prevent further disturbance. The tests indicated strength loss and increased strain at failure with increasing depth. Strength loss also was evident with increased storage time, increased temperature of the core during testing and increased oil content. Evidence of gas evolution was given by bubbling, core shape alterations and in some cases longitudinal splitting of 1.8-2.4 m cores.

Sampling of the oil sands was continued with a pressure core barrel in hopes of controlling pore pressures. A conventional bit was used. The cores were 60 mm in diameter and up to 1.8 m long. Core depths were from 8 to 46 m. Altogether, sixteen cores were taken. Four of the cores were frozen in dry ice in the core barrel until testing in the laboratory. During sampling, handling and testing there were problems in maintaining pressure on the samples. The in situ stress magnitudes and pore pressures could not be estimated. Unconfined compression test results showed decreasing strengths with depth, again evidencing unsuccessful sampling due to disturbance and associated strength loss. The depth correlates with increasing pore pressure and dissolved gas content.

Stern (1981) performed drained hollow cylinder triaxial tests to simulate stress paths experienced by oil sands in response to shafts and tunnelling. Stern states sample preparation techniques are responsible for the majority of sample disturbance. The HCTD (hollow cylinder triaxial device) allows control of all 3 principle stresses.

Sterne tried to reduce sampling disturbance by taking block samples of oil sand that had slabbed off the face of an open pit mine wall. The block samples were placed on a mattress and transported by vehicle to the laboratory. Then the block samples were wrapped in cheese cloth, coated in wax and stored in a moist room until testing.

Some samples were prepared for oedometer and triaxial tests. These samples were frozen and lathed to the required dimensions. The hollow cylinder sample preparations were complicated requiring freezing in dry ice, diamond coring with nitrogen to remove the centre hole of oil sand, and lathing and trimming with carbon tungsten bits.

Index properties determined were grain size (before and after tests), density, porosity, and, bitumen and water content. The samples were oil rich and had cross bedding. Samples were prepared perpendicular to the cross bedding. Due to the increase in fines after testing it was apparent that grain crushing occurred. Densities and porosities of samples before and after sample preparation showed sample disturbance. Sample preparation disturbance is attributed to heat build up during trimming which is exaggerated in smaller samples. Higher strains to failure correlate with higher porosity and lower strength. Arching occurred in a hollow cylinder triaxial oil sand sample at post collapse. This arching did not occur in Ottawa sands under similar conditions.

Kosar (1983) coupled heat and fluid flow in a finite element analysis to investigate the problem of a heated foundation on a stratum of oil sand. To study oil sand properties for his analysis Kosar used 94.5 mm samples from a Saline Creek outcrop as described by Agar (1984). Plastic sealing and cold (-20 to -25^{0}C) temperatures were used to store the core. Specimens were prepared by lathing frozen samples to the proper dimensions.

Data on four samples is given illustrating two types of samples. One type has greater bulk density, dry density, water and sand (solid) contents, but lower bitumen contents and void ratios than the other sample type. Thus the density differences appear not to be due to sampling but are representative of the in situ oil sand. Although Kozar says (p 95) the density difference and test response were due to the degree of sample disturbance.

Kosar performed heated drained triaxial tests. Cumulative volume changes of the soil structure (not the grains) versus temperature under drained conditions verifies that contraction correlates with density on temperature increase. Also affected by disturbance is the temperature dependent incremental coefficient of thermal expansion. This is shown by tests on dry sands where looser sands contract on temperature increase more than the dense sands. On temperature increase, interparticulate forces decrease and, to accommodate the same effective stress, the packing becomes denser. This reorientation occurred at temperatures up to 50°C. All indicators of sample disturbance here seem to imply that denser means less disturbed but not mentioned is that density differences occur in situ.

Scott and Kosar (1984) sampled from a frozen (winter) outcrop at Saline Creek and from a 160 m deep borehole. The samples were high grade oil sand. The borehole samples were obtained with a triple-tube barrel, with a perforated PVC liner, 3.3 m in length. Cores were chilled to -25°C and pressurized to 1700 kpa using nitrogen. The in situ porosity was calculated from extraction results on the core. The volume of gas in the samples was set to zero and the in situ porosity calculated as the volume of fluids divided by the volume of fluid and solid. This assumes that the core was saturated in situ and gas evolved on sampling causing expansion of the core with no change in fluid content. The Saline Creek samples had I_D's less than 8%, the borehole samples about 14% with a reduction to 10% expected following reconsolidation.

Scott and Kosar (1984) recommend the use of the pore pressure coefficient B as an indicator of sample disturbance. The pore pressure coefficient is the ratio of pore pressure change to isotropic total stress increment in a soil. The low compressiblity of the soil skeleton relative to the water and bitumen phases led to low B values. Thus lower B values tend to indicate stiffer soil structure and less disturbance in a saturated soil. Bulk density as a disturbance indicator is affected by the variable fines content. In several test results (modulus, Possion's ratio and P'-Q diagrams), the densities greater than 2 g/cm^3 and less than 2 g/cm^3 are used to evaluate sample disturbance affects.

Agar (1984) performed numerous tests including triaxial tests under differing stress paths. Core expansion leads to gas in voids which during testing is driven into solution with the addition of water and pressure causing a difference in fluid phase composition from in situ conditions. Agar took samples from a frozen outcrop of Saline Creek with a diamond coring system. The sample diameter was 100 mm and core barrel length 470 mm. The depth of the samples was from 0.3 to 1.0 m. Coring took place in the winter and the shallow oil sand samples were frozen in situ. A single tube core barrel cored out the holes. Then the barrel was removed. The core was sheared off with a wedge and lifted out of the ground with hooks. The samples were sealed in paraffin wax and plastic wrap then stored in insulated plywood boxes with dry ice. On site and laboratory bulk density measurements were the same. It seemed that carbon dioxide diffusion occurred through the plastic wrap. This was stopped by placing the samples in sealed paint cans. The carbon dioxide apparently caused expansion when the sample was warmed from -80 to -20°C for storage and subsequent trimming. Agar may have witnessed sample gas evolution and expansion due to methane gas even at -20°C (Tan, 1988). This low temperature expansion was also noticed by this author and Peacock (1988).

Freezing of oil sand samples reduces disturbance by providing tensile resistance due to pore water freezing, increased bitumen viscosity, increased solubility of gases in the liquid phases and causing shrinkage which reduces pore pressures. An in situ porosity of 33% was assumed in calculating I_D values for the Saline Creek oil sand. (See Chapter 9, Reevaluation of High Quality Samples, as Plewes (1986) used the same assumption and samples from Saline Creek as Agar.) Carbide bits were inadequate for sample trimming and diamond tipped bits proved successful. Grain size curves, SEM photographs and mineralogical determination by X-ray diffraction were done.

Sample disturbance may occur during sampling, handling and storage, trimming and test preparation, and testing. By comparing values of core sample porosity (ϕ=100 mm) with test sample (ϕ=76 mm) porosity, it was apparent that porosity expansion up to 15% can occur during sample preparation for testing. It is noted that changes in porosity due to test preparation were reduced, as experience was gained, to less than 1%.

Sample disturbance reduces the magnitude of drained thermal expansion of oil sand particularly for I_D values greater than 15%. Reasons for disturbance affects are frictional loss between grains and larger pore space to accommodate grain size increases on heating. Undrained thermal expansion of oil sand is significantly affected by I_D's greater than 8%. Since samples are back saturated, disturbance causes an increase in pore space and water content. Thus the additional water and it's thermal expansion characteristics result in higher volumetric expansion on heating for the whole sample.

Compressibiltiy tests showed that first cycle compressibility may be greatly affected by disturbance and cyclic compressibility is not affected by I_D's less than 10%. Sample disturbance increases the undrained compressibiltiy of oil sands, since, as for thermal expansion, the increased pore space is occupied by water. The water is more compressible than the oil sand grains.

Two samples of about 1% porosity difference experienced similar stress-strain and volumetric change behaviour but one had appreciably higher strength. Agar attributes this to localized microfabric disturbance evidenced by the porosity difference. Another two samples of about 2% porosity difference showed typical stress-strain, shear strength and volumetric strain response with porosity difference. Test induced disturbance is shown due to the presence of a lateral strain gauge clamp in the triaxial test. Agar believed that clays are removed during the soxhlet extraction process leading to unrepresentative grain size curves and bitumen contents. However extractions run on clay blanks by this author showed that neglible fines are removed in a Dean-Stark extraction. The results of the Dean-Stark extraction on the clay samples were compared with standard water content values from oven drying.

Agar states that permeability is affected by sample disturbance and in situ porosities can not be duplicated. Agar concludes that difference in multiphase fluid flow modelling due to using remoulded samples or packed sand cores instead of undisturbed cores is not significant. Not addressed in Agar's thesis is the anisotropy of properties.

Plewes (1986) shows low strains to failure (1-2%) correlating with high bulk densities (2-2.2 g/cm^3) for drained triaxial compression tests. Plewes performed undrained triaxial tests on Saline Creek oil sand. He used the same samples as Agar (1984) and the sampling procedures are described previously. The samples were cored in the winter and were thus frozen in situ. The samples remained frozen until testing while under a 500 kpa confining stress during the sample temperature increase. I_D's were calculated for the Saline Creek samples by assuming an in situ porosity of 33%. The lowest I_D was 2.7%. The highest I_D was 26.1%.

The choice of an average in situ porosity of 33% was based on the results of Smith et al (1978). The core showed bedding with occasional thin partings of silt and rich oil sand seams. Grain size distribution curves were very close for the samples. Samples were cycled isotropically in an attempt to recompact them to in situ void ratios. Changes in compressibility were small after the first loading cycle. The compressibility of the samples was related to effective confining pressure. Grain crushing was evaluated by determining grain sizes before and after testing. Plewes concludes that isotropic stress does not cause significant grain crushing.

Shallow, bitumen poor oil sands from the Syncrude lease were subjected to triaxial tests. The samples were taken with a Pitcher barrel sampler from depths of 11 to 14 m and repressurized in nitrogen and frozen. Index of disturbances were less than 10% and bitumen contents were less than 5.3%. Plewes notes that the use of compressibility to evaluate sample quality can be misleading if inclusions of argillaceous material exist. Plewes states that I_D's up to 14% indicate samples of high enough quality for geomechanical testing. Plewes' I_D values are affected by the assumption of a constant in situ porosity of 33%. Since this is dubious due to the inhomogeneous nature of oil sands, it would be both more accurate and correct to relate his disturbance discussions to porosities or densities. I_D as a concept was to account for the variability of the deposit and provide a measure of porosity changes due to disturbance not natural variations. This is discussed further in the section on reevaluation of high quality samples.

Rich oil sand samples were taken by Peacock (1988) from the overburden stripped highwall of Syncrude's open pit mine in the Athabasca oil sands deposit. He used a Pitcher core barrel with Shelby tubes. Sampling took place in the winter with an average ambient temperature of -20^{0}C. Rich oil sand was sampled as deep as 39 m below the surface. There were problems with the Shelby tube bottom edge bending due to hard strata which was intentionally avoided, if possible. The Shelby tubes were cut to the length of the recovered core and ends sealed with metal plates. The core and tubes were placed on dry ice and transported to Edmonton for cold room storage at -25^{0}C. Extrusion was noticed during the sampling and for one sample during uncapping in the cold room. Peacock concluded that initial gas lost on sampling was negligble. The bubble point pressures in the samples corresponded with the premining bench elevation. This implies free gas in situ. Free gas in situ could cause more sampling disturbance despite immediate core placement in dry ice. If free gas did not exist in situ then the time required to develop gas bubbles before freezing would allow better samples to be taken. Freezing increases bitumen viscosity, limits bubble formation and lowers the diffusion rate of gases in solution. Samples not frozen quickly enough will expand in response to gas evolution until the bubbles and core fractures allow drainage of the excess pressure.

2.5 Sample Quality Classifications

Hvorslev (1949) listed three catagories of samples, non-representative, representative and undisturbed. Non-representative samples are removed from the borehole drilling fluid by sedimentation and are a mixture of soil from different strata. Representative samples are from the same strata but the soil structure is disturbed. Undisturbed samples may be used for laboratory determination of strength, consolidation, permeability and other physical parameters.

Idel, Muhs and von Soos (1970) suggested five quality classes for soil samples. The placement of a sample in a catagory depends upon the changes in the grain size distribution (and/or Atterberg limits), moisture content, dry density, shear strength and the compression index of a sample. They also recommend a sample size of at least 75 mm.

Kallstenius (1971) proposed a combination of quality groups and classes for use in evaluating soil sample quality. The groups are:

A- environmental qualities (in situ conditions)

B- mechanical and rheological properties

C- composition

D- stratification

The classes indicate the degree of exactness that can be achieved and are as follows:

I- direct measurability
II- requiring calibration
III- requiring estimation

As an example, undisturbed samples may be classified as B II.

Saiki (1971) studied the quality of silts and clays. He suggested a quality classification consisting of A to E classes depending on values of the undrained modulus, undrained strength and strain at failure.

Rowe (1972) revises the table of quality classes from Idel, Muhs and von Soos (1970). Rowe includes fabric, permeability and coefficient of consolidation. He also gives a table for clays which recommends specimen size based on clay type, macro fabric and permeability for a given parameter determination.

Hvorslev's quality classes are the most widely used. However when more detail is desired the classification put forth by Idel, Muhs and von Soos is then chosen.

2.6 Core-Log Studies

Brooker (1975) concluded sample disturbance was occurring in oil sand cores based on differences in core densities and geophysical log densities. Density measurements on samples were from 1.9 to 2.05 g/cm^3 and from geophysical logs 2.1 to 2.3 g/cm^3. Brooker points out that oil sand coring is necessary for lithologic determination and strength evaluation.

Log-core correlations in the Athabasca oil sands were provided by Collins (1976). Cores were obtained in plastic liners and frozen. The cores were slabbed before testing. Porosities from geophysical logs were from 23.5 to 33% and sample porosities were from 32.0 to 35.8%. Recommendations given include using both core and log results to determine fluid saturations and porosities, and a core length of about 1/2 m should be homogenized when determining bitumen saturations to allow comparisons with logs. This is because the logs do not reflect the heterogeneous nature of the reservoir.

Zwicky and Eade (1977) discuss the effects of using core, and cores and logs together in tar sand formation analysis. They note that water contents determined on cores are dubious due to evaporation or imbibition and laboratory methods. They recommend calculating water contents by using density log data and core data. They assume the log density correct, the volume of in situ gas to be zero, and extraction water contents incorrect. They adjust bitumen, solid, and water contents, and porosities accordingly. For an average tar sands deposit, tar-in-place calculations based on core or density logs and cores will not be critical in deciding whether to develop the resource. Porosity, fluid saturations, and permeability are the important parameters in resource evaluation. Permeability is most critical for in situ recovery schemes. Therefore the method of calculating porosity, core or log, is very important and should be held in consideration. The authors state that the log porosities are more accurate than back calculated in situ porosities from cores. Thus they are saying that water imbibition occurs in cores. A proper balance of cores and logs is the best solution and is dependent on the stage of the project; reconnaissance, reserve evaluation, or development, and financial considerations.

Vogel and Amirijafari (1982) used chemical analyses on oil sands cores and correlated the results to geophysical logs successfully. The oil saturations were similar for the toulene extraction on samples and Archie's equations which were applied to the suite of geophysical logs. The success of the correlation means that expensive coring in the future could be reduced and more reliance can be placed on the geophysical logs to evaluate the reservoir.

Conventional cores, wireline logs and borehole gravity surveys were used to obtain porosities in the South Belridge and West Cat Canyon oil fields of California, as described by Beyer (1984). Porosity measurements on unconsolidated cores are questionable even when they are subjected to in situ pressures. Cores also do not provide porosities associated with fractures due to their small size. Core porosities are greater than log porosities. Wireline log derived porosities result from equations based on rock models, are subjected to borehole effects and inadequate volume of formation. Porosities were calculated from borehole gravity surveys by using grain densities and assuming a pore-fluid density of 1.00 g/cm^3. The gamma-gamma log overestimated densities due to drilling mud with barite fluid invasion above 503 m depth at South Belridge. In the South Belridge and West Cat Canyon oil fields it was recommended to use together; cores, gamma-gamma log and borehole gravity survey data to calculate porosities.

Britton (1984) showed the problems involved in evaluating a heavy oil resource with particular reference to the San Miguel tar sand deposit. Direct porosities from cores are too large due to core expansions. Logs require known physical properties of the matrix and pore fluid. Of several logs tried the compensated formation density (FDC) log was deemed the best for porosity determinations. Saturations, based on logs, were inaccurate. Water loss in cores leads to incorrect Dean Stark extraction results and therefore porosities that are unrepresentatively low. Drilling fluid invasion was not significant for the San Miguel tar sands. Bitumen loss in cores is not a problem due to its high viscosity. Tar saturations were corrected based on the ratio of core to FDC log porosities. This is equivalent to what Zwicky and Eade (1977) did. Since geophysical logs test intervals were of the order of 1/2 m, they do not provide a true indicator of the heterogeniety of a reservoir but cores do.

Dusseault and Scott (1984) derived in situ oil sand porosities from sample porosities back calculated assuming that any gas in the samples did not exist in situ. It is stated that water imbibition in the samples could cause the calculated in situ porosities to be high. This was based on comparable geophysical log derived porosities. Evidently the authors at this time had more confidence in the geophysical density log than in situ density quantification obtained from extraction results. Since there is a verifiable difference between the density log values and density estimations from cores, the implication is that the logs are correct and the core extraction results are not.

Geophysical density logging and core derived no gas densities (figure 6.1) were in agreement for tailings sand at the Suncor oil sands mine in northeastern Alberta (Plewes, McRoberts and Chan, 1988). The tailings sand was derived from oil sand following bitumen removal. The logging was performed by Century Geophysical Corp. and the logs were $\frac{\Sigma Z\text{'s}}{\text{molecular weight}}$ corrected. Some form of $\frac{\Sigma Z\text{'s}}{\text{molecular weight}}$ correction is usually applied to geophysical density logs (see section 6.6.4). However this investigation does not explain the core-log discrepancy for oil sand which exists even when the $\frac{\Sigma Z\text{'s}}{\text{molecular weight}}$ correction is made.

2.6.1 A Note on Water Imbibition in Oil Sand Core

Woodhouse (1976) provides detailed comparisons of core derived minimum porosities and log derived values for Athabasca oil sand. The core porosity values are higher than the log porosities in shaley and clean oil sand. In shaley zones the distinction of adsorbed and free water is held accountable for the core-log porosity differences as extractions on cores do not distinguish between the two forms of water. In clean sands water imbibition is blamed.

Zwicky and Eade (1977) state that water loss or imbibition can occur in oil sand cores. The water loss mechanism is explained in Eade (1975) and is due to unfrozen core being exposed over a period of time before extraction procedures take place. The imbibition mechanism is explained by Woodhouse (1976) as a pore volume increase which allows water imbibition. Causes of the pore volume increase are given but gas evolution is not explicitly stated. What Woodhouse misses are three points that must occur simultaneously for water imbibition to occur:

1. A source of water is necessary.
2. A gradient for water flow must exist.
3. Sufficient permeability is required to allow water flow to occur within a restricted time period.

These conditions are not met during coring of oil sands and thus the source of higher sample minimum porosities than density log converted porosities is still open to question.

2.7 Geology of the Athabasca Oil Sand Deposit

The Athabasca oil sand deposit is the largest of five heavy oil reservoirs found in Alberta, Canada. The Athabasca deposit is located about 400 km, 15^0 grid azimuth, from the city of Edmonton. The Athabasca oil sand deposit contains 138×10^9 m^3 of initial bitumen in place (Outrim and Evans, 1978). The majority of Athabasca's bitumen reserves are found in the McMurray Formation with a small portion also found in the Wabiskaw Member of the Clearwater Formation.

The McMurray Formation was deposited on a north-northwest trending trough of Devonian limestone in what is now northeastern Alberta. The trough was bounded on the east by the Devonian Methly Formation and the Precambrian Shield, and on the west by the Devonian Woodbend Ridge carbonates. The trough likely resulted due to salt removal from the Devonian limestone which was aerially exposed with a well developed drainage system.

The McMurray sands are dominantly quartz and were sourced from the Proterozoic Athabasca sandstones on the Precambrian Shield to the east and to a lesser extent the Jurassic sands to the south (Stewart and MacCallum, 1978).

Outcrop exposures of the McMurray Formation delineate 3 zones (figure 2.1). A lower zone of thick-bedded sand with trough cross stratification (Middle McMurray), overlain by high angle beds of sand (still Middle McMurray) and capped by argillaceous sand in the Upper McMurray zone. However, borehole investigation has shown a general increase in shale content over outcrop exposures and subsurface strata tend to lack the sloping beds of the Middle McMurray (Mossop, 1980).

The Lower McMurray is found in paleo-topographical lows in the limestone, and is comprised primarily of conglomeratic fluvial water sand.

The Middle McMurray is the main pay zone and its origin is subject to debate. The Clearwater Sea transgressed and regressed the basin several times. Carrigy (1971) writes that the Middle McMurray was deposited over many small deltas in fresh and brackish shallow-water environments. Mossop (1980) sees the deposition of the Middle McMurray as fluvial with slight marine influence. The most widely accepted theory is that the Middle McMurray was deposited under estuarine conditions (Stewart and MacCallum, 1978).

Carrigy (1971) interprets the inclined oil sand beds (shown in figure 2.1) to be foreset beds of a Gilbert-type delta and the underlying thick-bedded oil sand to be alluvial point bar and channel sands.

Mossop (1980) envisions the Middle McMurray Formation to be synchronously deposited in 20 to 30 m deep sinuous channels with a high suspended solids load. The meandering channels cut through a pre-existing sediment to leave trough cross-stratified channel bottom sands and epsilon cross strata (Allen, 1963) on the more gently sloping side of the channel in point bar deposits.

The two main oil sand mining companies in the Athabasca area, Syncrude and Suncor, conform closely to the Stewart and MacCallum (1978) interpretation of the Middle McMurray facies (Cuddy and Muwais, 1987, Beardow and Horne, 1987). These Middle McMurray facies include tidal channel sands, tidal flat deposits, and tidal channel breccias. Reworking of tidal channel sands and tidal flat deposits by tidal channel systems in response to the interplay of the northerly sea has resulted in a complex mixture of the estuarine facies. Widespread bioturbation adds to the complexity.

The Upper McMurray is a zone of horizontally bedded argillaceous sands and mudstones. The Upper McMurray is heavily bioturbated and clay ironstone beds are commonly found. The Upper McMurray Formation was deposited in a marine environment.

The McMurray Formation consists of unconsolidated water wet oil sand, comprised of about 95% quartz grains, 2-3% mica flakes and clay minerals, and small traces of other minerals. The clay component is kaolinite and illite with minor amounts of montmorillonite. The sand is poorly graded, uniform or well sorted, all three descriptions being synonymous. There is extreme lateral and vertical variability with difficult-to-predict volumes of shale interbedded with oil sand.

The clay shale's are usually low plastic, or inorganic and heavily overconsolidated. The oil sands are considered locked (extremely dense) with high friction angles (up to 60^0). The oil sands contain varying quantities of dissolved gas and are highly dilative on shearing.

Other lithologies are associated with the Athabasca oil sands and they can be very important factors in resource recovery. At the top of the Devonian limestone a thin zone of limy Devonian paleosol may exist. Basal clays and basal aquifers may be present at the Devonian unconformity. Throughout the McMurray Formation thin zones of oil-barren water sand may exist and often reduce core recovery. Indurated siltstone and sandstone stringers can be found and add to the severe conditions mining equipment experiences. These indurated sediments may or may not be saturated with bitumen.

Above the McMurray Formation, marine conditions continued with the Wabiskaw sands of the Clearwater Formation which can contain glauconite. As the Clearwater Sea transgressed and the energy of the depositional environment decreased, the Clearwater Formation shales were deposited. The Grand Rapids Formation with oil barren sand and shale zones overlies the Clearwater shales. Pleistocene and Recent deposits of gravel, sand, silt, clay and till overlie the Clearwater shales. Muskeg lies on the surface and is thinly covered by low-grade spruce and tamarack.

These sediments deposited in the McMurray trough are Lower Cretaceous in age, lying unconformably on the Devonian limestone. Glacial erosion permited Pleistocene and Recent deposits to lie unconformably on the Cretaceous sediments. The depth of burial of the McMurray Formation increases away from the Athabasca River valley to the west. Open pit mining is economically restricted to overburden thickness of less than 50 m.

The Middle McMurray depositional environment may be open to question but an attractive reservoir contains clean sand deposited in a high energy environment. Facies mapping may provide local indications of where these high quality reservoirs are but these zones should be confirmed by coring and geophysical well logging.

2.7.1 Geology of the AOSTRA Underground Test Facility Phase A Site

The AOSTRA Underground Test Facility (UTF) is located about 70 km northwest of Fort McMurray in Alberta, Canada (see figure 4.1). At the UTF the McMurray Formation is overlain by over 100 m of overburden. Rottenfusser, Palfreyman and Alwast (1988) divide the McMurray Formation and Wabiskaw Member here into 8 informal units. These units are alphabetical from A to H in order of increasing depth. Of these units, unit E is the best reservoir and contains cross bedded sands deposited in a high energy environment. The western half of the phase A site is the most attractive as the E zone is well developed there (see figure 4.2).

Unit D over lying unit E is considered to be of reservoir quality but contains more shale interbedding. The critical zone is unit F. Unit F appears to be a continuous shale zone and is present in 9 out of 11 wells on the southeast side of the phase A site (see figure 4.2). Unit F may provide a barrier to bitumen and steam flow between the horizontal injectors and producers.

2.8 Geotechnical Properties of Athabasca Oil Sands

Athabasca oil sands are a four phase system of bitumen, water, unconsolidated solid grains and dissolved gas (and under special circumstances free gas). The predominantly quartz grains are water wet. Athabasca oil sands are extremely dense and are classified as locked sands (Dusseault and Morgenstern, 1979). The high density of the Athabasca oil sands is a result of diagenetic quartz dissolution and recrystallization to form a highly interpenetrative structure. This fabric is not reconstitutable in the laboratory and gives oil sands its characteristically high strengths.

The behaviour of oil sands on shearing depends on the dissolved gas content and confining stress. At high confining stresses the grains are sheared and dilation is suppressed. At moderate and lower confining stresses oil sand is highly dilative. A nongaseous soil will experience a pore pressure drop on dilation. For oil sand however, dissolved gas comes out of solution when the bubble pressure is reached. This will offset the pore pressure drop to a degree dependent on the dissolved gas concentration.

Oil sands do not have tensile strength. Dusseault (1977) gives a power law to provide an upper bound failure envelope from triaxial data as follows:

$$\tau_f = 5.83\ \sigma_n^{0.84} \qquad (2.2)$$

where τ_f = shear stress at failure (kpa)

and σ_n = normal stress at failure (kpa)

A power law relationship accounts for the curvilinear strength envelope which arises due to the varying failure modes at different confining stresses.

Based on an upper bound, linear relationship from consolidated drained or consolidated undrained triaxial tests, Athabasca oil sands has a ϕ' of 60^0 ($c'=0$) (Scott and Kosar, 1984). The residual effective friction angle is about 35^0. Dusseault (1977) obtained permeabilities of 5×10^{-6} to 7×10^{-8} cm/sec. Scott and Kosar (1984) give a cyclic coefficient of volume compressibility of 10^{-6} kpa^{-1}. The B value is the ratio of pore pressure change to isotropic stress increment. Due to a stiff soil skeleton, Athabasca oil sand B values can be as low as 0.6. Poisson's ratio, while slightly higher at low confining stress is a fairly constant 0.25. Axial strains to peak stress in triaxial tests are small and in the order of 1 to 2%.

Dusseault (1977) gives density values of 2.11 (+ or - 0.06) g/cm^3 for clean medium to coarse grained (Lower to Middle) McMurray oil sands and 2.21 (+ or - 0.06) g/cm^3 for fine grained Middle McMurray oil sands. Dusseault also notes that shear strength parallel to oil sand bedding planes should be the lowest.

Throughout the papers on the geotechnical strength of Athabasca oil sands there is a noticeable scatter of data. This scatter is commonly blamed on sample disturbance as reflected in the varying density of the test specimens. However, other reasons for the variance are natural differences in density and fabric, anisotropies, and test inherent.

Intimately associated with oil sand formations are the less stiff intraformational and basal clays. These clays can have peak friction angles of up to 29^0 and residual angles of as low as 7^0 (Au, 1984). This explains why oil sand behavior can be controlled by the weaker interbedded or basal clay layers.

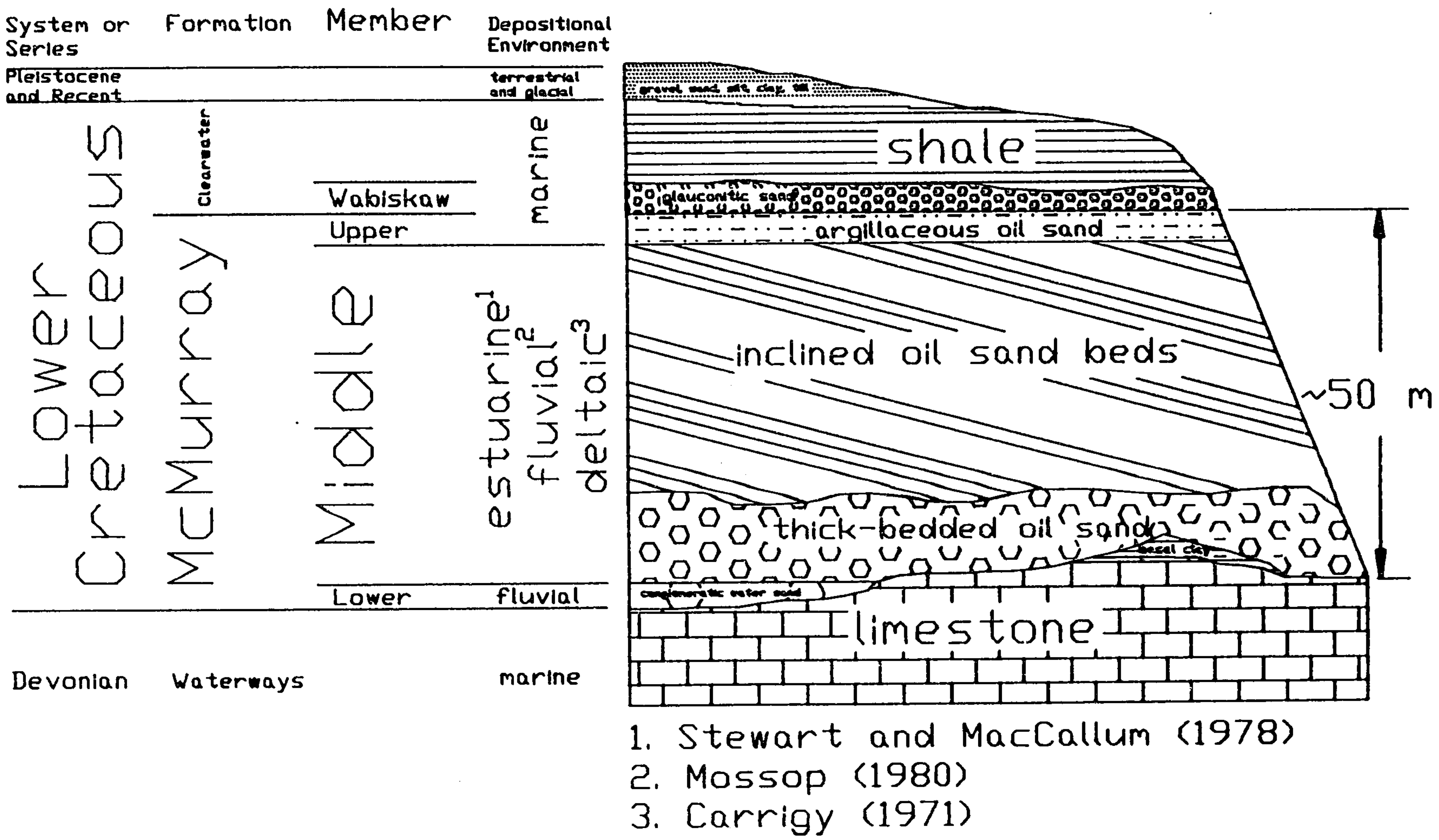


Figure 2.1 Simplified cross-section of Athabasca river outcrop near surface mineable Athabasca oil sand area (drawing modified after Mossop, 1980)

3. Oil Sand Core Barrel Design Procedures

3.1 Introduction

3.1.1 Objectives

The most suitable sampling tool was to be chosen and modified as necessary in order to reduce volumetric expansion disturbance of oil sand samples.

3.1.2 Scope

The design of the modified samplers is outlined in this chapter. Reasons are given for the sampling bit type and materials chosen. Thought processes followed in designing the modifications to reduce radial and longitudinal expansion are detailed. Model tests were performed as a check on the suitability of these modifications and anticipated failure modes for the samplers are included.

A review and discussion of soil and rock samplers in general, bits and core catcher types is beyond the scope of this thesis.

3.2 Core Barrel Basics

A core barrel is a tube-bit assembly which connects to the bottom of drill rods. A core barrel advances the borehole and retains a core sample. Core barrel lengths can vary from 1.5 to 18 m.

There are three basic types of core barrels; single-tube, rigid double-tube and swivel double-tube. In a single-tube core barrel the drilling fluid is pumped through the inside of the barrel, through the annular area between the incoming core and the outer tube, around the crown of the core bit and up the annular area between the borehole wall and the outer tube. A rigid double-tube core barrel has a middle tube added. This middle tube rotates with the outer barrel and bit but protects the core from drilling fluid erosion as the drilling fluid flows down between the inner and outer tubes. Since the middle tube rotates relative to the core this causes sample disturbance. To avoid this a swivel double-tube core barrel has bearings which allow the outer tube and bit to rotate but not the middle tube. The addition of a liner to the swivel double-tube core barrel aids in core handling. The liner and swivel double-tube assembly is sometimes called a triple-tube core barrel. A core catcher can be placed at the bottom of the middle tube to allow the core to enter but not leave the core barrel.

Conventionally once the core barrel is full of core the drill rods are removed and the core is recovered. A wire-line core barrel has the middle tube (on swivel bearings) and core pulled through the drill rods on a wire. The empty middle tube assembly is dropped through the drill rods in a free fall to latch with the outer tube of the core barrel.

3.3 Choice of Sampler

Ells and the Boyles Brothers in 1943 (Ells, 1962) successfully used a non-rotating double-tube core barrel to core oil sands and displaced the auger as the oil sand sampler of choice. Since that time only varieties of the basic non-rotating core barrel have been used successfully to obtain quality oil sand samples.

The University of Alberta has had some success with the Pitcher core barrel in obtaining high quality oil sand samples at shallow depths (Dusseault and Scott, 1984). The Pitcher core barrel is a double-tube core barrel, its distinction being a variably protruding middle tube. In soft strata the spring loaded middle tube preceeds the coring bit and the outer tube. In hard strata the bit preceeds the middle tube. The type of middle tube used by the University of Alberta was a Shelby tube with a sharpened bottom end. The annular area around the core is removed by cutting with the Shelby tube, washing by the drilling fluid and cutting by the coring bit. The problem with the Pitcher core barrel is that the bottom edge of the Shelby tube is easily bent by those frequent layers of fine hard strata in an oil sands deposit. At the Syncrude open pit mine the strata is well defined by extensive geophysical logging. Thus Peacock (1988) used the Pitcher core barrel and purposely drilled through 11.4 m with a tricone drill bit in the middle of his sampling interval in order to avoid an interbedded zone. This can not be done in most areas.

In an effort to improve our knowledge of unpublished and current coring techniques, drilling and coring companies and suppliers were canvased. Their experience in sampling oil sands was discussed and their equipment viewed. The companies included; Tonto, Westcoast Drilling Supplies, Canadian Longyear, JKS Boyles, SDS Drilling, Elgin Exploration, Hirate and Garrity Baker. Finally after much consideration a basic double-tube core barrel with liner was chosen. The liner is necessary to preserve and reduce sample disturbance. A wireline system was chosen due to the reduced jarring upon retrieval over conventional tripping out of the hole and the faster retrieval time which would allow the core to be placed in dry ice quickly. Dry ice lowers the core temperature to reduce gas evolution and impart tensile strength to the core.

The University of Alberta oil sand testing apparatus are designed for 54 mm samples. A slightly larger core must be taken to allow for trimming on a lathe to accurate dimensions. A much larger core would allow the effects of radial expansion to fill the liner to lessen for the same clearance between the bit inner diameter and the liner inner diameter. (This is illustrated in table 3.2 and elaborated on later.) Once the core is frozen the liner can be removed. Even though our test apparatus could not handle a large diameter sample it was decided to order a Craelius SK6L wireline core barrel which gives a 102.1 mm core. In the future new test apparatus could be built to handle larger samples and at present large diameter core could be lathed down. The Craelius SK6L requires drill rod of PW size to allow the middle tube to pass through. PW size drill rod in Canada is rare and expensive. The 4 5/8 Christensen wireline core barrel gives a 69 mm core with a liner and is more of a standard oil sand sampler. Drill rod for the 4 5/8 Christensen is more available. So as a precaution a 1.5 m 4 5/8 Christensen core barrel was also ordered. Usually the 4 5/8 Christensen is a 3 m core barrel and used two at a time to reduce turn around time on the surface. The barrel has a split middle tube and can be used with or without a liner. The split tube facilitates removal of the sample when a liner is not used.

3.4 Coring Bit

The Stratapax bit or polycrystalline diamond compact (PDC) is a common type of coring bit for Athabasca oil sands. Plate 3.1 shows the 4 5/8's Christensen Stratapax core bit. It consists of drill blanks offset to cut an annular surface around the core. Each drill blank is made of a layer of polycrystalline diamond and cemented tungsten carbide. The blanks are brazed onto carbide studs. Each blank removes the rock by shear and low bit weights are used (Adams and Charrier, 1985). The Stratapax bit cuts a smooth core with minimal disturbance and was our choice based on recommendations by the supplier (Westcoast Drilling Supplies). The Stratapax bits used were not face ejection bits since they do not provide sufficient cuttings removal capacity.

After determining the core size required, 3 Stratapax coring bits were ordered. This would allow standard and modified usage (see next section) of the 4 5/8 Christensen core barrel. Standard Stratapax core bits for the 4 5/8 Christensen core barrel would be rented later when coring at AOSTRA's Underground Test Facility Phase A site. Bit dimensions are shown in table 3.1.

3.5 Sampler Modifications

3.5.1 Radial Clearance

The next concern was to reduce radial and longitudinal expansion of the core. To reduce radial expansion the difference between the inside diameter of the liner and the core diameter would be reduced. This would require modifying the core barrels. Thus the barrels are called modified to distinguish from their standard forms. Since gas evolution does not occur until pore pressures decrease, excessive radial clearance in the liner is not necessary to prevent jamming due to core expansion. Clay swelling occurs too slowly to be a factor in radial jamming. To reduce the likelihood of core jamming a 1.5 m sample length was chosen over more typically longer lengths. The wireline system would reduce the time to retrieve a core and resume coring, decreasing the extra cost of taking a short sample by conventionally being forced to pull the drill string and replace the drill string with every core taken.

Table 3.2 is a summary of the effect of the reduction in the difference between the inner diameter of the plastic liner and the diameter of the core. Table 3.2 is based on the initial and final dimensions of the plastic liner inner diameter and the core diameter. A 1.27 mm (5/100") clearance between the bit and plastic liner inner diameter was chosen. Assuming a rich oil sand of 2.15 g/cm^3 in situ bulk density and 100% fluid saturation, radial expansion of the core to fill the liner will cause a density decrease to 2.12 for the Craelius SK6L modified and 2.08 g/cm^3 for the Craelius SK6L standard core barrel. For the 4 5/8 Christensen core barrel the core density taken with a modified sampler would be reduced to only 2.11 while in its standard form to 2.01 g/cm^3.

3.5.2 Longitudinal Core Expansion

The problem of longitudinal expansion was more difficult. While the core is still in the core barrel it is restrained at both ends by the steel core catcher at the bottom and by the lower end of the middle tube latching assembly at the top. However when the liner and core are removed from the middle tube there is no axial restraint at either end of the liner to prevent gas induced extrusion. Initially it was thought that placing the disconnected middle tube with its lower shoe and core catcher intact into dry ice would be adequate. A top retainer would be used to prevent extrusion through the top of the liner. This would necessitate either waiting about 1 hour for the core temperature to be reduced before the middle tube could be used again and/or using several middle tubes, liners, core catchers and core lifter cases at once. The two samplers were ordered and upon delivery when the core barrels could be examined it was realized that freezing the entire middle tube with core would not be the best way of eliminating axial extrusion of the core, particularly since we only had 1 barrel each.

Oil sands are known as locked sands, that is diagenesis has produced a puzzle-like assortment of grains, interlocking and of low porosity. Locked sands are distinct from loose and dense sands having the lowest porosity of all. Oil sands, due to their dense nature have a greater capacity to arch. This was illustrated in the field where samples taken with a Pitcher barrel sampler did not extrude when the Shelby tube of the sampler had a slight dent or two in its lower end (Dusseault and Scott, 1984). Thus it was reasoned that a plastic ridge or lip in the bottom of the liner may also prevent axial extrusion. A modification on this idea was a fish scale type approach with imbricate lips. Each lip would be bent to facilitate core movement into but not out of the liner. Finally continuing along this train of thought one step further it was reasoned that a split ring core catcher built right into the liner would be the best solution. This could be done a number of ways. A plastic shoe could be added to the bottom of the liner containing the split ring core catcher and the core lifter case. A split ring core catcher operates in a tapered core lifter case. Stock liners are far too thin to allow a taper to be cut into the bottom. However gluing in a thicker piece of plastic to the bottom of the liner would necessitate modifications to the steel parts of the middle tube to accommodate the thicker and hence wider part of the bottom of the liner. The design progressed to check on its feasibility and it was found that the components of the core barrel would not accommodate the increased middle tube thickness across a small length. Thus the only other alternative was to use made to order extruded liners thick enough to allow a taper to be cut for the split ring. The plastic core catcher placed in the liner would operate in conjunction with the steel core catcher at the bottom of the middle tube. The thicker liners would require a smaller core to be cut and the steel shoes and split rings would have to be changed to accommodate the smaller core.

3.6 Core Catcher Design

To ease manufacture and simplify design, dimensions were chosen for the inside taper of the split ring which were different than the existing dimensions of the steel components of the core catchers and core lifter cases from the bought barrels. Dimensions were standardized for both the SK6L Craelius and 4 5/8 Christensen plastic and steel split ring core catchers and core lifter cases. From figure 3.1, the variables of core catcher and core lifter case can be seen. The core lifter case has a diametrical taper over a length. The core catcher which is a split ring can have internal and external tapers, a length or height, and a gap width. A split ring core catcher allows the core to enter the core barrel. The split ring must be forced open as the core passes to allow it to grab the core when it is time for the split ring to catch. If the split ring was not forced open by the core then in many instances it would not be forced closed as a large enough normal force would not be exerted between the inside surface of the split ring and core to develop the required friction force, in any case large core movements would at least occur. When the barrel is full the core is broken off and the core barrel is lifted out of the hole to recover the core. The core must be restrained from falling out of the inner barrel. As the core moves downward firstly while it is being broken off and then possibly under the force of gravity, the split ring which fits snugly around the core drops in the core lifter case. The taper in the core lifter case causes the split ring to close tighter and the core is jammed in the case. It is critical that a high frictional force be built up between the core and the inside diameter of the split ring. This can be accomplished by cutting a buttress thread. A sharp thread is cut in one direction. This grabs the core. The thread is smooth in the other direction to aid passage of the core through the split ring as the core enters the core barrel. Slots as shown in the top view of figure 3.4 were made in the steel split rings to improve flexibity. Slots were not used in the plastic spit rings because the added flexibility was not necessary for the plastic. Although the inside diameter of the steel split rings from Craelius and Christensen were tapered slightly it was easier for manufacturing purposes and essentially functionally just as adequate to keep this inside diameter constant. The angle of taper in the core lifter case or liner taper was chosen to be 4^0. Angles for the core lifter case and split ring taper are specified instead of top and bottom dimensions because the machinist sets up his lathe by these angles. In unconsolidated material such as oil sand the bottom lip of the split ring should be flush against the core lifter case inside. This reduces debris clogging between the bottom of the split ring and the core lifter case. This means that the angle from the vertical of the outside surface of the split ring (X) should be less than the angle of the taper in the core lifter case (Z) (figure 3.1). The angle of taper in the core lifter case chosen was 4^0, and thus the angle of the outside surface of the split ring was chosen to be 3^0.

The middle tube inner diameter was fixed by the purchased barrel dimensions. The liner thickness required to provide rigidity over a 1.5 m length and cut a taper into the bottom was 0.25" (6.35 mm). Chosing a small clearance between the middle tube inner diameter and the liner outer diameter fixed liner dimensions, that is outer and inner diameters. Next allowing for 0.05" (1.27 mm) between the core as cut and the inside diameter of the liner fixed the core diameter. The length of the tapers in all cases was set at 2.0" (50.8 mm). The height of all split rings was set at 1.5" (38.1 mm). The gap width of the split rings in a relaxed state was 0.2" (5.08 mm) and 0.3" (7.62 mm) for the 4-5/8 Christensen and the SK6L Craelius respectively. A 0.10" (2.54 mm) spread in the split ring gap was chosen. That is, the core would increase the gap in the split ring by 0.10" (2.54 mm). This would maintain contact between the core and split ring at all times. The constant inner diameter of the split ring was therefore fixed. This left one dimension to chose, the top outside diameter of the split ring, G (figure 3.1).

So far we have fixed the way in which the split ring catches the core. The core is caught evenly along the entire length of the split ring since it is of constant inside diameter. A variable inside split ring diameter is found in the 4 5/8 Christensen standard core barrel, this introduces a bit of distortion in the shape of the split ring. This distortion is small and essentially the gap width can be assumed constant. Therefore the mechanism of the 4 5/8 Christensen standard core barrel is that the top of the split ring catches the core and the bottom of the split ring is forced shut by the inside tapered edge of the core lifter case. These various mechanisms affect the calculations used to determine the drop in a core for different dimensions of core catching assemblies. Thus a computer program was written. Changes could be made in any of the core catcher assembly dimensions and its affect on the performance could be evaluated quickly. The program is listed in Appendix A and contains documentation.

3.6.1 Core Catcher Assembly Model Tests

Table 3.3 gives split ring dimensions for various drops. Models were made of the 4-5/8 Christensen and SK6L Craelius size plastic core catcher assemblies for drops of -0.10, -0.05, 0.0, and 0.05 inches. Plate 3.2 shows 2 models next to the actual Christensen and Craelius core lifter case and core catcher assemblies. At first wooden dowels were used to simulate cores but they proved to be too smooth and only cores that fit tight in the lifter case would catch. Then the dowels had sand paper glued along their outside edge to provide a better simulation of an oil sand core. The outside diameter of the sand paper on the wooden dowel matched the core sizes. These new 'cores' showed improved performance (plate 3.3). Also the machinist improved his buttress threads to provide more bite. It was noted that the machining capability was only accurate to about 0.10" (2.54 mm) for the plastic parts. Accounting for this, anticipating jamming problems and realizing the oil sand core would bite into the split ring better than a wooden dowel, a drop of

0.10" (2.54 mm) was chosen to fix the value of G. Thus all dimensions of the core catchers and core lifter cases were fixed, awaiting manufacture and finally field trials. During the taper cutting of the plastic tubes a wooden dowel of the same core size was used to check the ability of the split ring in the taper to catch the core. This accounted for any inaccuracy in machining and reduced the likelyhood of core jamming.

3.6.2 Arching Tests

In order to check on the ability of oil sand to arch in the plastic core lifter case at the bottom of a liner a simple test was performed. The PVC models were packed alternately with dry and wet sand and the reconstituted core pushed out the core lifter case. The dry sand poured out (plate 3.4) but the wet sand had sufficient capillary pressure to develop some arching and retain itself as the PVC split ring closed around its outer surface (plate 3.5).

3.7 Liner Top End Restraint

The tops of the liners must also prevent axial extrusion. This was done by gluing in an annular doughnut of rigid PVC in the top of the liners for the 4-5/8 barrel. The hole allowed fluid passage through the centrally located ball valve just above the liner. The SK6L had 2 ball valves closer to the outside edge of the cirular area directly above the liner. Thus, in order not to obstruct fluid flow and still provide a large enough cap to prevent axial extrusion a 2 tiered cap system was chosen. This is just a doughnut of variable hole size. The small diameter hole faces the core in the liner while the larger diameter hole of the cap fits next to the ball valve holes.

3.8 Final Design Drawings

Final drawings are shown in figures 3.2 to 3.11. Shown are the 4 5/8 lower steel shoe (figure 3.2), the 4 5/8 Christensen upper steel shoe (figure 3.3), the 4 5/8 Christensen steel core catcher (figure 3.4), the 4 5/8 Christensen core lifter case cut into each 0.25" (6.35 mm) thick plastic liner (figure 3.5), the top retainer to be glued into the top of each 0.25"(6.35 mm) thick plastic liner (figure 3.6), the SK6L Craelius steel core lifter case (figure 3.7), the SK6L Craelius steel split ring core catcher (figure 3.8), the SK6L Craelius core lifter case cut into each 0.25" (6.35 mm) thick plastic liner (figure 3.9), the two tiered upper PVC plug for the SK6L Craelius modified liner top ends (figure 3.10), and the PVC split ring core catchers for both the SK6L Craelius and 4 5/8 Christensen plastic liners (figure 3.11). The PVC split ring core catchers are the same as their steel counterparts except that there are no slots cut in the PVC split rings.

The lower end of the middle tube assembly is shown in plate 3.6. The steel and PVC split ring core catchers are visible. The PVC core catcher was put in a taper cut in the bottom of the modified liners.

The lower part (not shown is the hanger bearings and latching mechanism) of the complete modified oil sand core barrel is shown in cross section in figure 3.12. The outer tube and bit, non-rotating middle tube and the modified plastic liner are included in the drawing. The oil sand core enters the core barrel as the bit cuts into the formation. Drilling fluid in the liner is displaced by the core through the end retainer and by the ball valve of the middle tube assembly. When the core barrel is full the middle tube is retrieved by running a wire line down to the middle tube and reeling up the assembly. The steel core catcher prevents the core from falling out of the middle tube due to gravity and during core breakage. Once on the surface, the middle tube steel shoes are removed and the liner taken out. The end retainer and plastic split ring provide longitudinal restraint to reduce volumetric expansion of the oil sand core. Radial core expansion to fill the liner is reduced by the minimal clearance between the bit inner diameter and the plastic liner inner diameter.

3.9 Materials

The steel parts were made of SAE 4340 steel. This is a hard, high quality steel and desireable to resist the possible high stresses core barrel components may face in usage from coring to disassembly for sample removal. Based on reasonable cost, manufacturing characteristics, extrudability, strength, and resistance to ultraviolet radiation, chemicals and oxidation, rigid PVC was chosen for the liners and the split rings that are made for the core liners. The extruded PVC for the plastic liners is a BF Goodrich product known as Geon. Elgin Exploration supplied the material, built the dies, and extruded the 2 sets of liners. The material chosen for the plastic split rings was UPVC-Type 1 supplied by Johnston Industrial Plastics in a solid circular bar form for machining in the University of Alberta Machine Shops.

3.10 Failure Modes

The failure modes that might occur in the plastic liner are as follows:

1. Circumferential cracking due to longitudinal core expansion at the thinest part of the liner, the top of the taper.
2. Bond failure between the top retainer and the plastic liner caused by core extrusion after the liner has been removed from the middle tube.

The possible plastic and steel core catcher failure modes are:

1. Failure of the split ring initiated at its bottom and caused by the core catching on the split ring lip and pushing the split ring up against the top of the taper in the liner.
2. Thread abrasion as the core passes by causing increased

inside diameter of split ring and affecting the ability to catch the core.

3. Debris clogging between split ring bottom and tapered edge of core lifter case preventing the core from entering the split ring.

Other problems could be core jamming due to the restricted clearances between the core and liner.

Table 3.1 Stratapax coring bit dimensions

Core Barrel	Bit Outer Diameter		Bit Inner Diameter	
	Inches	mm	Inches	mm
4 5/8 Christensen modified	5.5	139.7	2.485	63.12
standard	5.5	139.7	2.700	68.58
SK6L Craelius modified	6.125	155.58	3.770	95.76
standard	6.125	155.58	4.016	102.01

Table 3.2 Radial coring disturbance for standard and modified Craelius and Christensen core barrels

	SK6LM	SK6L	4 5/8 M	4 5/8
PL ID (mm)	97.03	105.60	64.39	73.53
Core ID (mm)	95.76	102.11	63.12	68.58
Density (g/cc)	2.12	2.08	2.11	2.01
Insitu Density (g/cc)	2.15	2.15	2.15	2.15
IDD(%)	1	3	2	7
Assumptions: Gaseous Rich Oil Sand				
insitu density 2.15 g/cc				
fluid density 1.01 g/cc				
solid density 2.66 g/cc				
100% fluid saturated insitu				
only radial expansion to fill liner				

Table 3.3 Split ring core catcher dimensions and drop

Craelius SK6L				
T(drop) (inches)	G (inches)	H (inches)	I (inches)	J (inches)
-0.10	4.029	3.738	3.738	3.872
-0.05	4.022	3.738	3.738	3.865
0.00	4.015	3.738	3.738	3.858
0.05	4.008	3.738	3.738	3.851
0.10	**4.001**	**3.738**	**3.738**	**3.844**
0.15	3.994	3.738	3.738	3.837
0.20	3.987	3.738	3.738	3.830
0.25	3.980	3.738	3.738	3.823
4 5/8 Christensen				
-0.10	2.744	2.453	2.453	2.587
-0.05	2.737	2.453	2.453	2.580
0.00	2.730	2.453	2.453	2.573
0.05	2.723	2.453	2.453	2.566
0.10	**2.716**	**2.453**	**2.453**	**2.559**
0.15	2.709	2.453	2.453	2.552
0.20	2.702	2.453	2.453	2.545
0.25	2.695	2.453	2.453	2.538

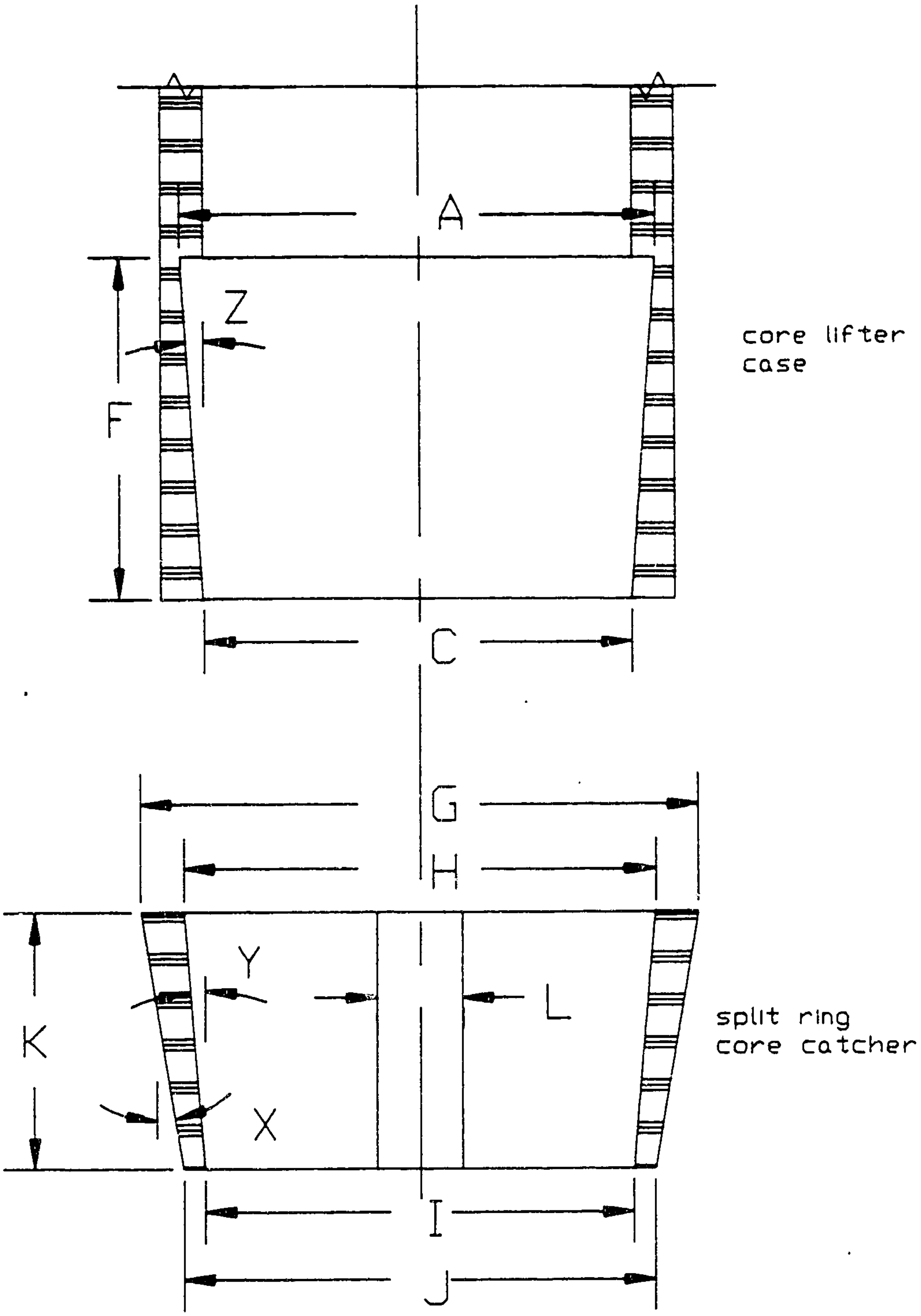


Figure 3.1 Core lifter case and core catcher design variables

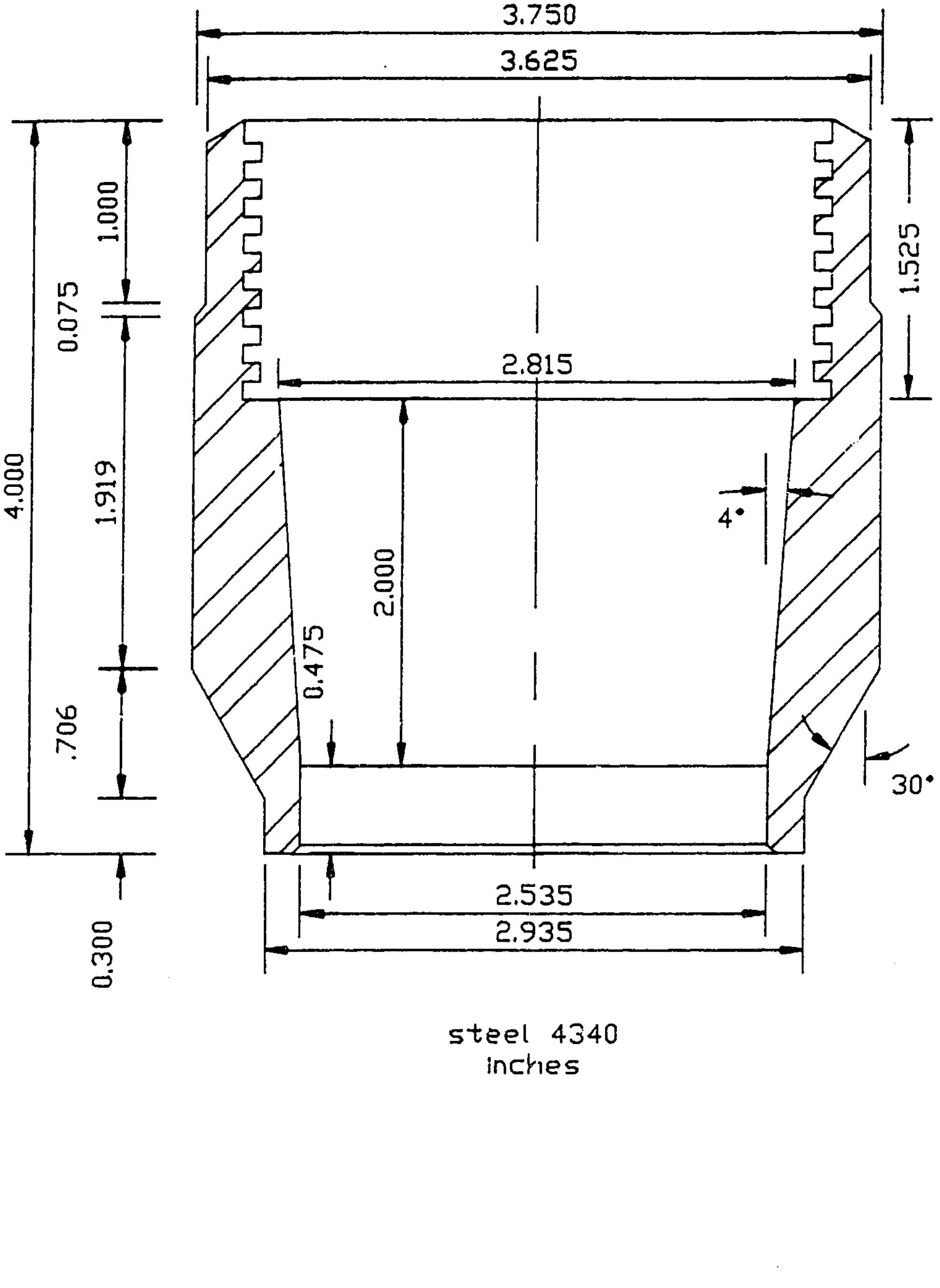


Figure 3.2 4 5/8 Christensen modified lower steel shoe cross-section

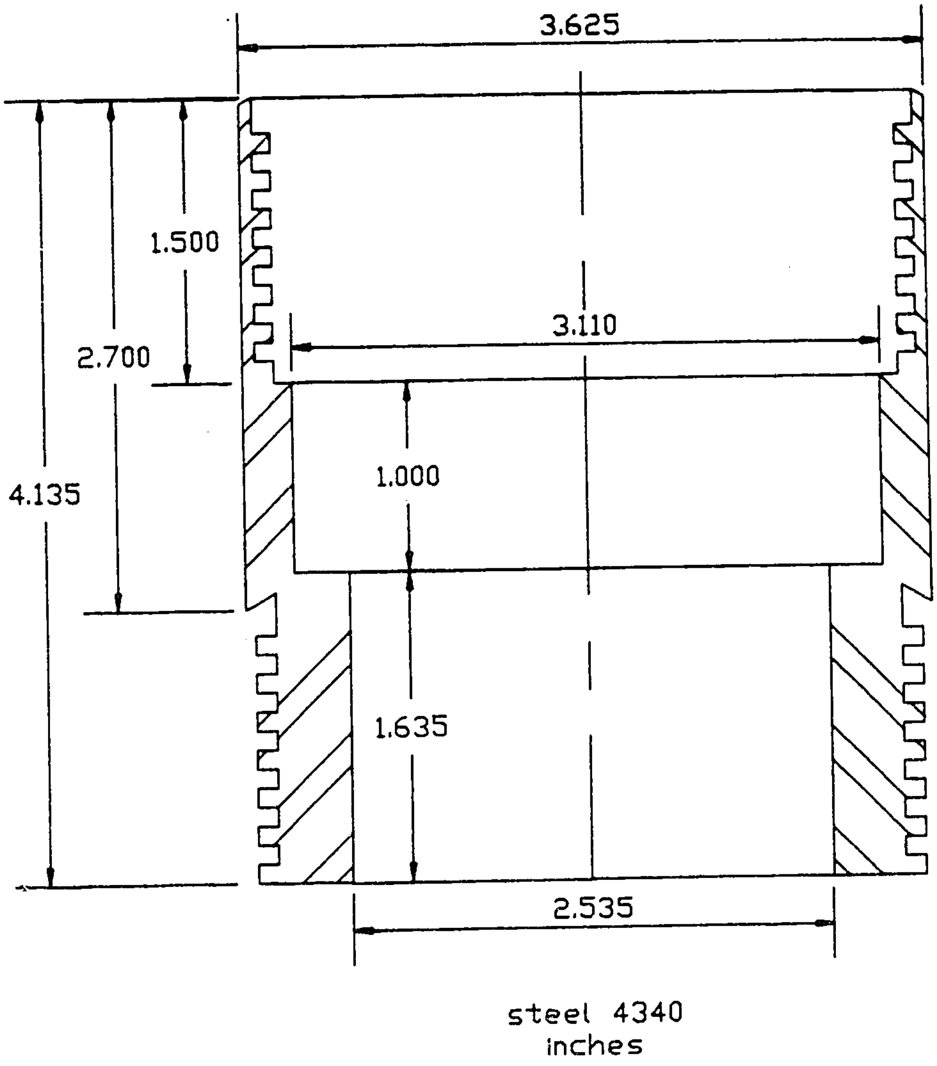


Figure 3.3 4 5/8 Christensen modified upper steel shoe cross-section

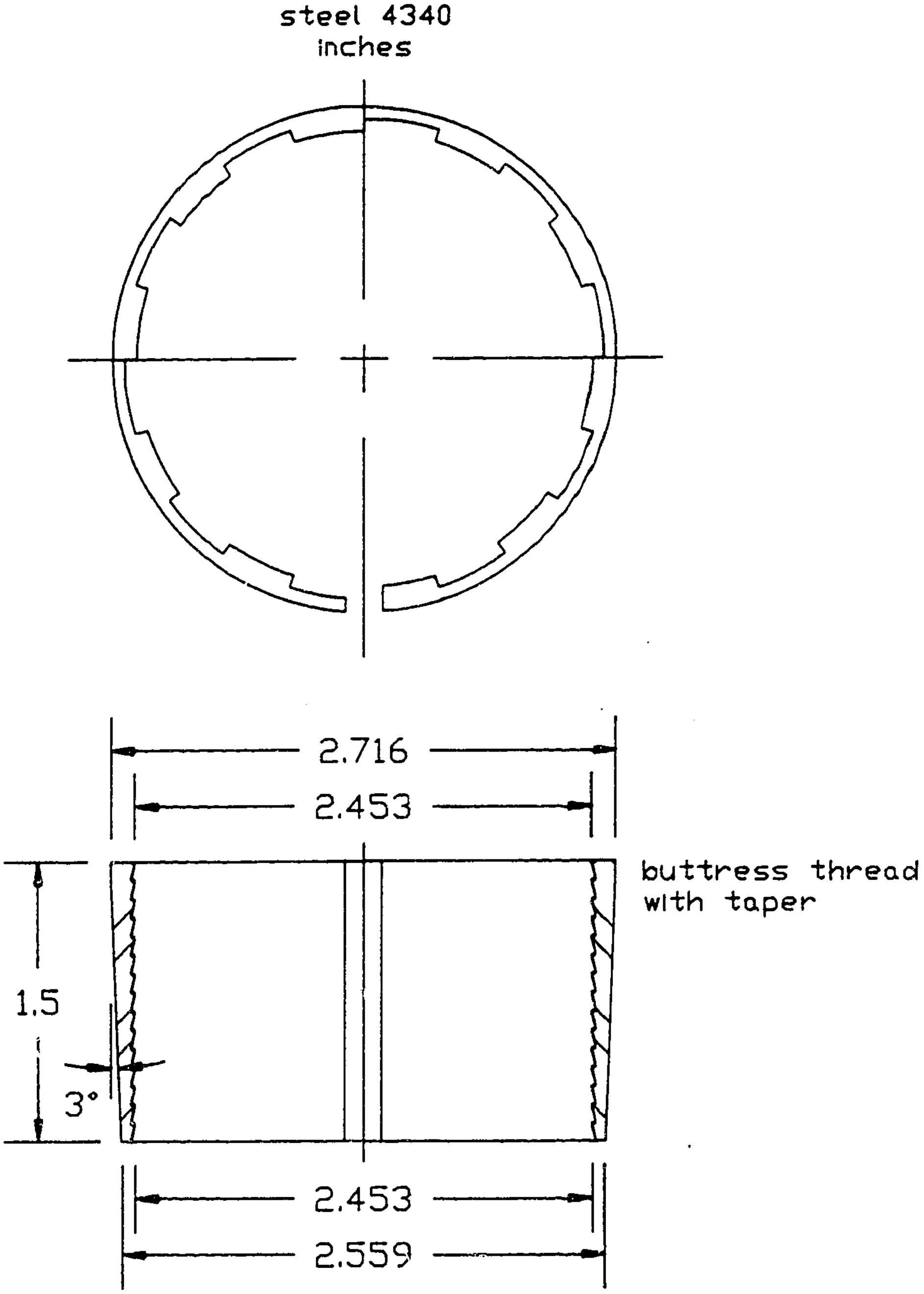


Figure 3.4 4 5/8 Christensen modified steel split ring

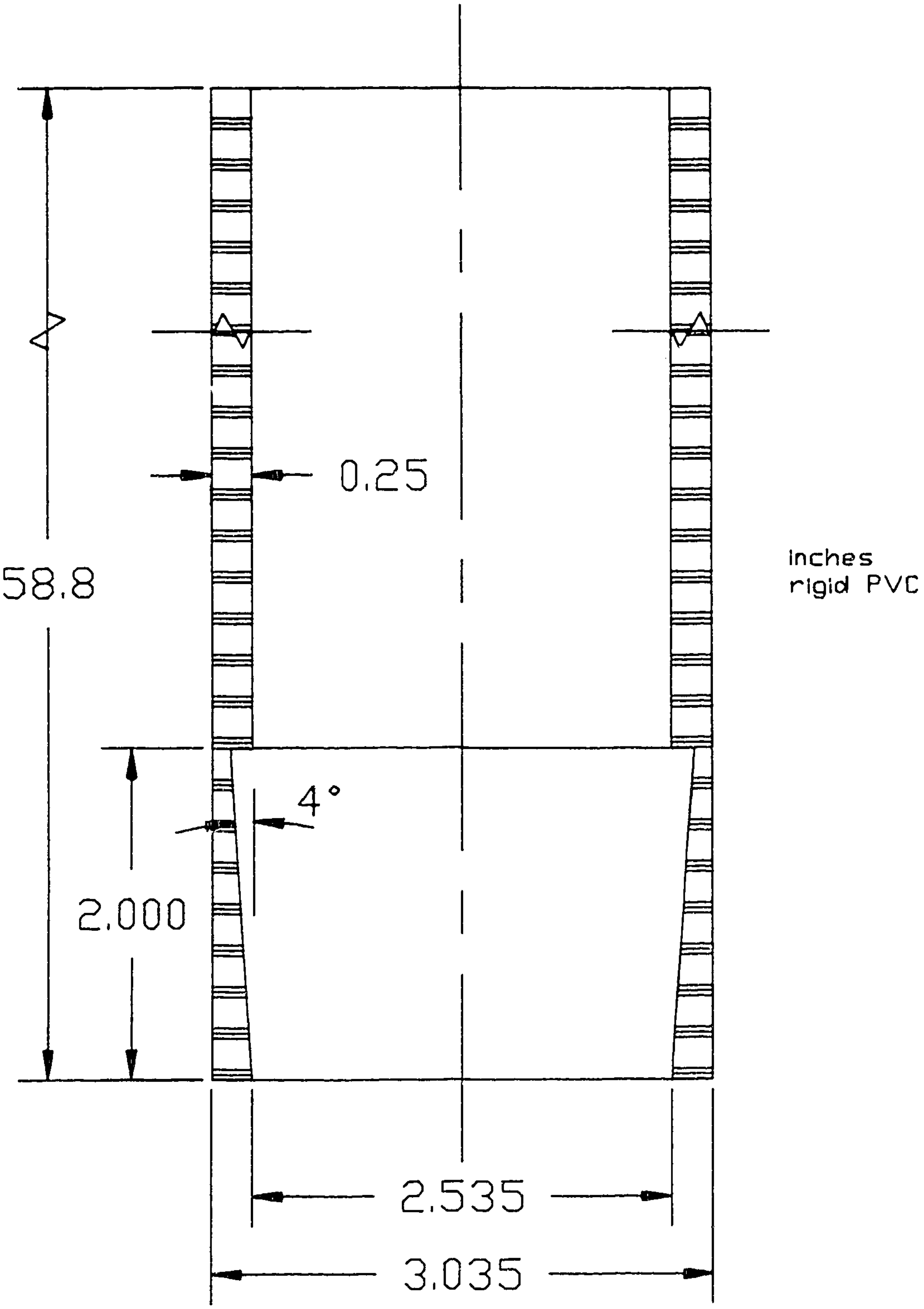


Figure 3.5 4 5/8 Christensen modified liner cross-section

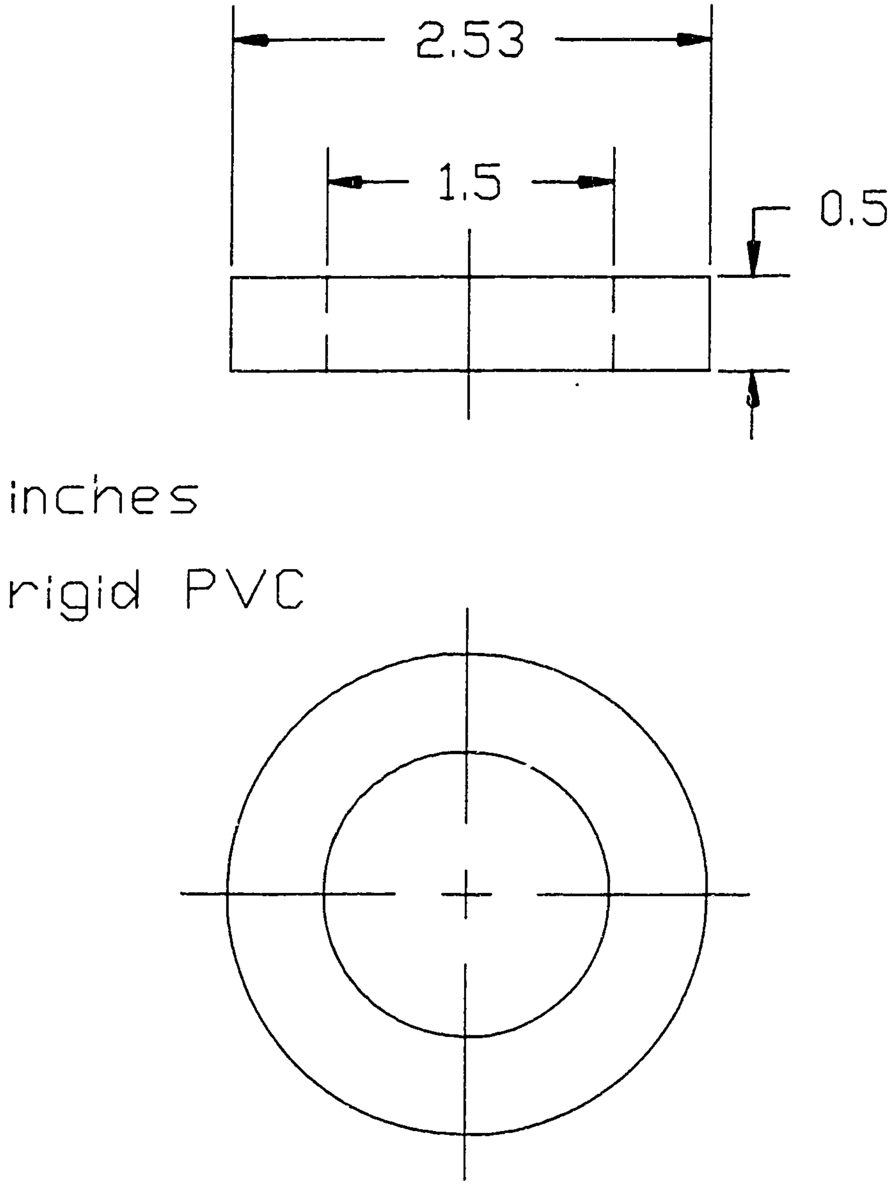


Figure 3.6 4 5/8 Christensen modified liner top retainer

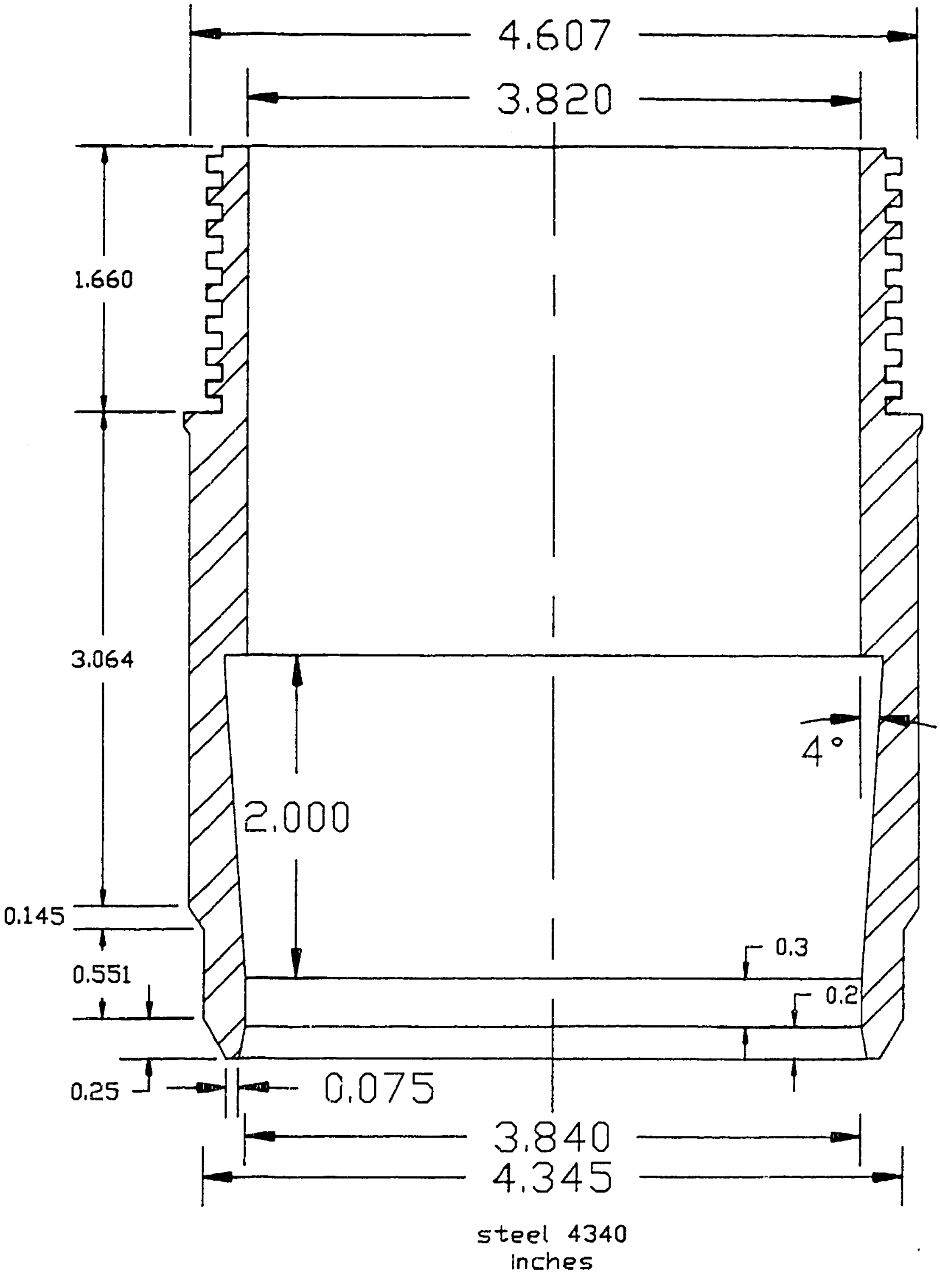


Figure 3.7 SK6L Craelius modified core lifter case

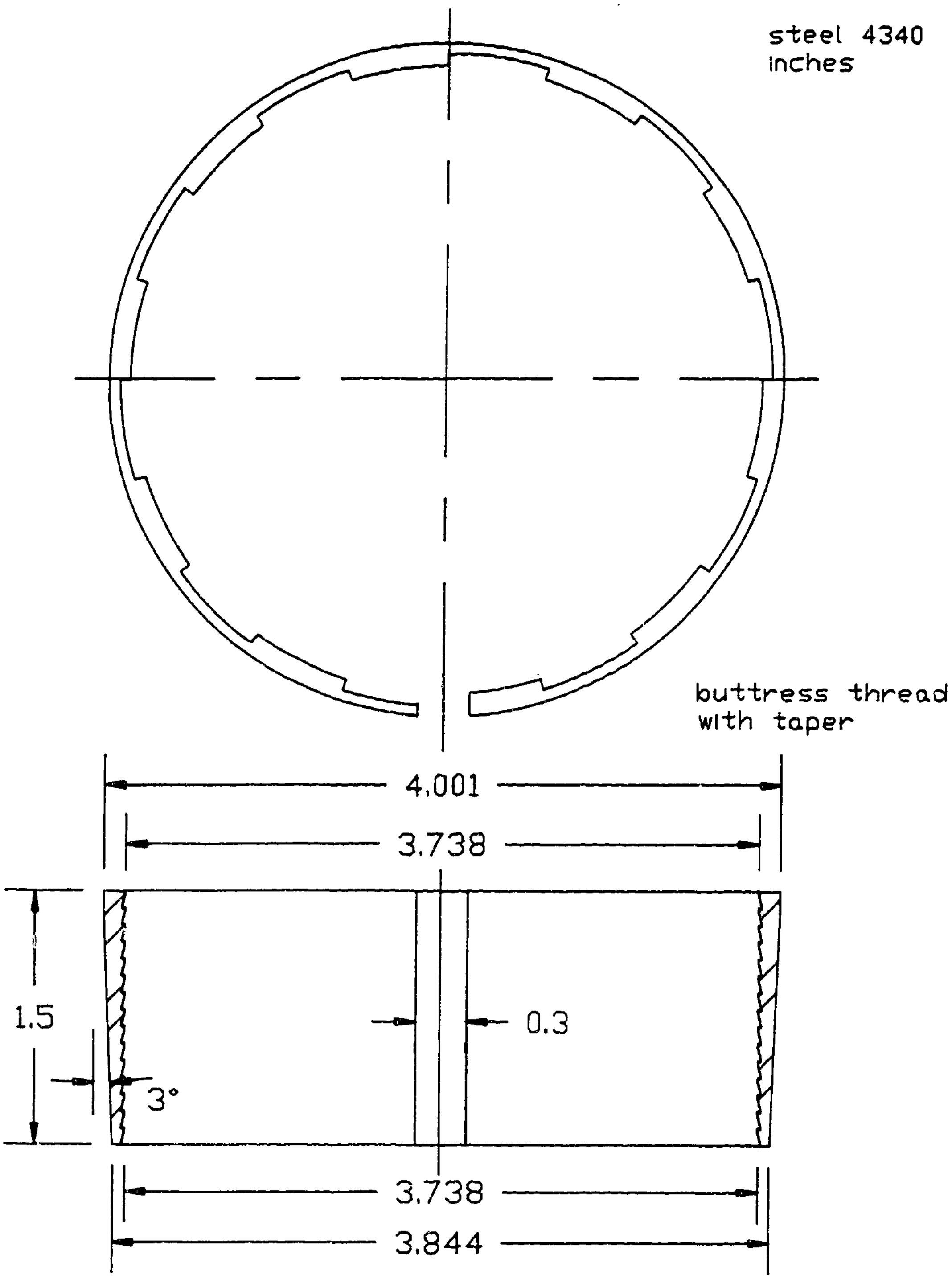


Figure 3.8 SK6L Craelius modified steel split ring

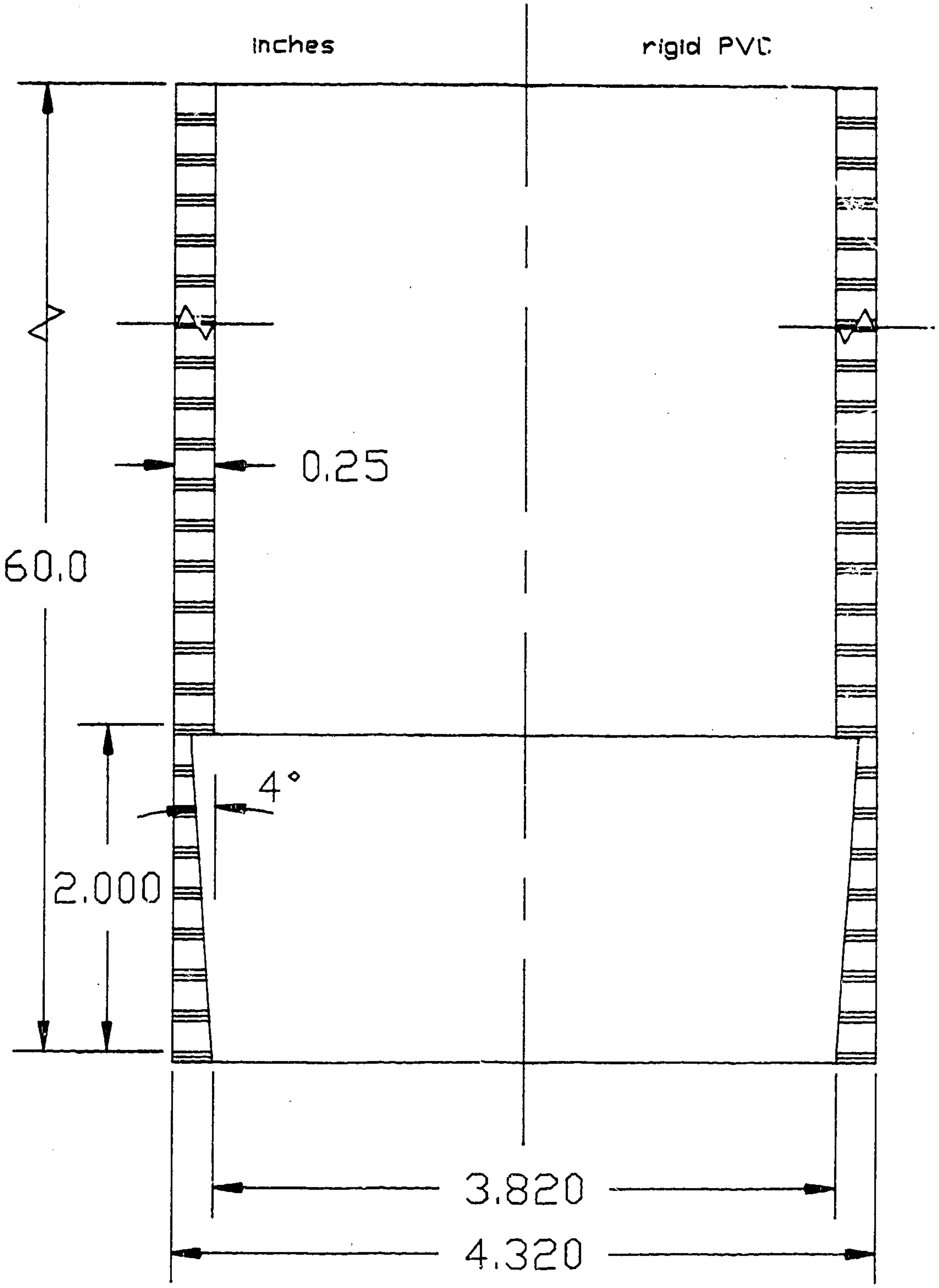


Figure 3.9 SK6L Craelius modified liner cross-section

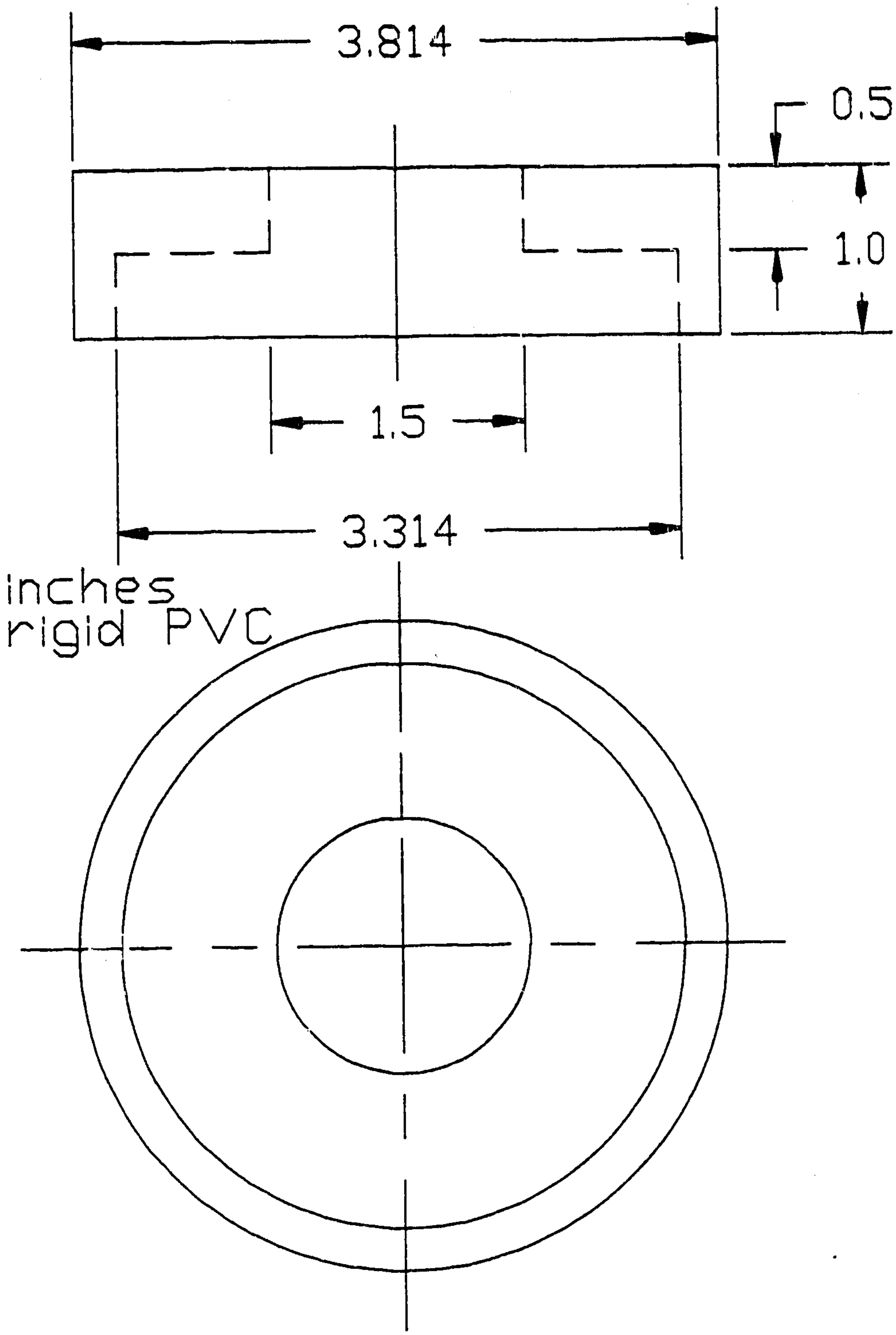
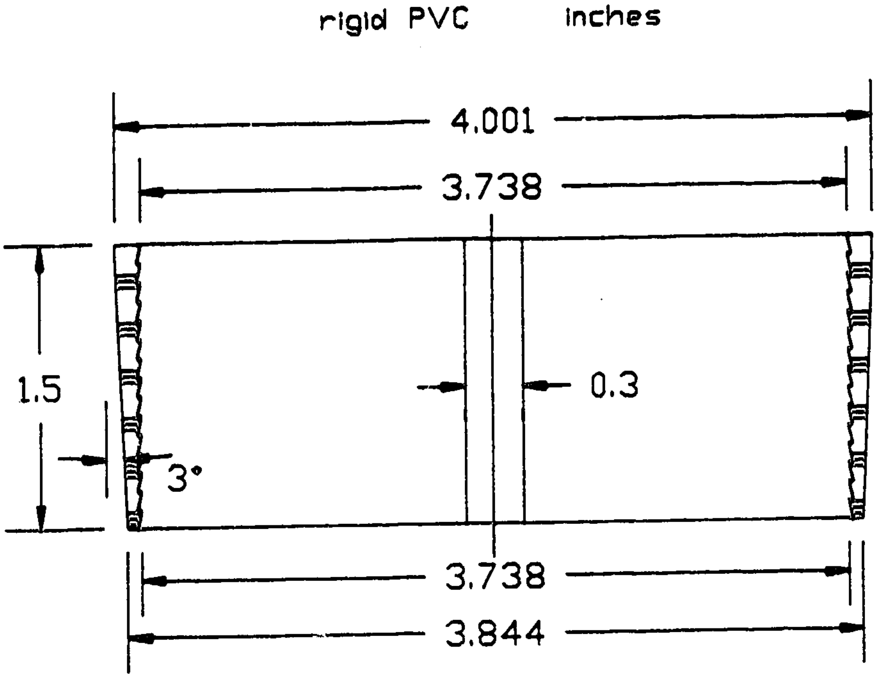
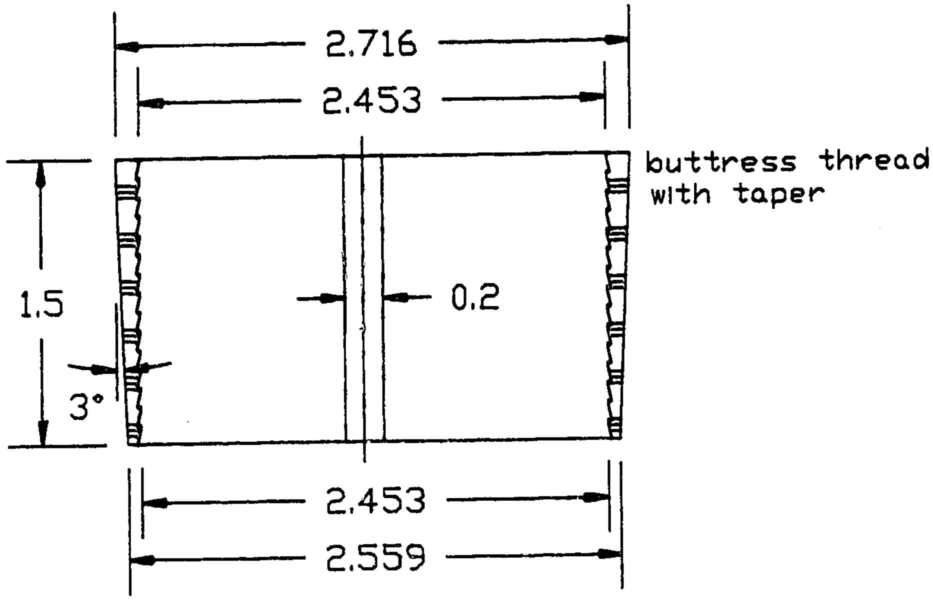


Figure 3.10 SK6L Craelius modified liner top retainer



Craelius SK6L PVC liner core catcher



Christensen 4 5/8 PVC liner core catcher

Figure 3.11 PVC core catchers

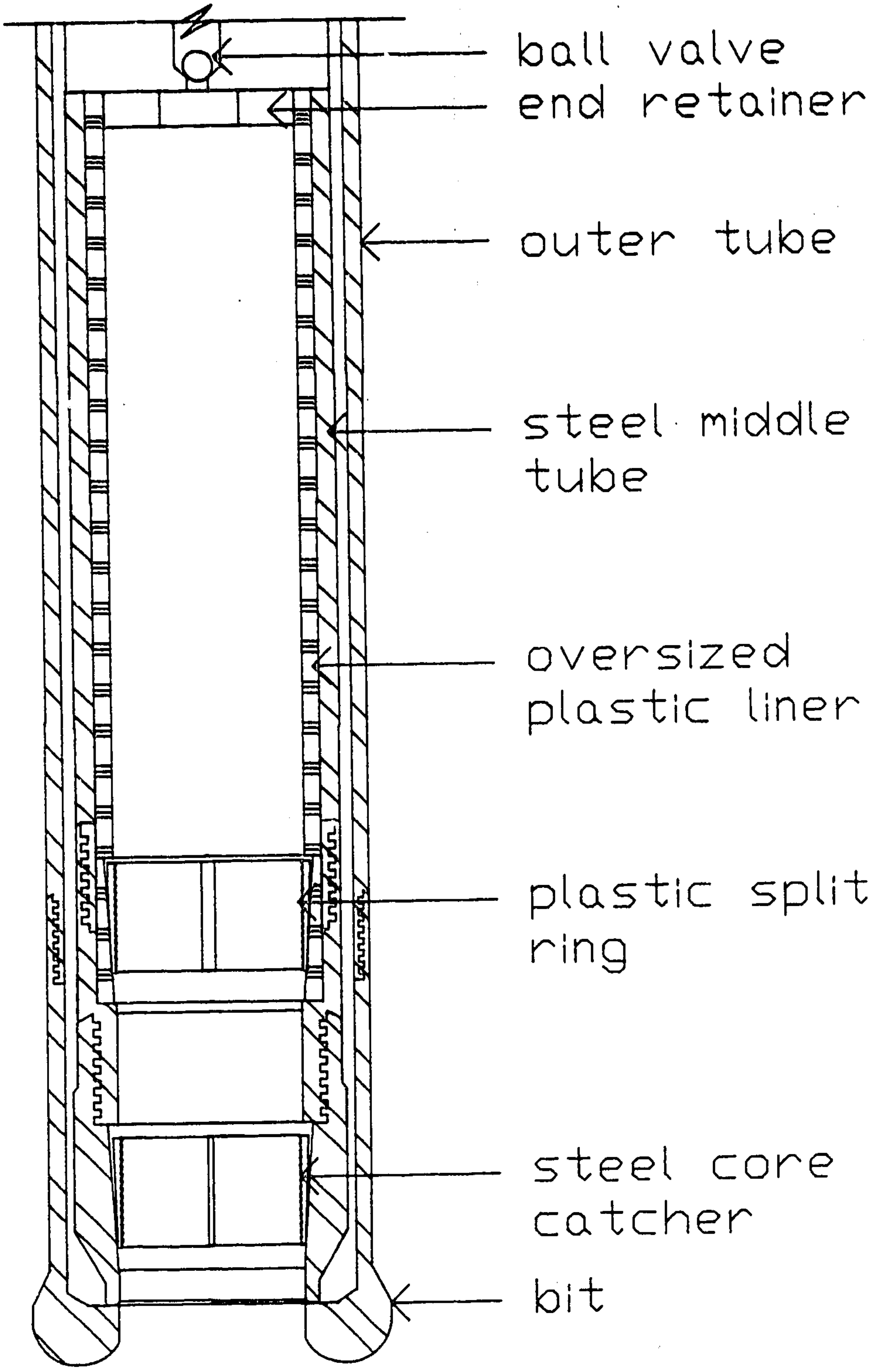


Figure 3.12 Oil sand core barrel

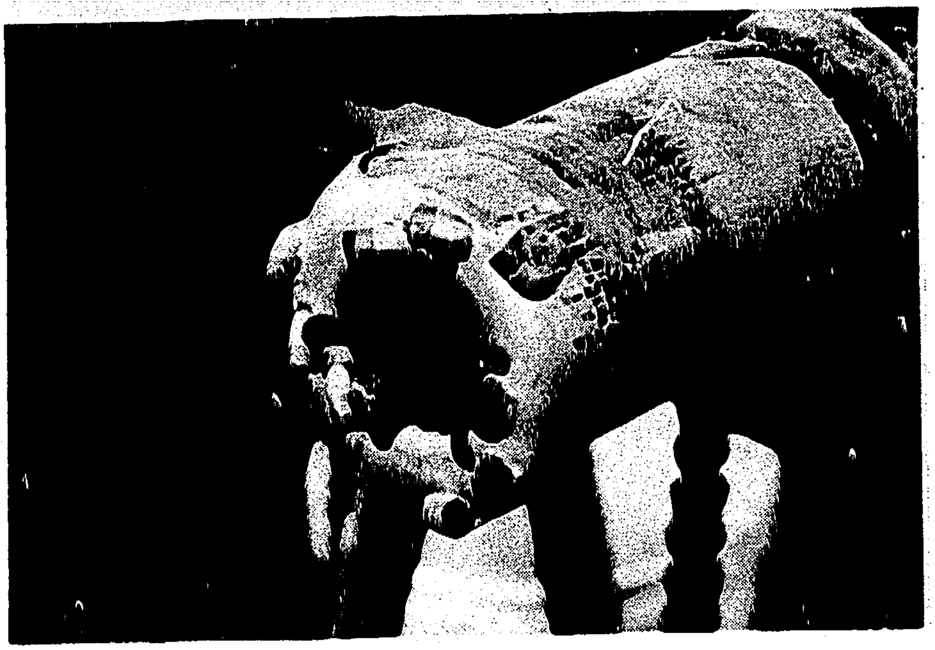


Plate 3.1 4 5/8 Christensen modified Statapax core bit, inner diameter 63.11 mm

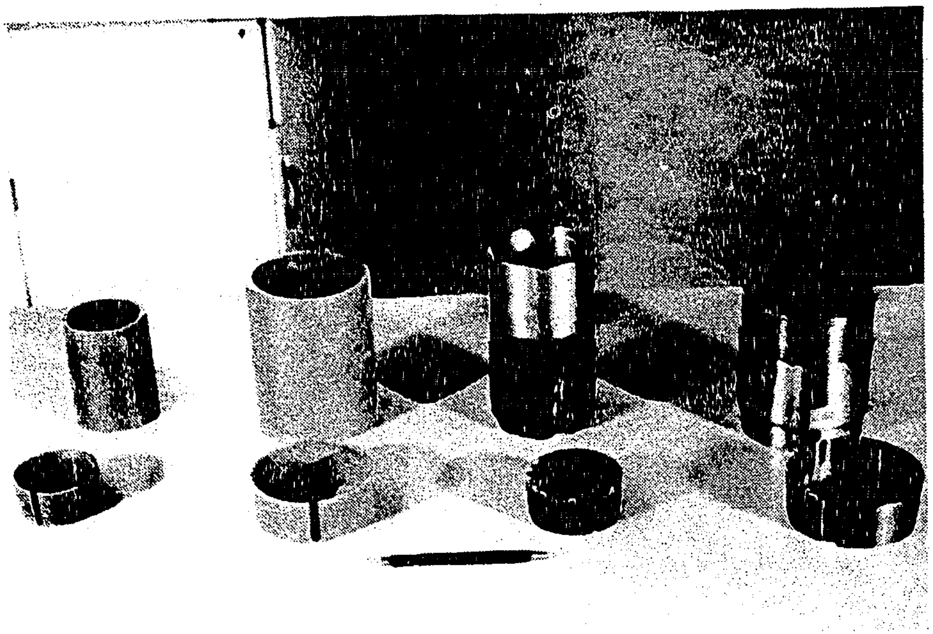


Plate 3.2 PVC core lifter case and core catcher models next to the actual Craelius and Christensen standard counterparts

Plate 3.3 Wooden dowel, PVC core lifter case and split ring model tests on core drop

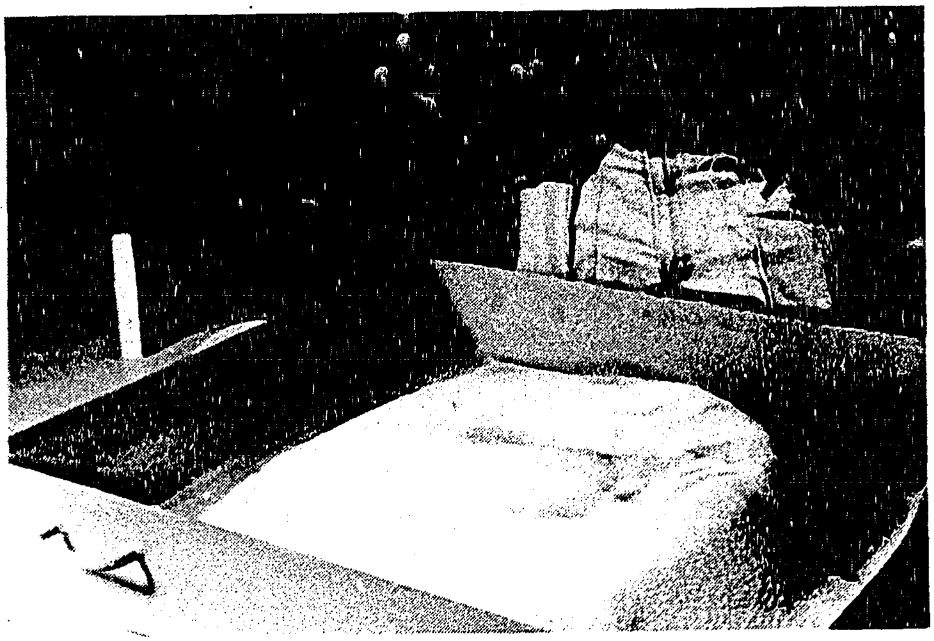


Plate 3.4 PVC core lifter case and core catcher model dry sand arching test

Plate 3.5 PVC core lifter case and core catcher model wet sand arching test

Plate 3.6 4 5/8 Christensen middle tube and liner assembly note steel core catcher and PVC liner core catcher

4. Field Trials

4.1 Introduction

4.1.1 Objectives

Core barrel design modifications were accelerated in order to participate in AOSTRA's Underground Test Facility (UTF) Phase A coring program. Since the UTF coring would be on a large scale the new core barrels were tried out at the Syncrude Canada Ltd. open pit oil sand mine first. Thus the purpose of the Syncrude coring was to ensure the core barrels with and without modifications worked and the purpose of the UTF coring was to further test the barrels and modifications as well as take high quality oil sand samples.

4.1.2 Scope

This chapter contains observations made during coring at both Syncrude and the UTF. Particular attention is paid to the core barrel performance. Coring procedures and sample handling techniques are included. Two holes were cored at Syncrude and 6 holes at the UTF (AGI1, AT7, CI, AT2, AT3, and AGI4).

4.2 Preliminary Syncrude Highwall Coring

Initial trials with the modified core barrels took place on July 30, 1987 from 13:00 to 20:00. The rig was set up on the Syncrude Canada Ltd. open pit mine highwall near borehole 18-14-2-1. Syncrude is located about 40 km north of Fort McMurray, Alberta in the Athabasca oil sand deposit (figure 4.1). The oil sand deposit of Syncrude is characterized by rich oil sand overlain by about 20 m of overburden. Due to the preliminary nature of the coring, the exact surface elevation was not surveyed. The overburden was removed several years earlier from the area where the coring took place.

The first hole was drilled out to 12.19 m. Coring commenced with the Craelius SK6L core barrel as purchased. The Craelius SK6L is a triple tube core barrel which gives a 102 mm core. Even though the SK6L and the 4 5/8's core barrels were both wirelines, the drill rig could only core with these barrels conventionally by pulling out the drill rods to recover each core. Table 4.1 contains a summary of the coring.

The first attempt with the SK6L standard core barrel did not recover any core. The drill rig experienced rocking due to the much larger hole drilled (280 mm) to the coring depth than the bit outer diameter (156 mm). The small drill rods were connected by a sub as shown in plate 4.1 to the larger outer diameter core barrel adding to instability. This was necessary since large enough drill rods were not available. When coring initially the stabilizer located at the top of the core barrel (see plate 4.1) did not bear against the extra large borehole. This wobbling and jarring caused the bit to move around cutting a smaller core than the core catcher was designed for.

On core run number 2 the driller noticed that coring had stopped even though he had a lot of weight on bit and good circulation of drilling fluid. Thus, the barrel was removed after only reaching a depth of 14.0 m. The core from the first attempt had taken up space in the barrel. There was difficulty removing the liner from the barrel. The top of the core barrel had to be removed and the liner and core pushed out from the top with another liner. The following liners were oiled as they were placed in the barrel. The core from core run 2 grew about 50 mm out the bottom of the liner in several minutes. As with all core taken the liner and core were placed in the freezer box with dry ice.

Core run 3 was only 1.37 m because that was the length left on the kelly bar and the rate of penetration should remain constant when coring. Core run 4 had a low recovery due to shale jamming in the steel shoe of the middle tube. The steel core catcher was lost down the hole. This could have resulted in damage to the bit if coring continued. Thus the rig was moved from this hole to begin a new hole about 3 m north of the old hole. The new hole was drilled down to 15.24 m with a small bit. Since time was limited barrels were changed and coring commenced with the 4 5/8's modified core barrel.

The 4 5/8's Christensen core barrel is a triple tube wireline core barrel used in oil sand sampling. The modifications made to the barrel were thicker liners, reduced radial clearance between the core and liner, top end retainer glued into the liner and a PVC split ring placed in the liner bottom. (See plate 4.2.) The liner end retainer can be seen in plate 4.3.

The first core taken with the modified 4 5/8's core barrel had a full recovery. The plastic core catcher was being pushed out the bottom by core extrusion indicating the need to cap the liners and freeze the core as quickly as possible. The core catcher was visible out the bottom of the tube. This means that the core had pushed the plastic core catcher so that its diameter was much less than the core diameter of 63 mm cut by the bit as it extruded out the bottom end (plate 4.4). Excessive time of several minutes lapsed before the liner was capped. This time expired partly to see if extrusion would eventually occur and to allow the taking of a picture. Pictures of core sticking out the bottom of a liner may be misleading since the core may have broken off at this point.

An oil sand plug of about 75 mm was forced out the top 25 mm hole in the liner of core run 2 (plate 4.5). This was loose slough left in the bottom of the borehole indicating improper borehole cleaning due to a combination of poor circulation and mud conditioning. Further evidence of poor mud conditioning was the excessive bitumen staining of the equipment. More typically as shown in plate 4.6, the oil sand core and slough would only fill the 13 mm thick by 25 mm diameter annular volume in the top cap of the liner. The top of the core is where the most disturbance has occurred since it is near the tensile fracture zone that develops when the previous core is taken. This weakens the core allowing it to deform into the annular area in the top of the liner. There was little extrusion out the bottom as the plastic core catcher was effective and capping of the liner and freezing was done quickly with rigid PVC caps. When handling the core, the liner and core should not be tipped vertically as it may help core push out the bottom.

The core and liner were usually removed from the bottom of the hole and placed in a core box with dry ice within 10 minutes.

Low recoveries were due to shale and silt jamming in the core lifter case. Poor drilling methods, particularly the lack of mud conditioning, contributed to the incidence of low core recovery. The driller varied the pump pressure and rpm in an attempt to improve the recoveries as shown in table 4.1. The recoveries with the Craelius SK6L were low but it was not given a satisfactory trial. The Christensen 4 5/8's recoveries were on average 75% which was quite adequate considering the less than optimum conditions under which it was used.

After further experience using the Christensen 4 5/8's core barrel at the UTF phase A coring program, it became apparent that another reason for the low recoveries was that the lead distance was not set properly. The lead distance is the length between the bottom of the middle tube and the inside of the bit. When the Christensen 4 5/8's core barrel was used at Syncrude the lead distance was not adjusted or checked. A proper lead setting aids in fluid circulation and borehole cleaning. This led to extensive jamming in the lower shoe of the middle tube particularly when shale and silt layers were encountered in the oil sands.

4.3 UTF Phase A Coring

The AOSTRA Underground Test Facility is located near Fort McMurray, Alberta in the Athabasca oil sands deposit (figure 4.1). The oil sand is under about 130 m of overburden. The AOSTRA Underground Test Facility (UTF) is an oil sands in situ recovery research project based on the Shaft and Tunnel Access Concept (SATAC). Two shafts connect a series of tunnels to the surface. From the tunnels, horizontal wells were drilled.

Figure 4.2 shows the horizontal and vertical well layout. The vertical wells were drilled to improve the understanding of the reservoir through coring, geophysical logging and instrumentation. The University of Alberta was involved in coring the vertical wells shown in table 4.2 over the given intervals except for AT6 which was cored with a standard triple tube 4 5/8's Christensen wireline. AT6 is included in this table because two 1.5 m intervals of core from this hole were used for comparison with core from the modified 4 5/8's core barrels and the standard and modified Craelius core barrel assemblies.

4.3.1 Hole AGI1

AGI1 was cored first with the Craelius SK6L standard triple tube core barrel which gives a 102 mm core. Rigid PVC caps were not available for the Craelius SK6L standard or modified liners so each end of the core filled liner was covered with a plastic bag and wrapped with duct tape. Limitation of axial extrusion is aided by a full liner for the end cap and plastic split ring to work together to provide a reaction against core longitudinal movement. The length of the liner itself is 1.524 m, the length from the top of the liner to the bottom of the middle tube's steel shoe is 1.64 m. Thus instead of coring 1.524 m lengths, 1.64 m lengths are required. Normally 1.524 m lengths are cut and the core is pushed into the liner. To core run 4, 1.65 m was cut (except for core run 2), but the geologist was worried about excess recovery and jamming so the coring length was reduced to the usual 1.5 m. The geologist's core record is given in table B.1

The first core cut resulted in no recovery. The second core run had a low recovery also. The reason was that the wrong bit was placed on the barrel. AGI1 was to have been cored with the 96 mm inner diameter bit but the 102 mm bit was put on by mistake. For the first 2 runs a 102 mm core was cut but could not fit into the 96 mm steel shoe. So instead of tripping out of the hole and changing bits, the middle tube shoe was changed and the standard liners used.

This was not the only problem. The sub used to connect the drill rods and the SK6L core barrel had an inner diameter of 121 mm. The sub is shown in plate 4.7 at the top of the outer tube and below the handling sub. The landing ring of the middle tube has an outer diameter of 122 mm. The landing ring is being held by the man on the right in plate 4.8. Thus the middle tube could not latch into the outer tube and sat about 400 mm too high in the barrel. The middle tube could be pushed upwards on core entry.

In spite of all this once the correct liner and steel shoe was placed on the SK6L Craelius inner tube, recoveries were excellent but usually over 100%. This excess is a combination of slough and disturbed core in the top of the liners. Core from the first 2 runs may have only been partly destroyed. Since the middle tube was not latched the oversize core could push the middle tube up inside the drill rods.

Core run 3 followed with the core able to enter the middle tube. The 119% recovery in core run 3 was quite probably due to this leftover core. The core could break off anywhere below the middle tube shoe to the bit face, a length of at least 400 mm. Core left hanging out of the middle tube was incorrectly attributed to extruding core in the geologists log. However gas expansion was minimal. There were no gas bubbles in the borehole. Gas extrusion was not visible at the surface in nearly all of the cores.

The local hydrogeological flow conditions appear to have resulted in a very low gas content oil sand at the UTF. Figure 4.3 shows the pore pressure distribution at the UTF. There is a zone near the Clearwater/McMurray boundary that has reduced the pore pressure. Lower pore pressure reduces the gas content of the oil sand. The drain zone may also allow diffusion of any gas produced by bacteria. In advance studies earlier in the UTF program, a gas exhalation test was performed by installing a well point in a hole to the McMurray Formation. There were no measureable quantities of gas. However Hardy Associates measured 146-327 cm^3 of gas per kilogram of oil sand from tests on oil sand core (AOSTRA, 1984). The core fit snuggly in all the modified liners but loosely in the standard Craelius liners where the clearances were greater indicating some expansion. Certainly gas content was much less than that experienced earlier at the Syncrude mine-site.

Recoveries were excellent even for core run 14 at depth 160.50 m to 162.00 m which contained basal Km shale. Core run 15 from 162.00 m to 163.50 m may have contained some water sand which is easily washed away. Core run 15 had a recovery of 49%. On core run 16 from 163.50 m to 164.50 m the geologist remarks that the Craelius core catchers would not hold the limestone even though the recovery for that run was 114%. The oil sand/limestone interface is a weak zone and if this is not in the middle tube before the core is broken it will be where the breakage occurs. Coring the CI hole later on with the standard Craelius gave consistently 100% recovery well into the limestone. Core runs 6, 7, and 11 initially had lost the core. In all cases the driller managed to go back down the hole and recover the core. What likely happened was that the core pushed the unlatched middle tube up the drill rods and never made it very far into the liner in the first place. The geologists log is misleading in that these problems of core loss are not mentioned.

To save time on cleaning the core catcher and shoe after each run, a university manufactured shoe and core catcher was alternated with a Craelius made shoe and core catcher. Earlier on a university made core catcher had been damaged and in core run 6 the university made core catcher was pushed up into the liner. After core run 7 only the Craelius core catcher and shoe were used. There is no doubt that the Craelius core catchers were superior in workmanship and strength especially for the first few catchers that were made at university, but when the middle tube was improperly latched the top of the core entering the tube may have been slabbed by the shoe and caught the catcher. Core catcher destruction and core loss is common even for the standard Christensen core barrel and is more prevalent in heavily interbedded oil sand-shale zones.

4.3.2 Hole AT7

The next hole to be cored was AT7. AT7 was cored with the Craelius SK6L wireline barrel in its modified form with oversized liners, end retainers glued in the tops of the liners and plastic split rings built right into the liners. The modified Craelius SK6L restricts sample expansion radially and longitudinally and provides a large sample of 96 mm in diameter.

The problem of the undersize sub preventing latching of the middle tube was still unnoticed. The x-ray images of all the core are shown in plate 4.10. The large diameter Craelius core is fractured. None of the small diameter Christensen core from AT3 tubes 13 and 19 were fractured at all. This is because the Craelius core was damaged passing unprotected from the bit face at least 400 mm to the middle tube. The top ends of the Craelius core show abrasion consistent with this as shown in plate 4.10.

The first core run from AT7 had little recovery as shown in the geologists log in table B.2. Both plastic and steel split rings were dislodged and pushed up into the liner. The first part of this core was cut by a 76 mm bit from the previously used core barrel and the last part of this core was cut by the Craelius 96 mm bit. This was possible since the hole was not reamed out past the 76 mm cut length of core left in the hole. The second core cut was only 0.40 m long since the driller felt he had a full barrel based on pump pressures. It was recorded in the geologists log that 0.27 m was recovered. It was obvious from the tube weight and x-ray images that this was incorrect and 1.054 m of core had been recovered. Normally when the core barrel is full the pump pressure will increase. The unlatched middle tube and exposed core would only allow pump pressures to increase if a section of unprotected core lodged against the outer tube and became twisted around even more by the rotating outer tube. That is why core run number 2 was not full.

For the third try the steel core catcher was pushed up into the liner and recovery was minimal. The fourth, fifth and sixth tries also had no success. Clues to the problem of the unlatched middle tube were being noticed. The steel core catcher had several times been pushed up. This was due to the uneven core entering the middle tube. In one case about 200 mm of core was in the top of the liner and the steel core catcher was in place. This implies that the liner was full of core but most of the core slid out past the core catcher leaving the top held in place by the inner face of the liner. The core slid out because drilling fluid erosion over the unexposed core length reduced the diameter to make the core catcher inoperative. The pin in the overshot became bent. The overshot pin is on the end of the steel cable used to retrieve the middle tube. It was bent because it was not centered on the landing ring of the middle tube. The middle tube was not sitting properly in the core barel allowing this to happen. The tool push and driller noticed that the core looked unusual and was out of round. They attributed this to drilling fluid erosion but they did not come up with a possible explanation as to how it could have occurred.

Up to core run 6 from 142.00 m to 148.85 m the noticeable lithology was lean oil sand, with a lot of shale partings. Shales are more susceptible to drilling fluid erosion than rich oil sand. Shale-oil sand boundaries are weak and places where the core is easily fractured. In a misguided attempt to improve recovery the plastic split rings in the liners were removed from core runs 7 and on. Core run 7 had more than full recovery. The lithology was now rich oil sand. Only the rich oil sand was competent enough to be cored even though the middle tube was not latched. The core sticking out the bottom of the steel shoe for core runs 9 and 10 could not have occurred if the middle tube was latched. From core runs 7 to 10 the recoveries were high. Core runs 11 and on progressively had lower recoveries indicating a lithology change from rich oil sand to more argillaceous oil sand and shales.

AGI1 cored with the standard SK6L Craelius was more successful. More competent rich oil sand may have been found in AGI1 but the lower radial clearances of the modified liners increased the susceptiblity of the barrel to low recoveries in its unlatched condition.

4.3.3 Chevron's CI Hole

The Craelius barrel, due to its low recovery was not planned to be used again at the UTF phase A coring program. Fortunately Chevron wanted large diameter core from their CI hole. Since the standard Craelius was relatively successful it was used for this hole.

Before coring hole CI the Craelius barrel was assembled at the surface as it should have been but was not for AT7 and AGI1. It was then that the undersize sub was noticed. The inner diameter of the sub was lathed out and the barrel was completely successful.

The AOSTRA wellsite core description for borehole CI is given in table B.7. The Chevron geologist removed 4-5 cm of slough from the tops of the liners in all but the first few tubes. Slough is distinguishable from core in that the slough is very loose and the core should be dense. However, it appears this may just have been disturbed core as described earlier. Examination of other core tubes and viewing of the core x-ray images (see plate 4.10) show the competent nature of the top of the core and not slough from poor mud circulation. Extrusion at the surface did not occur. The recoveries were usually 100%. Core runs 6, 9 and 12 in the oil sands had recoveries slightly greater than 100%. Core run 14 had 60% recovery due to the lithology change from oil sand to limestone. The steel core catcher was pushed up in the core lifter case. The limestone surface is uneven and there is occasionally water sand just above the limestone. A water sand may have been washed away and the uneven limestone surface caught the core catcher and twisted it around. This prevented further entry of core into the barrel. Core run 15 only cut 0.90 m in an attempt to recover the additional 0.60 m from the last core run. However only 0.66 m was recovered. On core run 16 the excess core was picked up with 1.72 m recovered from 1.00 m cut. The final run, core run 17 had 96% recovery.

4.3.4 Hole AT2

Hole AT7 was followed by hole AT2. AT2 was cored from 123.0-154.4 m with the 4 5/8's Christensen modified core barrel giving a 63 mm core. Before coring the lead distance of the core barrel was set to 3 mm. The lead distance is the distance between the steel shoe of the middle tube and the kerf of the bit.

The AOSTRA wellsite core description is given in table B.3. The first core run had 91% recovery in the Clearwater shale. Core run 2 was in the water sand of the Wabiskaw and the recovery was 65%. Water sand is easily flushed away by the drilling fluid resulting in low recoveries when encountered. Core run 3 had a recovery of 92% and may have been low due to the presence of water sand. Core run 4 had 100% recovery. Core runs 5, 6 and 7 had no recovery at all. The bit was plugged with silt and clay from core run 5. The middle tube did not latch properly due to the plugging of the area near the bit. The drill string had to be removed from the hole and the bit cleaned. Commencing with core run 8 the recovery increased to 75%. Core run 9 had 100% recovery. Core run 10 had 89% recovery and marked the appearance of lean oil sand at a depth of 137.83 m. Once in the oil sand the recoveries were good. The coring length was increased from 1.5 m to 1.65 m to try to pack the barrel full from core run 13 on. However the actual length of core that will fit in the liner and lower shoe is 1.59 m. This is further complicated by the liner length being 1.493 m not 1.524 m as the geologist would assume when calculating the net length of core recovered. Thus the recoveries are not usually 100% and could not be when 1.65 m of core was cut. The rpm averaged 70.

4.3.5 Hole AT3

AT3 was cored next from 123.00 to 154.50 m below the ground elevation. Again the Christensen core barrel with the modified liners was used. The core size was 63 mm.

The first core run only cut 1.20 m because the driller's pump pressure went up signifying a full barrel. 1.59 m were recovered, the excess being slough. On core run 3 at 125.80 m a dense sand layer containing pyrite jammed in the shoe and the rest of the core was ground up. The net length of core recovered was only 0.10 m. From core run 5 on it was decided to cut 1.65 m again to fill the middle tube completely as the oil sand zone was approaching. Recall above where it was noted that really only 1.59 m of core will fit in the core barrel. After core run 7 it was decided to cut 1.6 m since 1.65 m appeared to be packing in the core too much.

The 25 mm diameter hole in the top of the modified liner was usually partly or completely filled with loose material as shown in plate 4.9. This likely was slough which was packed in the top of the barrel when 1.65 m was cut instead of 1.59 m. The core was being broken off at the bottom of the shoe which is near the back of the bit face.

For core runs 17 to 19, 1.65 m instead of 1.60 m was mistakenly cut in order to fill the barrel in the rich oil sand zone.

The AT3 coring went very smoothly and recoveries were quite good. There was no extrusion out of the bottom of the liner noticed at the surface. Some typical coring times are shown in table 4.3. It took about 20-25 minutes to complete one core in entirety from running in the middle tube to placing the capped and marked liner on dry ice.

4.3.6 Hole AGI4

AGI4 was cored on the second trip to the UTF on October 7, 1987. AGI4 was cored with the 4 5/8's Christensen core barrel and modified liners. Rigid PVC end caps were placed on the bottom of the first three liners after which there were no more end caps. The top ends and the remaining bottom ends were covered with a plastic bag and wrapped in duct tape. Tubes and core were weighed before placing in dry ice.

The interval cored was 135.00 m to 164.80 m. The AOSTRA wellsite core description for AGI4 is given in table B.6. The steel core catcher and shoe were for most of the hole (to core run 10) immaculate, requiring no cleaning before reassembly. The other holes cored with the modified Christensen barrel started at 123.00 m and the kim mud eventually became tired due to the larger coring interval. The bitumen staining at the Syncrude site was of another magnitude altogether. Kim mud keeps the equipment clean of bitumen. Bitumen staining was noticeable from core run 11 on as the kim mud was fatiguing a little. Kim mud also causes minimal fluid invasion of the core and leaves little mud cake on the borehole wall to improve geophysical log readings. 1.60 m was cut to try to fill the middle tube completely. On core run 11 the driller felt some core on reentering the barrel so only 1.30 m was cut. The excess core was left from core run 10 where 1.29 m of 1.60 m cut was recovered. A similar situation likely occurred with core runs 8 and 9. Extrusion was only noticed in 2 tubes. Tube 17 extruded about 30 mm at the surface.

Since the final total depth of AGI4 was 175.00 m and the end of coring was 164.80 m, instead of tripping out of the hole, replacing the drill string and drilling down to total depth, the 4 5/8's Christensen core barrel was used to core out the last 10 m of limestone. The Christensen core barrel performed well in the limestone. A modified liner without an end retainer or plastic split ring was reused for the extra 10 m of core with the core being removed from the liner and disgarded.

4.3.7 Hole AT6

The AOSTRA UTF coring summary for hole AT6 is given in table B.5. Hole AT6 was cored with the standard Christensen 4 5/8's core barrel with liner. Core lengths were 3.0 m when possible and the core diameter was 69 mm.

This coring procedure is standard for obtaining high quality oil sand samples. It allows more radial and longitudinal extrusion than the modified core barrels used by the University of Alberta.

Table 4.1 Syncrude coring summary July 30, 1987

Core Run	Cut	Rec	Driller's Depth (m)		Tube	RPM	Pump	Core	% Rec	Remarks
Number	(m)	(m)	From	To	No.		Pres(psi)	Dia (m)		
1	1.52	0	12.19	13.72	No tube	110	200	102	0	hole size change vibrations
2	0.3	1.2	13.72	14	1	120	100	102	na	core from previous run, 50 mm extrusion out bottom
3	1.37	1.37	14	15.4	2	120	100	102	100	18 min from pulling drill rods to core in dry ice
										1.37 m cut since at end of drill rod
4	1.52	0.38	15.4	16.92	3	120	100	102	25	
Move to new hole 3 m north due to steel core catcher lost in hole										
1	1.52	1.65	15.24	16.76	1	120	100	63	108	extrusion
2	1.52	1.52	16.76	18.28	2	120	100	63	100	
3	1.52	0.61	18.28	19.81	3	120	100	63	40	12 mm extrusion
4	1.52	0.3	19.81	21.34	4	120	100	63	20	
5	1.52	1.52	21.34	22.86	5	120	200	63	100	
6	1.52	1.52	22.86	24.38	6	120	200	63	100	some extrusion
7	1.52	0.72	24.38	25.91	7	120	200	63	47	
8	1.52	1.25	25.91	27.43	8	120	200	63	82	
Gaseous rich oil sand										

Table 4.2 UTF coring summary for University of Alberta, 1987

Well	Cored Interval (m)	Core Dia (mm)
AGI1	141.80-164.50	102
AT7	142.00-163.35	96
AT2	123.00-154.40	63
AT3	123.00-154.50	63
AT6	123.00-154.40	69
AGI4	135.00-164.80	63
CI	146.20-172.00	102

Table 4.3 Typical coring times for UTF

Hole #	Drillers From (m)	Depth To (m)	Start Coring	Stop Coring	Middle Tube Released	Middle Tube at Surface	Core in Dry Ice
AT3	130.35	132.00	1:24	1:31	1:34	1:36	1:48
AT3	132.00	133.65	1:50	1:57	1:58	2:01	2:17
AGI4	139.70	141.30	12:24	12:29	12:30	12:37	12:45
AGI4	141.30	142.90	12:42	12:47	12:48	12:56	13:05
AGI4	144.50	146.10	1:22	1:28	1:31	1:35	1:42
AGI4	146.10	147.70	1:59	2:03	2:04	2:11	2:18
AGI4	150.80	152.10	2:59	3:04	3:08	3:12	3:22
AGI4	152.10	153.70	3:36	3:40	3:42	3:48	3:56
CI	147.70	149.20	5:44	5:48	5:53	5:58	6:34*
CI	149.20	150.70	6:27	6:31	6:36	6:39	7:16*
CI	150.70	152.20	7:16	7:21	7:26	7:31	8:15*
CI	155.20	156.70	8:39	8:43	8:48	9:53	10:10*
CI	164.20	165.70	11:18	11:23	11:26	11:29	12:15*

*Core tube ends sealed with resin and placed in dry ice after all coring completed

Due to the unavailability of copyright permission, figure 4.1, Location of Syncrude and the UTF in northeastern Alberta near Fort McMurray (Rottenfusser, Palfreyman and Alwast, 1988) has been removed. This figure contained a map of the location of the UTF and Syncrude of Canada Ltd. in northeastern Alberta.

Due to the unavailability of copyright permission, figure 4.2, UTF phase A observation well layout (Suggett, 1988) has been removed. This figure contained the locations of the UTF phase A boreholes, including the boreholes discussed in this thesis.

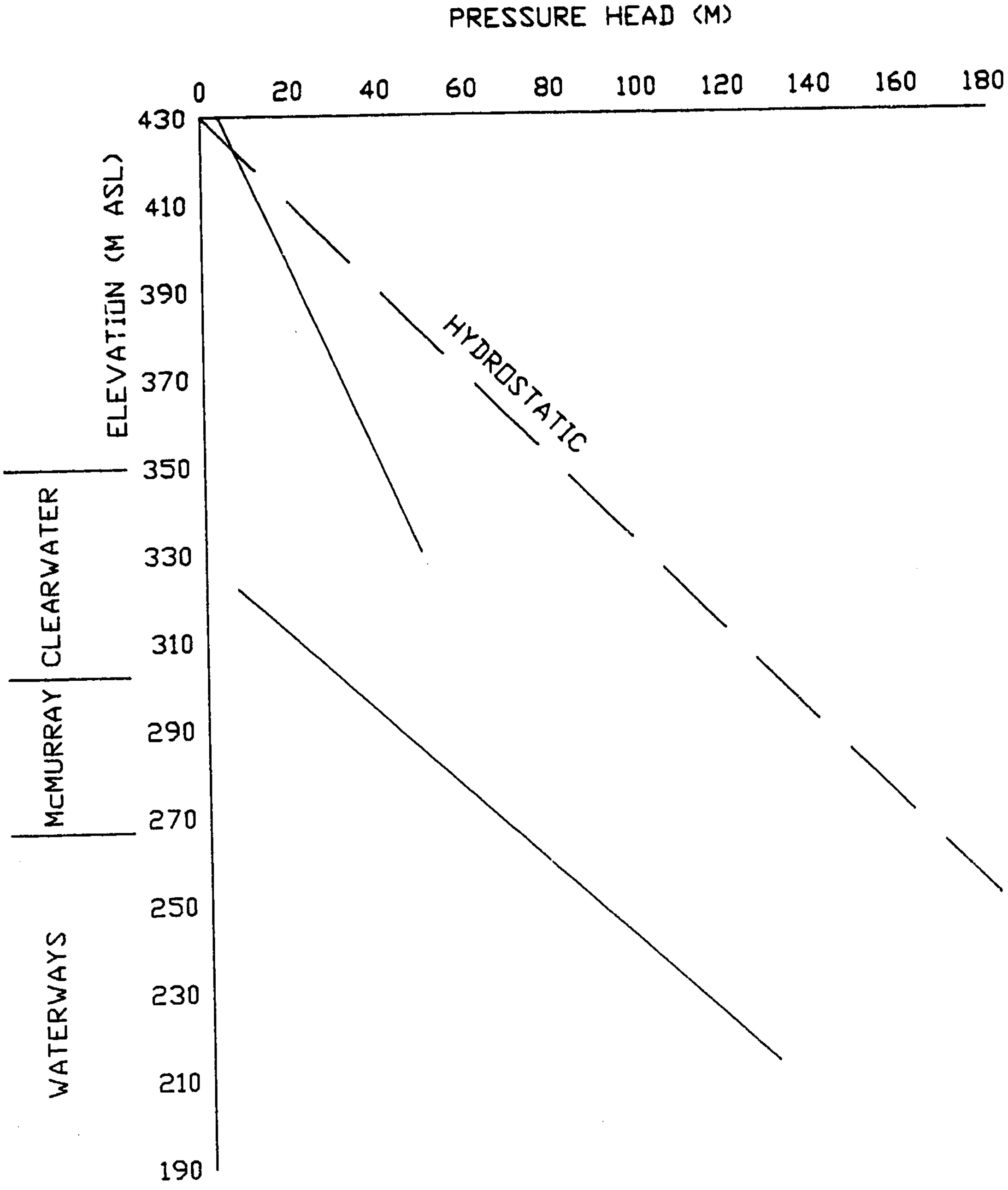


Figure 4.3 UTF piezometric profile

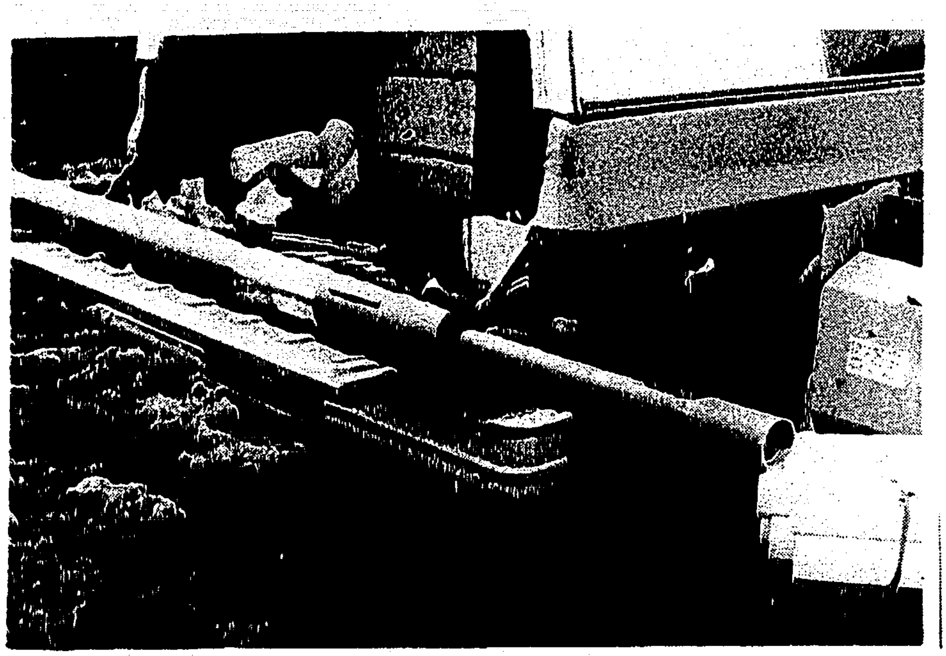


Plate 4.1 Craelius SK6L core barrel with adapter sub

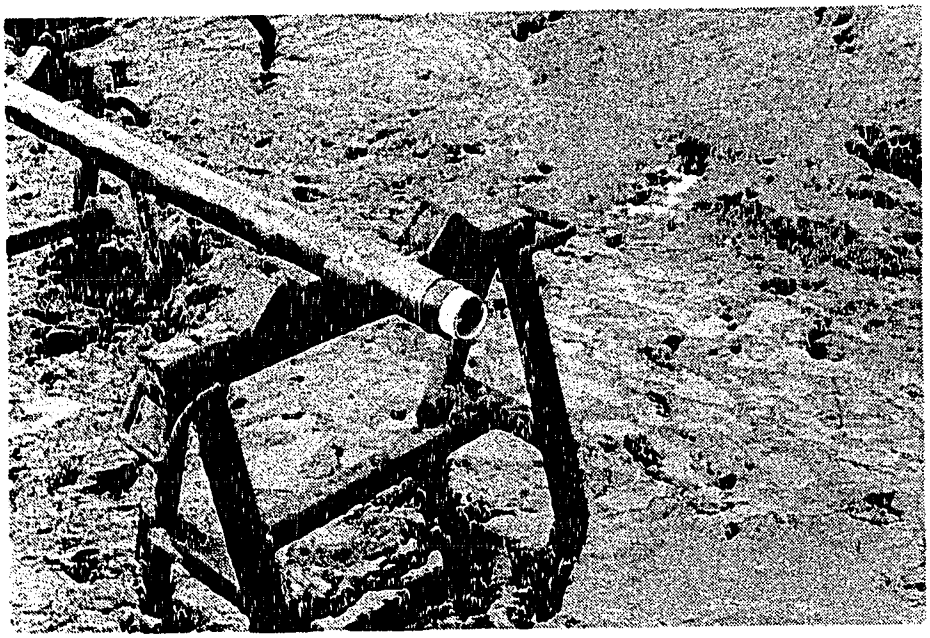


Plate 4.2 4 5/8 Christensen middle tube and modified plastic liner with PVC split ring

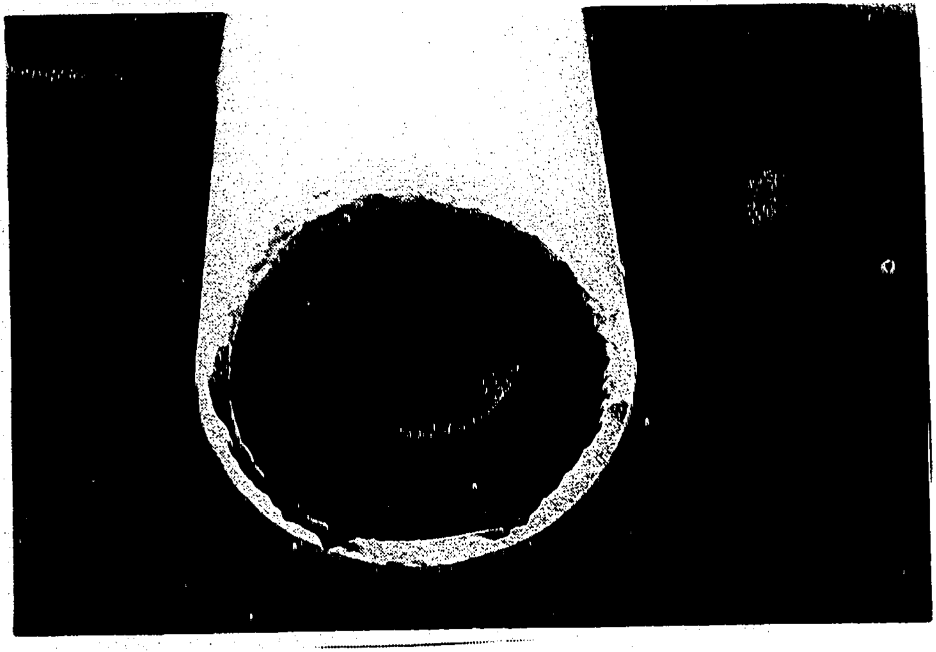


Plate 4.3 4 5/8 Christensen modified liner end retainer

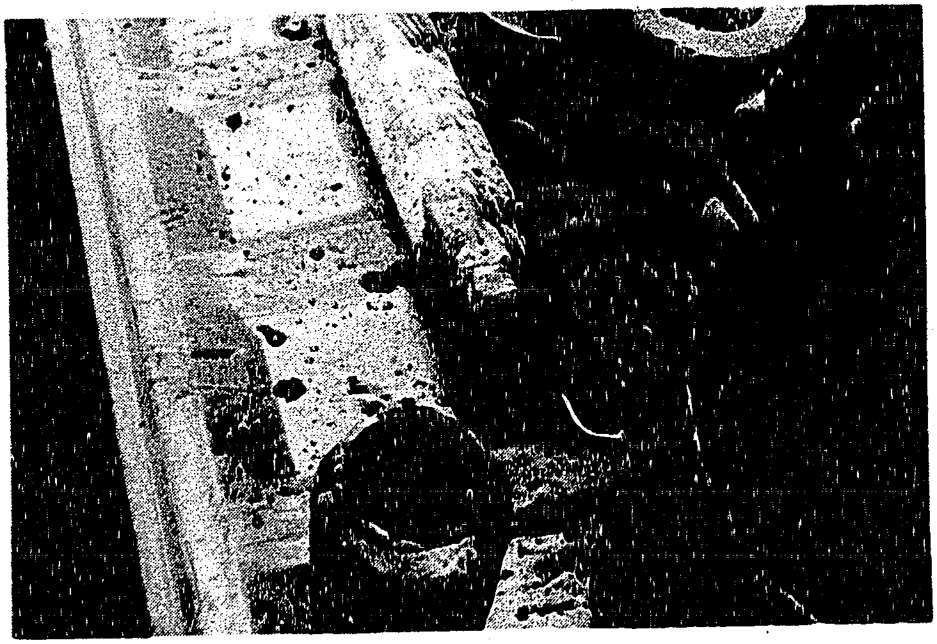


Plate 4.4 4 5/8 Christensen modified liner with plastic core catcher being pushed out by expanding oil sand core

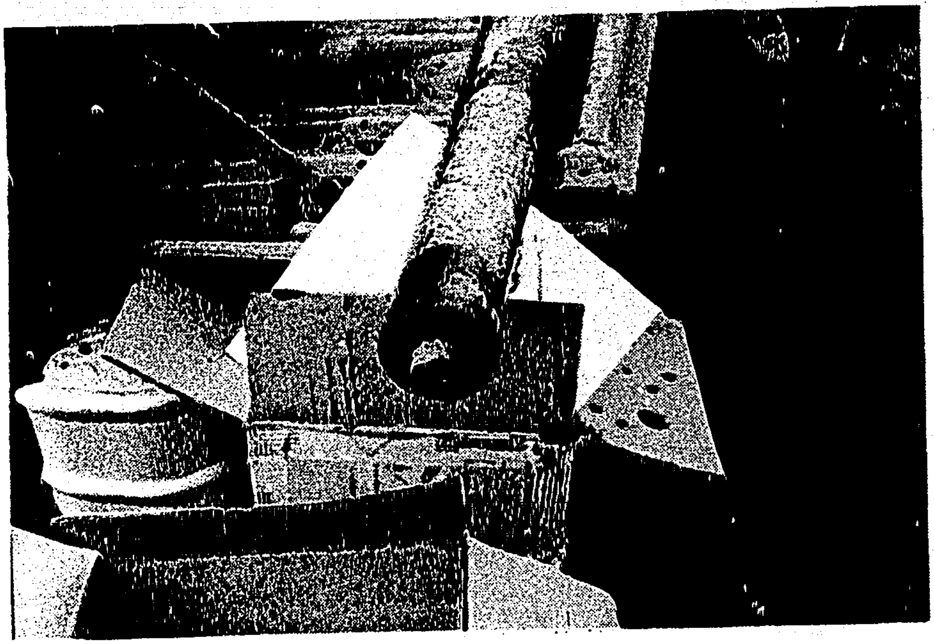


Plate 4.5 Oil sand plug coming out the top end of the 4 5/8 Christensen modified liner

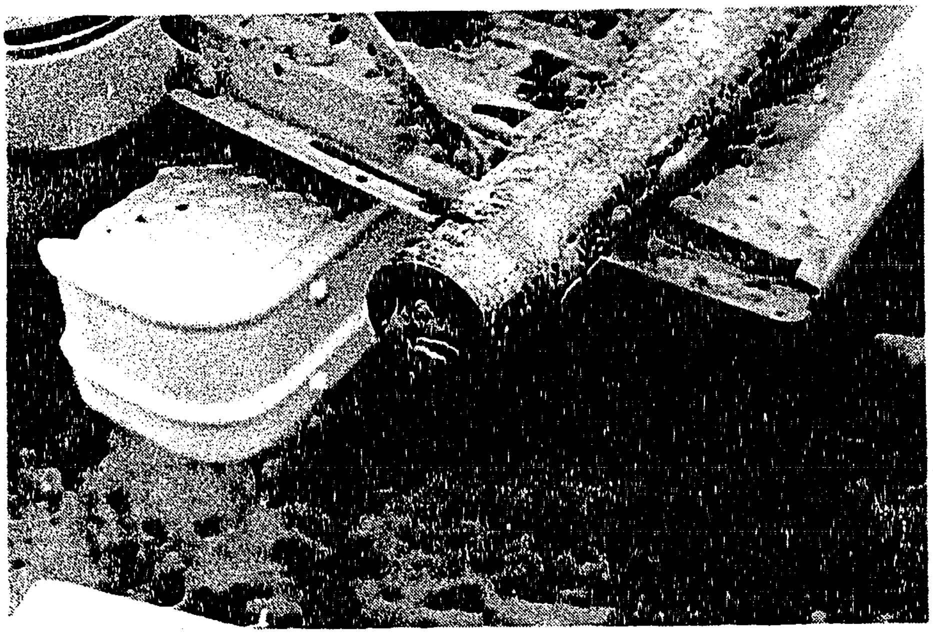


Plate 4.6 Oil sand filling the annular volume in the 4 5/8 Christensen liner top retainer

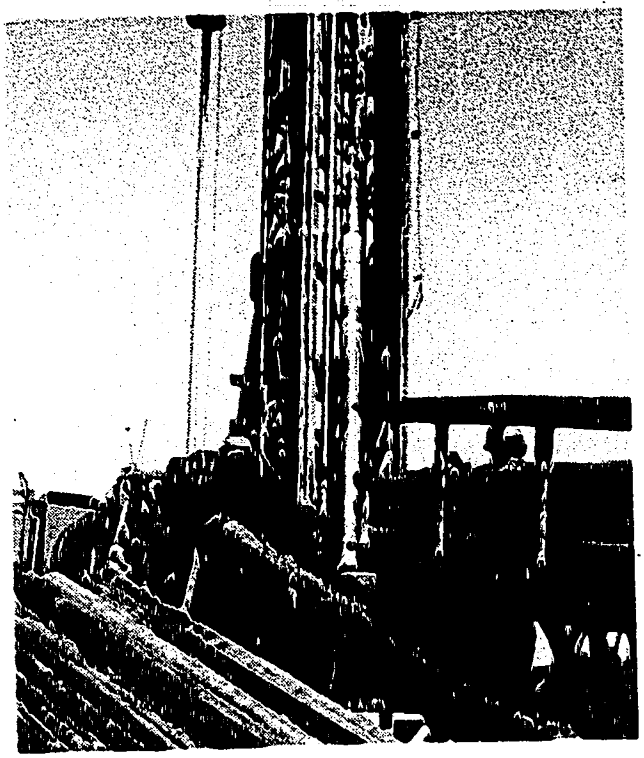


Plate 4.7 Craelius SK6L outer tube ready to go down hole

Plate 4.8 Craelius SK6L middle tube and overshot

Plate 4.9 4 5/8 Christensen modified core tube top retainer restraining oil sand core

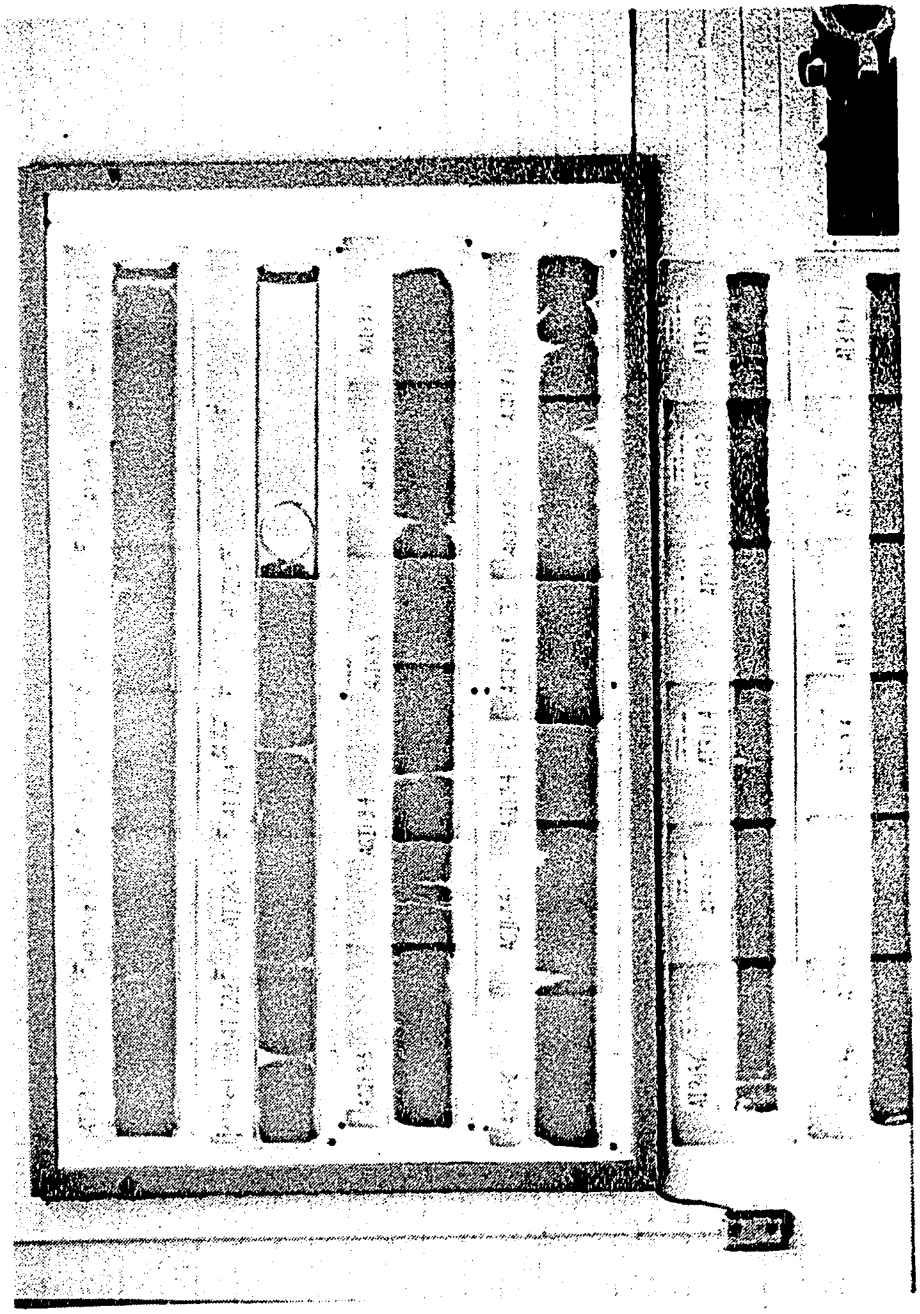


Plate 4.10 UTF core x-ray images

5. Core Testing

5.1 Introduction

5.1.1 Objectives

Core tests were performed to determine the quality of the samples and thereby the performance of the modified oil sand samplers. It was important to reduce and note test related disturbance, thus special sample preparation techniques were used. The sample tests chosen had to be common and relatively simple to perform.

5.2 Syncrude Sample Tests

In order to get a feel for the quality of samples received from the Syncrude highwall it was decided to initially choose the best two tubes and perform density measurements, oil, water and solid determinations and grain size analysis. If the densities were high enough indicating high quality samples, more tests would be run on the core. The 4 5/8 Christensen modified core of 63 mm diameter where expansion is more restricted was chosen over the standard Craelius core. Tubes 5 and 6 were chosen on the basis of having high recoveries, that is full liners. Tube 5 was cored at a depth of 21.34 to 22.86 m and tube 6 at 22.86 to 24.38 m (table 4.1). Tube 6 was chosen first. The tube was transferred from the cold room where it had been stored since its removal from the dry ice filled insulated box on its return from coring at Syncrude. The cold room temperature was -20°C. The PVC tube for core #6 was split on each side of a diameter along its length with a table saw (plate 5.1). The tube was placed back in the cold room, the PVC tube separated and two, 230 mm samples detached (plate 5.2). On splitting the tubes lengthwise, the core seemed to grow radially. The core in tube 5 at the bottom split as it stuck to the inside of the split PVC tube (plate 5.1) This suggests the need to place the PVC tube and core in dry ice before removing the core from the tube. The samples were carefully placed in plastic bags and then in a series of two paint tins welded together with a lid on top. This was done as common practise at the University of Alberta (Agar, 1984) and may not be necessary to prevent CO_2 diffusion. The can was covered with dry ice to cool the samples for lathing. The sample was placed in the lathe in the cold room and the outer diameter was lathed down to about 56 mm. Since the sample had been out of dry ice for about 50 minutes at this time it was placed back in the dry ice to cool off again for about 1/2 hour. Lathing was continued and the cold room table saw was used to cut off the radial ends making the sample length closer to 150 mm. Then the lathe was used to square off both ends of the sample. Densities were taken before and after lathing. The 150 mm sample was placed in a double bag and tagged. The two end pieces left over were also placed in a double bag and tagged. The bitumen gave off an odor when the diamond saw blade was used to cut the ends of the sample. This indicated excessive heat production. Bitumen staining was evident on the inside of the white PVC tube (plate 5.1). The end pieces were used to perform solvent extractions to determine the bitumen, water and solids content.

A similar procedure was followed for tube 5. Tube 5 was also weighed. A total of four densities were derived from four lathed samples. Densities were taken by measurement with a caliper and weighing. Densities based on lathed and unlathed samples were the same. However lathing was continued for completeness.

A Dean-Stark distillation apparatus was used to determine the oil, water and solids content of the four samples. The water in the sample is distilled and measured. Bitumen is extracted by refluxing with touluene. The total fluid mass is the difference between the original sample mass and the dried extracted sample mass. The water mass is measured directly. The bitumen mass is the fluid mass less the water mass. The solids mass is the weight of the dried extracted sample. The oil, water and solid contents are presented as percentages of the total mass.

Grain size analyses were performed with number 10, 20, 40, 60, 100, 200 and 325 sieves. The number 325 sieve was performed wet. The number 325 sieve while not a standard sieve size for geotechnical purposes is for the petroleum industry.

5.3 UTF Sample Tests

To evaluate the performance of the modified 4 5/8's Christensen and the modified SK6L Craelius core barrels a comparative core testing program was envisoned. Four different diameters of core were taken: 63 mm, 69 mm, 96 mm and 102 mm. The 69 mm and 102 mm core were standard. They were taken with off-the-shelf core barrels. The 63 mm and 96 mm cores were taken with the modified core barrels with extra thick liners, glued in top retainers and PVC split rings built right into the liner (except for AT7, see field notes section 4.3.2). Two tubes of each core diameter were taken for testing, one tube from about 142 m below the ground elevation and one tube from about 151 m. The tubes chosen had high recoveries. The 142 m depth tubes were to examine the core barrels' relative performance in lean oil sand where it was expected the gas content and subsequent gas expansion would be less than in the lower interval. At the 151 m depth the core would be higher grade oil sand with less fines. Thus eight tubes from four wells were chosen to evaluate the four core sizes in lean and rich oil sand intervals.

After each core was taken at the UTF, it was immediately placed in insulated boxes with dry ice. Then the core was stored in a freezer truck at -20^0C until the phase A coring was complete. The freezer truck transported the core to the cold room of Core Laboratories in Edmonton. Most of the core was then transported in insulated boxes with out dry ice to the Alberta Research Council Clover Bar Laboratories in midwinter. There the core was x-rayed with single beam attenuation. Core not x-rayed was slabbed, dried and photographed. By mistake the two tubes of the 69 mm core from hole AT6 were slabbed. This core was the representative of the 4 5/8's Christensen standard core barrel in lean and rich oil sand. Half of this core was kept frozen and tested regardless of the possible increased disturbance. The other slabbed half was dried and showed clearly lithological changes and aided in chosing samples. Plates 5.3 and 5.4 show the frozen slabbed core tubes, the lithology and the position of the samples.

The other three sets of tubes were x-rayed. Each tube was x-rayed on 250 mm centers. The x-ray point source bombards the tube and an image is produced on a film behind the core and source. This results in a similar triangles effect where the diameter of the image is larger than the object and distortion along the length increases away from the center of the point source. These effects are magnified in the large diameter tubes. X-ray imaging allows identification of lithology changes and fractures. Oil sand zones are light, while coal, shale and silt layers are dark. The smaller tubes provided better images than the larger tubes. An example of a shale lense is shown in plates 5.5 to 5.7. The shale lense is distinct on the x-ray image and in the unlathed and lathed samples.

Samples were chosen every 300 mm in constant lithology or more if fractures or lithological changes were evidenced. Samples were numbered by hole, tube and individual sample in a specific tube. For example sample AT6-7-1 is sample number 1 in tube 7 from hole AT6. The frequency of sampling the core was greater for the slabbed core of AT6 since this was the first core tested and a feel for data variation was required. This variation could be due to small geologic changes as well as variation inherent in the test procedures. Each core was cooled in a dry ice filled insulated box before machining. The slabbed AT6 core was cut radially according to sample designation and lathed to a diameter of 26 mm. Densities were calculated from caliper measurement and weights. End pieces left over from lathing were used for oil, water and solids determinations and sieve analysis (plate 5.8). The core from AT3, of 63 mm diameter, AGI1 of 102 mm diameter and AT7 of 96 mm diameter were lathed to cylindrical shapes of 55 mm, 89 mm, and 89 mm respectively. Sample lengths were about 150 mm before lathing and 110 mm after lathing and facing off of the ends. A diamond tipped blade on a radial saw was used to cut the samples radially while still in the PVC tube. The lathe and radial saw were in the cold room. The tubes were then cut lengthwise on a table saw located adjacent to the cold room. The tubes were then removed (plate 5.9) and each sample lathed as required with a diamond tipped bit (plate 5.10). Each sample was worked on separately so that densities could be measured as soon as possible after sample handling had been completed. Pictures were taken of each lathed sample. Sample descriptions were recorded. Intervals not sampled were left in their PVC tubes and placed in two plastic bags and tagged. Lathed samples were also double bagged and tagged. The main difference between the handling of the UTF samples and the Syncrude samples was that the Syncrude core tubes were not placed in dry ice before tube removal and the UTF core was cut radially before tube removal to reduce the length of tube that was to be cut off at one time. This diminished the disturbance connected with the heat production of cutting the tube lengthwise. The placing of samples in tins while in the dry ice for cooling before lathing was not done. This procedure was originally started due to concerns about carbon dioxide diffusion into the core. This however has not been proven.

A significant observation was made during sample preparation. The core in the low, 1.3 mm clearance modified liners of the Craelius and Christensen core barrels fit snugly in the liner as shown in plate 5.11. The UTF core taken with the standard Craelius with its respectable small clearance of 3.5 mm was loose in the liner. This shows that the gas concentrations were small.

Some insight into sample disturbance preparation can be had by examining the individual case of sample AT3-19-4. This core was handled like any other sample with one exception. After removing the core from the liner section and again during and after lathing, the core was carefully examined and photographed. The interesting feature of this sample was the shale band which had been so visible on the x-ray image. (plates 5.5 to 5.7). Taking pictures required bathing the sample in the hot rays of an incandescent light. This and the extra time for observation caused sample AT3-19-4 to become very disturbed. The first density measured on the just lathed sample was 1.77 g/cm^3. This was obviously low and was rechecked immediately whereupon it was further reduced to 1.71 g/cm^3. The lathed diameter had also become uneven. The sample was immersed in dry ice for four hours and its density measured again. This time it was 1.69 g/cm^3. The time dependent disturbance was heat induced from the lathe and light.

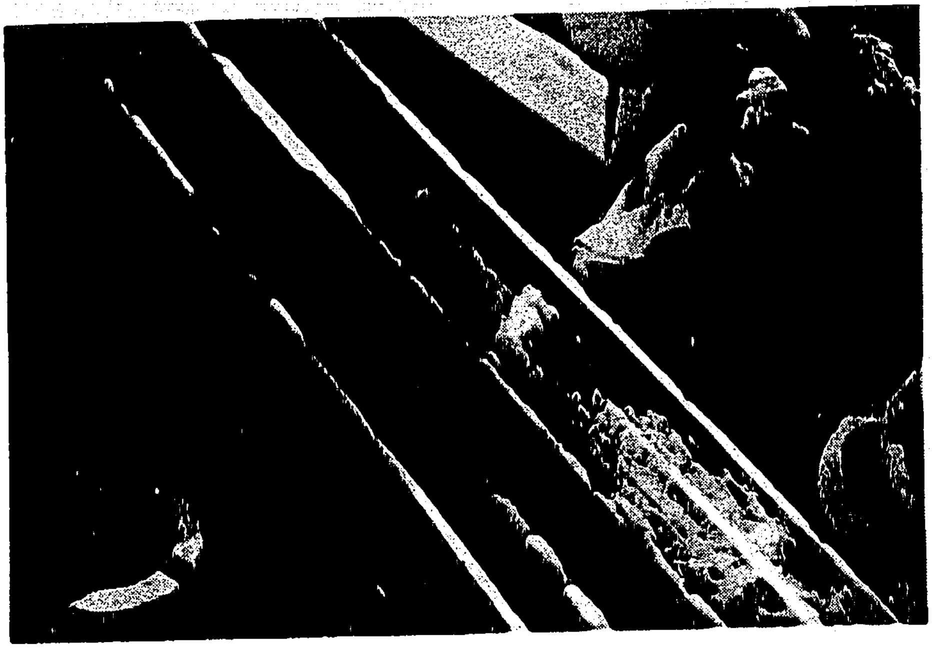


Plate 5.1 Syncrude 4 5/8 Christensen modified core removal from liner

Plate 5.2 Syncrude unlathed core sample in cold room

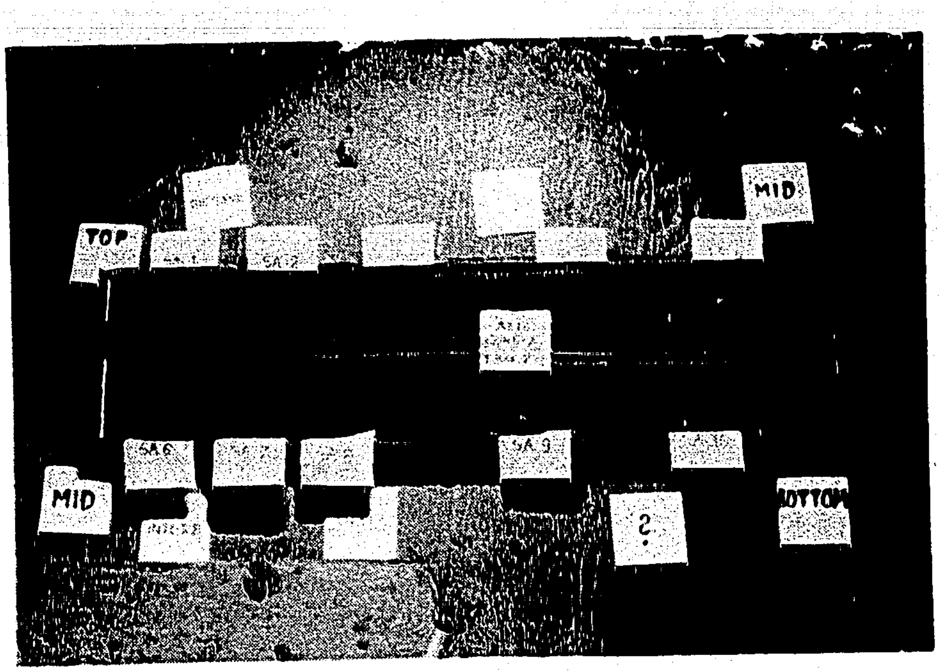


Plate 5.3 AT6 slabbed core lithology and sample locations, core 7

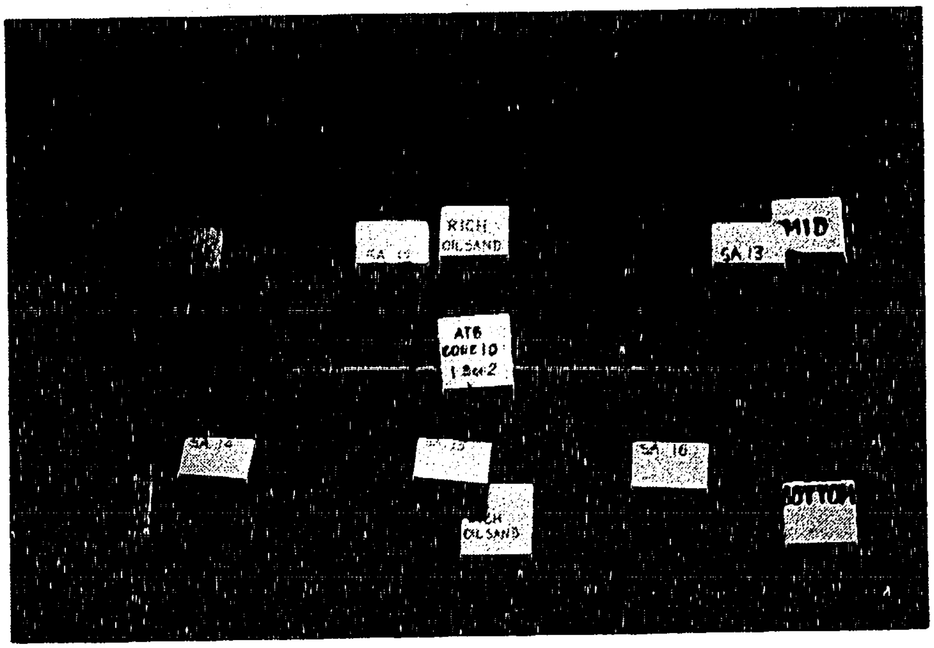


Plate 5.4 AT6 slabbed core lithology and sample locations, core 10

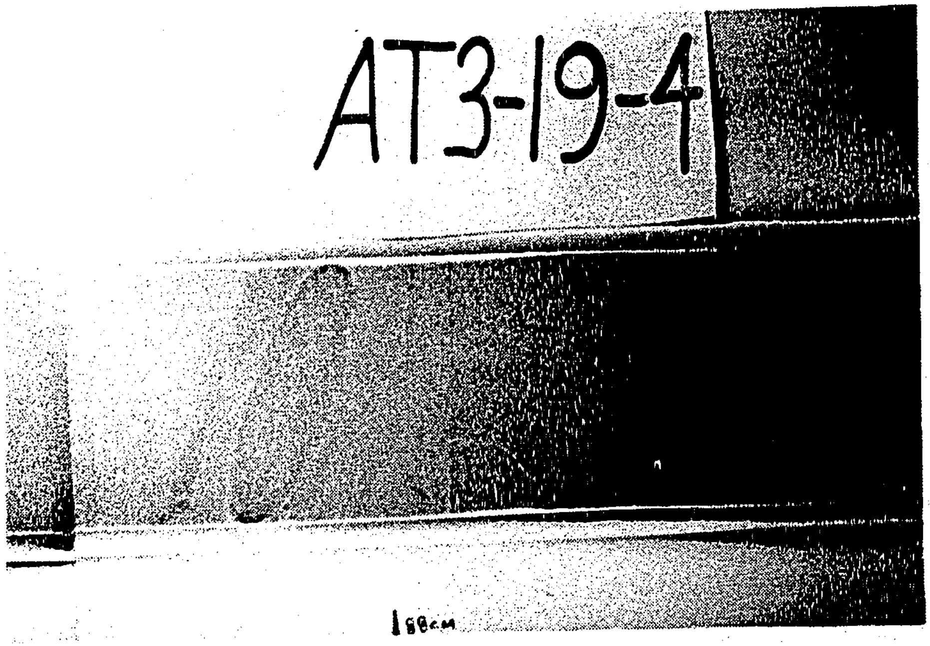


Plate 5.5 Core sample AT3-19-4 x-ray image

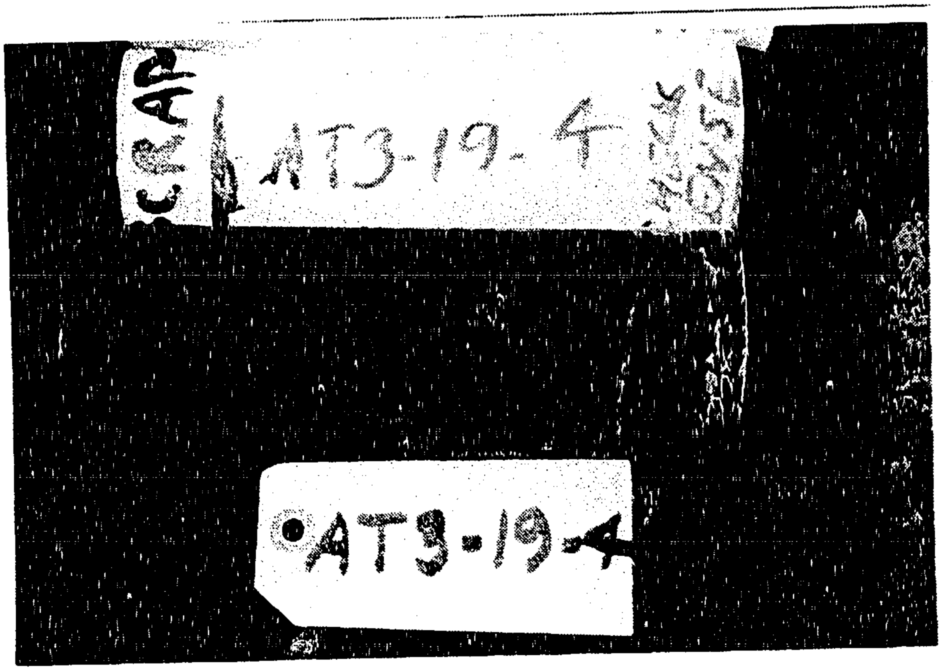


Plate 5.6 Core sample AT3-19-4 unlathed

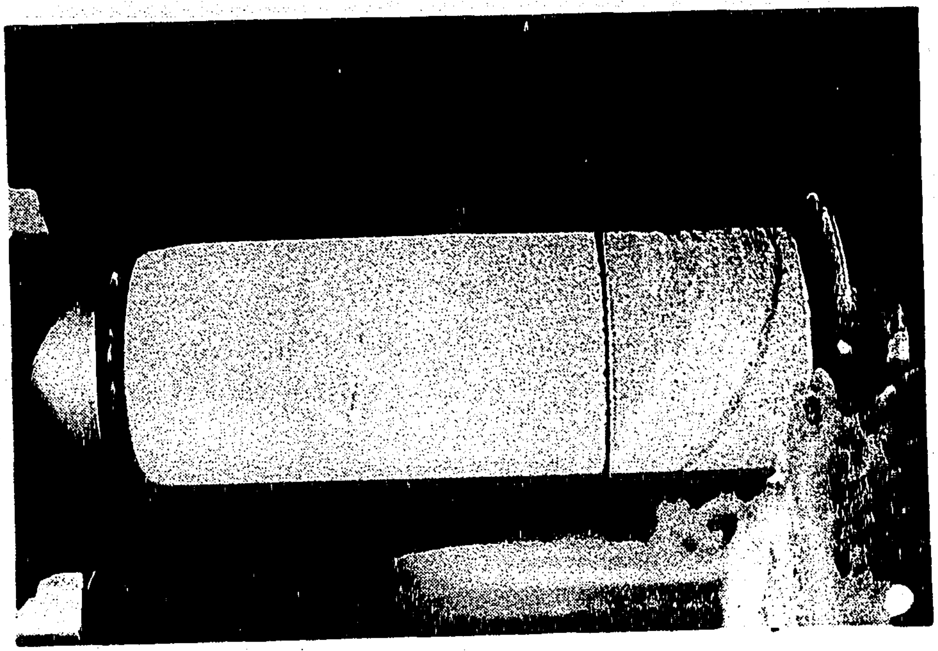


Plate 5.7 Core sample AT3-19-4 lathed

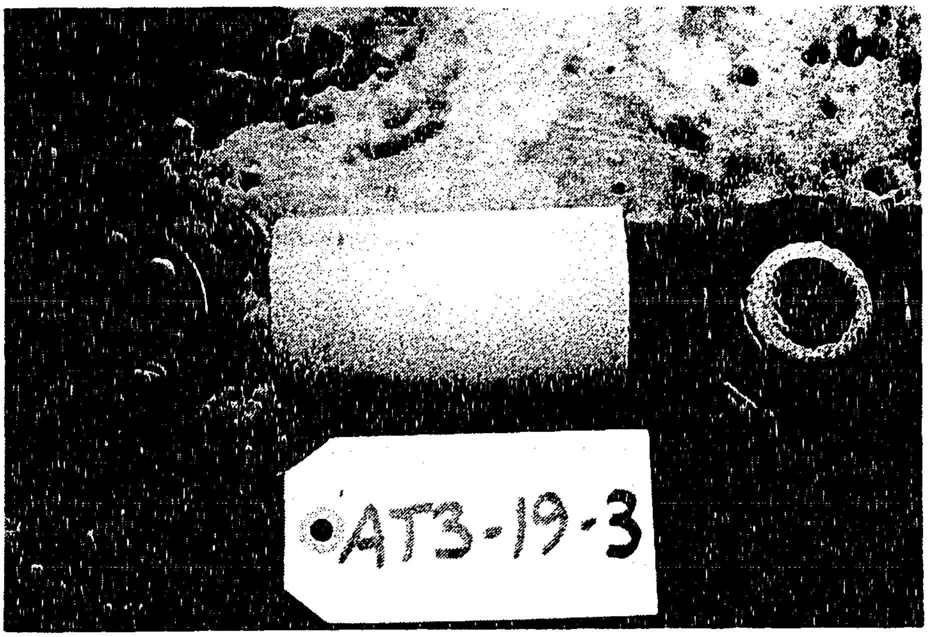


Plate 5.8 Lathed core sample AT3-19-3 and end pieces

Plate 5.9 Core sample AT7-9-4 cut radially then tube removed by two longitudinal table saw cuts

Plate 5.10 Lathing a core sample

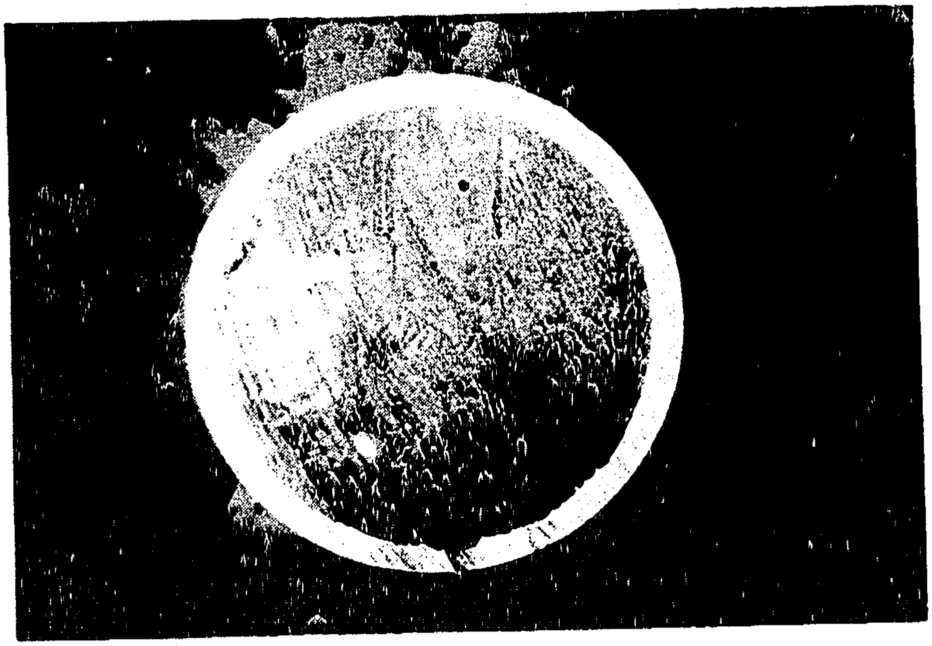


Plate 5.11 Cross-section through Craelius SK6L modified liner showing snug fit

6. Discussion and Conclusions of Test Results

6.1 Introduction

This chapter illustrates the use of the test results to quantitatively evaluate sample disturbance. The test data is also inspected to allow observations on the variability of the samples.

The Syncrude and UTF data is analysed to evaluate the sample quality and the samplers' performance.

The core-log discrepancy is demonstrated with a previous researcher's (Branco, 1988) data and data from this work. The estimation of in situ oil sands densities from core results and logs is discussed and recommendations are given.

6.2 Quantitative Evaluation of Sample Disturbance

The raw data from measurements and tests on the core include:

1. density
2. bitumen, water and solid contents by mass
3. gradation of the soil particles
4. in tube core weights and lengths.

A difference in porosity between two samples could be natural and not due to sample disturbance, thus lithology is an influence on the data. Lithology as used here refers to the composition and texture of the soil (Whitten and Brooks, 1985). Gradation expresses the varying lithology with rich oil sands containing less fines than lean oil sand, interbedded oil sand and shale.

Bitumen, water and solid contents by mass from solvent extraction in a Dean Stark apparatus are related. They all add to 100% and the densities of the fluid phases; water and bitumen are taken to be equal and constant. The density of the solid phase is taken to be constant also. The bitumen content is important for relating the richness of the core. However in all cases, of the UTF and Syncrude samples under consideration, by limiting the percentage of fines passing the #200 sieve to less than 25% the samples will be restricted to rich oil sand of greater than 10% bitumen content. (Except for the marginal case of 9.1% of sample AT3-13-1.) This is illustrated in figure 6.6. Thus only the percentage fines passing the #200 sieve and the solids content need be considered as a result from the extraction process in attempting correlations. In fact the solvent extraction process provides a very accurate total fluid and solid content but may overestimate the bitumen content and underestimate the water content (Eade, 1975).

The density of the sample from measurements on a lathed cylindrical core is a measure of the weight divided by the volume. The weight includes that of the fluid and solid phases while the volume also includes the gas phase. From the density, solid content and percentage passing the #200 sieve the samples can be defined sufficiently lithologically and descriptively, to allow calculation of porosity, no gas porosity, no gas density, and I_{DD}. The back calculated no gas porosity and density assumes the gas content in the samples to be zero (see figure 6.1). The basic relationships are as follows:

$$n = 1 - \frac{\rho\ S}{\rho_s} \qquad (6.1)$$

$$n_{ng} = \frac{1}{1 + (S\ \rho_f)/(\rho_s(1-S))} \qquad (6.2)$$

$$\rho_{ng} = \frac{1}{(1-S)/\rho_f + S/\rho_s} \qquad (6.3)$$

$$I_{DD} = (\rho_{ng}-\rho)/\rho_{ng} = 1 - \rho\ (S/\rho_s + (1-S)/\rho_f) \qquad (6.4)$$

where ρ = density of sample

S = solid content by mass

ρ_s = density of solid portion of oil sand

ρ_f = density of fluid portion of oil sand

n = porosity = ratio of the volume of voids to the total volume of the sample

n_{ng} = no gas porosity calculated assuming the volume of gas in the void spaces is zero = ratio of the volume of fluid to the volume of solid and fluid

ρ_{ng} = no gas density calculated assuming the volume of gas in the void spaces is zero (Dusseault and Scott, 1984)

The liner weights are used to determine the average maximum and minimum core liner densities. The average maximum liner density assumes the core remains at the diameter it was cut. The minimum average liner density assumes that the core diameter has increased to that of the inner diameter of the liner. This puts limits on the average density of the core in the liners. It should be noted when comparing maximum and minimum average liner densities with measured sample densities what the lithological variation is within the tube. A shale sample in a tube predominantly of oil sand may have a density greatly exceeding the average maximum liner density. For the core examined at the UTF the lithological change was small except perhaps for the heavier shale and interbedded zones found in samples AT6-7-7 and AT6-7-8. Since the AT6 core was slabbed and not weighed in the liner the average maximum and minimum liner densities could not be calculated. Maximum and minimum liner densities are affected by extrusion along the length of a core tube. Longitudinal extrusion lowers the values of the liner densities. A 50 mm extrusion in a 1.5 m long tube reduces the average tube density by 3%. Loose slough in the top of a liner should be removed before measuring and weighing the core in the liner as the slough may not impede the end of a tape measure and can add extra weight giving unrealistically high liner densities. Loose slough is not a problem when proper coring procedures are followed.

I_{DD} is the recommended indicator of disturbance. I_{DD} is the difference between the no gas density and the sample density divided by the no gas density. Since the components of the fluid phase are assumed to have the same density, only the solid content, and the measured density of the sample are required to define the quality of an Athabasca oil sand sample.

The density of the fluid phase was chosen as 1.01 g/cm^3 after Dusseault and van Domselaar (1982). Tests on bitumen from the UTF have shown the bitumen density to be 1.00 g/cm^3 (AOSTRA, ARC, 1988). Using 1.01 g/cm^3 as the bitumen density is conservative when quantifying disturbance and, in actuality, not significant to 0.01 g/cm^3 for density calculations. The density chosen for the water phase in rich oil sand affects disturbance calculations even less since water contents conservatively range from 1 to 3%.

A value of 2.66 g/cm^3 was chosen as the mean density of the solid portion of the oil sand. Quartz composes the sand size grains of the oil sand. Quartz has a density of 2.654 g/cm^3 (Schlumberger, 1987). Other mineralogical components of oil sand are minute quantities of feldspar, and a clay fraction of varying size. The clay fraction in the Athabasca area is 60% illite and 40% kaolinite (Dusseault, Soderberg and Stern, 1984) with specific gravities of 2.8 and 2.6 respectively. This yields a mean specific gravity of 2.72 in the clay fraction. Since the minor fractions of the oil sand solid components have a greater density than the dominant quartz fraction the specific gravity of the solid portion was chosen to be the quartz specific gravity rounded up to 2.66. It was assumed that all silt and clay sizes (passing the #200 sieve) have a specific gravity of 2.72. If 25% of the solid mass of an oil sand sample passes the #200 sieve, a calculation based on a fully saturated sample with an 84% solid content accounting for the heavier fines portion yields a density of 2.12 g/cm^3. That same calculation done assuming the solid portion has a mean specific gravity of 2.66 yields a saturated density of 2.11 g/cm^3. If the clay component even reached 50% of the solid mass the true density would still only be 2.13 g/cm^3. Thus the assumption of a constant specific gravity of the solid portion of 2.66 is valid and not sensitive to the variation normally found in any Athabasca oil sand.

Dusseault and van Domselaar (1982) use I_D to quantify sample disturbance. I_D is based on porosity and is the difference between the sample porosity and in situ porosity divided by the in situ porosity (equation 2.1). The petroleum industry prefers to think in terms of porosities because of its relationship to permeability and gross pay in a reservoir. I_D is really only a function of the measured sample density and the solid content of a sample. Figure 6.2 shows the relationship between I_D, I_{DD}, density and solid content. The in situ values of porosity and density were back calculated assuming the volume of gas was zero. This thesis uses I_{DD} to quantify disturbance. I_{DD} is simple and based directly on the concept of densities. I_{DD} values constitute a family of straight lines on a density solid content plot. Conversely I_D values are a family of curves and at higher solids content show greater slopes on the density solids plot. Figure 6.2 can be used to convert I_{DD}

values to I_D values if desired. I_{DD} provides a direct meaning; a 5% value means a 95% maintenance of the samples no gas density.

6.3 Syncrude Test Results

The core in tubes 5 and 6 from Syncrude was a homogeneous very rich oil sand with few fines. A geologically interpreted log of nearby borehole 16-14-2-1 evaluates the sedimentary facies of tubes 5 and 6 as Syncrude's code number 11. These Middle McMurray sediments were deposited in a subtidal estuarine environment. The facies is a channel complex. The lithological and sedimentary structure of code #11 is described as follows:

> "Moderately to well-sorted, medium to fine grained sands. Commonly occur as homogeneous thick sand beds. May have planar to high angle cross beds and local clay drapes." (Cuddy and Walid, 1987)

As shown in table 6.1, the bitumen contents were all greater than 14% by mass. On average only 4% by mass of the samples were passed through the #200 sieve. The samples were gaseous as evidenced by visible surface extrusion, gas bubbling out of the borehole and their propensity for disturbance. The densities measured were low, on average 1.74 g/cm^3. The average no gas density assuming complete saturation was 2.05 g/cm^3. This difference can be attributed to various forms of disturbance:

1. Recent in situ stress relief and pore pressure reduction

occurred due to removal of the overburden by man. Syncrude had removed 17 m of overburden from the highwall surface and cut a deep slope about 50 m away. The back calculated no gas density was on average 2.05 g/cm^3. Since this is the density at which the core would be saturated and it is higher than the average maximum liner density it shows the extent of precoring disturbance due to removal of the overburden. Peacock (1988) provides further evidence of the existence of free gas in situ in rich oil sand at Syncrude's highwall under similar conditions where 17 m of overburden had been removed earlier. The gas saturation pressure corresponded to the premining piezometric pressures and not to the existing lower piezometric pressures.

2. Poor coring practice exemplified by not setting the lead distance on the core barrel and properly conditioning the mud. The improper lead distance affects the drilling fluid's ability to clean the bit.
3. Improper sample handling and sample preparation disturbance. Based on the weight of tube 5, the inner diameter of the liner and the net core length, the average minimum density of the homogeneous core in tube 5 was 1.92 g/cm^3. Sample preparation disturbance was mainly due to not lowering the temperature of the core sufficiently while removing the PVC liner from the core. A lower temperature increases the gas content dissolved in the fluid phase and adds tensile strength to reduce

volume increase. Even at -20^{0}C methane gas in oil sand cores can be readily expandable and undissolved (Tan, 1988) with a bubble point pressure greater than the atmospheric pressure. The tubes should have been placed in dry ice before liner removal and cut radially in smaller sections. This would reduce cutting, and handling time and allow a more accurate cut of the tube preventing the blade of the table saw from penetrating the core itself. Plate 5.1 shows core breaking down its length on middle tube removal due to deficient cooling.

4. Sampling pore pressure relief drove gas out of the fluid phase of the oil sand core causing volumetric expansion. If the diameter of the core remained at 63 mm as it was cut then the densities would have been about 2.00 g/cm^3.

Figure 6.3 shows the changes in core density as the core is brought out of the hole and the middle tube removed. A prerequisite for these various forms of volumetric increase is a high gas content and a very dense or locked structure. The presence of free gas in situ due to overburden removal reduces the time for bubble formation and increases the susceptibility of a sample to disturbance even though the core temperature is lowered quickly (Peacock, 1988). The extent to which the shear induced volumetric increase on coring contributed to the low densities is difficult to separate from the gas induced disturbance and may account for part of the drop in density from 2.05 to 2.00 g/cm^3 shown in figure 6.3.

From tube and core weights, and core lengths in liners, the average maximum and minumum liner densities were calculated for the July 30, 1987 Syncrude core. These are shown in table 6.2. The values show that the densities of the core as cut, the average maximum liner density for the modified Christensen and larger standard Craelius barrels were both about 1.87 g/cm^3. This value is reduced to about 1.81 g/cm^3 in the liner of the modified Christensen core barrel and further reduced to 1.75 g/cm^3 on average in the standard Craelius core after expansion to fill the liner. However, a Student's t test at a 0.01 level of significance indicates that there is no difference between the modified Christensen core and the standard Craelius core based on the average maximum or minimum liner densities for the Syncrude samples (table 6.2).

6.4 UTF Sample Results

6.4.1 UTF Index Tests Results and Relationships

As described in Chapter 4 on field work eight core tubes were taken from the UTF Phase A coring program. The tubes represent four different triple tube core barrels used in an interbedded oil sand zone and a more homogeneous rich oil sand zone. Fifty samples were prepared, measured, weighed, extracted and sieved. The results are shown in table 6.3.

Figure 6.4 is a plot of depth versus percentage fines passing the #200 sieve. The interval 141 m to 145 m is part of stratigraphic unit D (Rottenfusser, Palfreyman and Alwast, 1988), and has more fines, or shale interbedding than the lower unit E. Unit D also has zones of low fines. The 150.0 to 153.0 m interval is part of unit E and has little fines.

Figure 6.5 shows the bitumen content as a function of depth. There is rich oil sand (greater than 10% bitumen) in both units D and E. The unit D tubes also contain some lean zones while the unit E tubes are exclusively rich.

Figure 6.6 shows the relationship between bitumen content and fines. The larger the percentage of silts and clays in an oil sand sample, the lower the bitumen content.

Mossop (1980) stated that in the McMurray Formation zones of clean sands were high grade pay zones. Interbedded zones with argillaceous sands and shales were leaner. The data from the UTF samples generally concurs. Units D and E are informally separated. They are quite similar in many ways particularly that rich oil sand is found in both units. Greater vertical and horizontal separation is required to verify absolutely generalizations such as made by Mossop (1980). The samples from unit E are homogeneous rich oil sand. There are rich oil sand samples in the unit D as well as argillaceous sands and shales.

It is helpful to distinguish between rich oil sand and more argillaceous samples. All samples in the UTF plots that are not rich oil sand and have either a bitumen content less than 10% or greater than 25% fines are marked with an X. Samples marked as not being rich oil sand on the plots were from unit D. Most of these samples were from AT6 where out of a 1.5 m long core only 15 cm of rich oil sand was found. For wells AT3, AGI1 and AT7 only two samples were not rich oil sand. AT3-13-1 had a bitumen content of 9.1% making it a medium oil sand. AT7-2-2 was almost a rich oil sand (9.6% bitumen) but had a high fines content of 33%.

Solid content as a function of depth is related by figure 6.7. A little less solid content is found in the rich oil sand of unit E than the rich oil sand of unit D reflecting the higher grade oil sand in the lower interval. This is explicitly shown in figure 6.5 where bitumen content is plotted against depth. The upper interval has an average rich oil sand only bitumen content of 13.8%, while the lower interval sampled has an average bitumen content of 14.6%. Figure 6.8 is a plot of solid content versus fines. It is the consensus that higher solids contents in oil sand samples correlate with higher fines contents. Figure 6.8 partially supports this but also shows that within a range of 0.81 to 0.86 solid content there is no relationship between solid content and fines.

6.4.2 Sample Quality and Sampler Performance Evaluation

Plots were made of the UTF data from table 6.3 to show some relationships and aid in the drawing of conclusions.

Figure 6.9 is a plot of density versus bitumen content and shows that there is no overall relationship. The two highest density values were shale samples AT6-7-7 and AT6-7-8. The bitumen range in the rich oil sand with little fines samples is narrow from 11.9% to 15.7%. The density shown is affected by all forms of disturbance. The lowest point of 1.77 g/cm^3 had extensive handling disturbance as described earlier and the next lowest rich oil sand point of 1.85 had a fracture the length of the sample which may have been caused by slabbing.

There is a general decrease in rich oil sand sample density with depth. Figure 6.10 show this. The average density in the upper interval of rich oil sand is 1.99 g/cm^3 and in the lower interval of rich oil sand 1.96 g/cm^3. The averages do not include samples with less than 10% bitumen or greater than 25% fines. This difference is small and overshadowed by the disturbance incurred during sample handling.

Further evidence of the high quality samples is shown in figure 6.11. The density values for the samples are related to the average minimum and maximum liner sample densities. The Craelius samples show densities slightly larger than their average maximum liner density. There was little gas expansion or other handling and preparation disturbance. Fractures which are not accounted for in the calculations, measurement inaccuracies and localized high densities explain the deviation of any density value above the average maximum liner density line. The modified Christensen samples also show little or no gas expansion with others affected by sample handling and preparation disturbance, particularly the 1.77 g/cm^3 value. The average maximum and minimum liner densities can provide an indication of sample quality without removing the sample from the tube. For the four different forms of the basic triple tube core barrel the difference in the average rich oil sand density is 0.01 g/cm^3 and is certainly within the accuracy of measurement. There appears to be a slight trend to better samples with the modified form of each core barrel size but absolute sample densities alone are not sufficient enough to describe the quality of a rich oil sand sample.

Density versus no gas density for the UTF samples is shown in figure 6.12. If the density measured reflected a gasless void space then the two values would be equal. It is not always correct to assume that in situ oil sand has 100% fluid saturation. This is evident in the Syncrude highwall samples due to their shallow depths and overburden removal. The UTF samples at depths of 140 m were saturated in situ as expected (Dusseault and Scott, 1984). Thus the in situ density is equatable with the no gas density. This is reinforced by samples from the UTF that had little or no gas present in the void space.

Plate 6.1 shows gaseous disturbance in slabbed core from AT6 at room temperature. Note the distorted slabbed surface. Although not done in this thesis, a quantification of gas volume in the samples would provide valuable information in assessing sample quality and disturbance potential. The differences from the 45^0 line in figure 6.12 reflect preparation disturbance, slabbing disturbance as in the case of AT6 core and coring disturbance. It is apparent that due to the low gas content of the oil sand, all the types of core were of high quality. High quality is relative to rich oil sand samples taken with standard coring methods which give densities as low as 1.75 g/cm^3. Figure 6.13 expounds on the two density forms showing density and no gas density for each sample. The amount of sample preparation disturbance is manifest in any increase from the 'high average' of the difference in these densities. This also demonstrates the need for a parameter such as I_{DD} to give a relative nondimensional disturbance value to remove the effects of varying solid content. I_{DD} relates the difference in the no gas density to the measured density nondimensionalized by dividing by the no gas density. I_{DD} is not necessarily a measure of only coring, sample handling and sample preparation disturbance, unless it can be assumed 100% fluid saturation in situ. Densities from geophysical logs should not be used for I_{DD} calculations. Reasoning for this will follow in section 6.6.3.

Figure 6.14 quantifies the density differences by the I_{DD} function versus the borehole number. This particular plot is masked by preparation disturbance which hides the small effects of gas expansion particular to the UTF core.

There was not enough gas dissolved in the fluid phases of the oil sand to really test the modified core barrels and compare their success against their standard sires. The low I_{DD} values attained can be used as a mark to attempt to reach in latter coring operations in more gaseous rich oil sand. Higher fines contents in oil sand samples does not significantly effect the evaluation of disturbance by I_{DD}. The no gas density is calculated with a mean soil specific gravity of 2.66. The fines components are heavier but section 6.2 shows that this is inconsequential for oil sand samples. There are two shale samples in the population, their true no gas densities are about 0.04 g/cm^3 higher than the no gas values used to calculate I_{DD}. Thus their real I_{DD} values are about 1.6% higher then has been recorded in table 6.3. The bitumen contents of the shales may be incorrect due to the nature of the oil, water and solid determination where any water not trapped and measured is assumed to be bitumen. This however does not affect I_{DD}.

The most important plot for showing sample disturbance is figure 6.15. Figure 6.15 relates density and solid content for the UTF samples. Levels of disturbance quantified by I_{DD} are shown. The no gas density line (I_{DD} = 0) represents no disturbance, precoring or otherwise. The no gas density line is only a function of solid content if the fluid densities and solid densities are constant throughout the range of solid content values. Figure 6.15 also shows the inaccuracies involved when a cut off density value is used to determine whether a sample is disturbed or undisturbed. A density of 2.0 g/cm^3 for a rich oil sand sample having a solid content of 0.80 is completely undisturbed. If the sample had a solid content of 0.86 and a measured density of 2.0 g/cm^3 it would be quite disturbed and have an I_{DD} of 7.6% corresponding to a 7.6% reduction in its no gas density value. Figure 6.15 incorporates the two main input values; sample density and solids content. It instantly shows sample quality in relation to the no gas density for each particular solids content.

The average I_{DD} values for the samples from each of the four barrel types are within approximately 1% of each other. This is true when considering all the samples or just the rich oil sand samples. The averages are shown in table 6.3. This is within the limits of accuracy of I_{DD} which is affected by the accuracy of density determinations and that of the solids determinations. Ruling out sample water imbibition (see section 2.6.1), the determination of solid content is most affected by getting a representative sample for the solvent extraction. If a channel sample of the entire length of sample in which the density is taken is used, the solids content will also be very accurate. Disturbance from the no gas densities averaged about 5% with several samples approaching 0%. Since the gas expansion potential was low and sample handling and sample preparation disturbance significant, a conclusive evaluation based on the UTF data would be dubious. A Student's t test at a 0.01

level of significance on the I_{DD} values from the UTF coring results (table 6.3) indicates that there is no difference between the samples taken by the standard and modified core barrels at the UTF. In general all coring and sample handling methods employed at the UTF Phase A coring resulted in high quality rich oil sand samples.

6.5 Branco's Syncrude Data

Table 6.4 summarizes data from core samples taken from Syncrude's mining bench in the Athabasca oil sands deposit (Branco, 1988). The author was not involved in this sampling expedition or the subsequent sample handling. A Pitcher core barrel and a Christensen double tube core barrel were the two different samplers used. Most of the samples were poorly graded fine sand with bitumen contents exceeding 10% (rich oil sand). Sample 8-2b was the only medium oil sand. Samples 3-1 and 8-2 were a poorly graded silty or clayey fine sand.

Branco's samples correspond to code #11 on the Syncrude Sedimentary Facies Chart (Cuddy and Walid, 1987). That is the same facies, lithological and sedimentary structure as described in the earlier section of Syncrude samples in this chapter. The presence of gas was evidenced by observations of up to 150 mm of extrusion out of the Pitcher core barrel although this may have just been core hanging out. Gas bubbles were noticed in the drilling mud. The Pitcher core barrel had a steel middle tube of a constant 73 mm inner diameter and a length of 830 mm. The lip of the steel tubes were sharpened. After coring, the middle tube and core were removed and the ends of the tube cut as necessary to eliminate any open tube space caused by incomplete recovery. A plastic cap was placed on their ends. Each tube was then placed in dry ice. The Christensen core barrel was only a double tube and had no liner. The Christensen core barrel had an inner tube inner diameter of 155.6 mm and a length of 3.0 m. The core from samples 26 to 28 was removed from a split inner tube and placed on chilled trays, wrapped in plastic, taped and stored in dry ice. The average densities of the samples from each core barrel were the same and equal to 1.93 g/cm^3. Figure 6.16 is a plot of percentage solid by mass versus density. The samples all had I_{DD} values greater then 5% and on average 8%. Put another way, the densities all dropped lower then 95% of the no gas value. On average only 92% of the undisturbed, no gas density remained following precoring, coring, sample handling and sample preparation disturbance. The Christensen core barrel samples had on average an I_{DD} value of 6.9% which is lower then the Pitcher barrel samples I_{DD} average of 8.7%. The small number of Christensen samples accounts for its apparent lower I_{DD} values over the Pitcher barrel sampler. A statistical analysis using the Student's t distribution at a 0.01 level of significance indicates that statistically neither the Pitcher barrel or the Christensen core barrel used by Branco at Syncrude obtained less disturbed samples. The Pitcher barrel samples were not better then the Christensen samples as expected.

6.6 Core-Log Discrepancy

6.6.1 Branco's Syncrude Core-Log Density Comparison

Densities from geophysical logs do not agree accurately enough with the back calculated no gas densities for use in an evaluation of sample quality. This is illustrated for Branco's Syncrude samples in figure 6.17. Figure 6.17 shows that the log densities chosen show no correlation with and are in general higher then the back calculated no gas densities from the samples. As shown on figure 6.16 along the $I_{DD}=0$ no gas line, the range of maximum sample density is 2.0 to 2.15 g/cm^3. Figure 6.18 is the geophysical log of a nearby borehole made before removal of 16 m of overburden. The log sample density range is 2.05 to 2.20 g/cm^3 (table 6.4). The low no gas density range does not agree with the log sample density range. This was previously shown by many authors including Eade (1975), Woodhouse (1976), Zwicky and Eade (1977), Britton (1984), and Dusseault and Scott (1984). Based on the solids content of the samples and assumed fluid and solids specific densities the no gas sample densities are the maximum possible values of the in situ densities. Evidence of in situ unsaturation due to overburden removal (Peacock, 1988), which also occurred for the Branco Syncrude samples, can only mean that the no gas densities are if anything higher then the in situ sample densities.

6.6.2 Underground Test Facility Core-Log Density Comparison

Geophysical density logs from the AOSTRA Underground Test Facility coring program holes AGI1, AT7, AT3 and AT6 are shown in appendices C.1 to C.4. Hole AT6 was the only hole whose core was completely geologically logged to allow a correction to the drillers depth. For AT6 at the intervals where the two 1.5 m cores were used for testing, a depth correction of up to 0.4 m was necessary. For holes AT3, AGI1 and AT7 no depth correction was possible with only the two core tubes tested from each hole since there were no identifiable marker beds such as a shale zone. This illustrates the problem that can exist when correlating core and log depths.

Table 6.5 summarizes the core-log density comparison. The core density is the back calculated, no gas value. Back calculated no gas density values of the Underground Test Facility oil sand core are significantly lower then the corresponding geophysical density log values. The core density values were only greater then the log values when large quantities of shale were present.

6.6.3 Density Values from Cores or Logs for Sample Disturbance Evaluation

Sample disturbance evaluation depends on accurately knowing the in situ value of density for a specific sample. In situ sample densities and their variation among samples is more accurately reflected from core data then from density logs.

Fluid phase expandability (with pressure or temperature), fabric dilation, and variations in solid and fluid densities can not explain the differences in geophysical log densities and the back calculated densities. Also the large volumes considered in the geophysical log densities, and the difficulties in choosing representative densities from the density logs themselves make the comparison of geophysical log densities to sample densities similar to comparing apples and oranges. Water imbibition does not occur in gaseous soils (Hvorslev, 1949) and is not the cause of the lower back calculated densities in oil sand cores when compared to the geophysical log densities. If water imbibition did occur then core-log density differences could be readily explained.

The University of Alberta solvent extraction results of water contents on oil sand samples are less than accurate and on the low side. The water content is determined from the volume of water condensed in a graduated cylinder. Water left on the sides of the glassware or otherwise lost adds to the bitumen content since the bitumen content is calculated from the weight of sample before and after fluids removal less the water measured. Total fluid contents (water and bitumen) are accurate and refer to the fluids in a sample, but is there a change in the fluid/solid ratio of an oil sand sample from its in situ condition? Is this change due to water imbibition? A possible mechanism for water imbibition could be as follows. Less then hydrostatic in situ pore pressure conditions which normally occur in Athabasca oil sands combined with hydrostatic borehole water levels to result in drilling fluid invasion of the uncored sample. However drilling fluid invasion is easily checked for and insignificant or nonexistant in the Athabasca oil sands. The low permeability of the fluid phase prevents this. Immediately after coring while the sample is being brought to the surface gas evolution elevates the pore pressure in the core fluid phase further preventing drilling fluid invasion. This pore fluid pressure maintenance is exhibited at the surface by bubbles and core extrusion. Imbibition of water during the sample handling phase is also unlikely. All University of Alberta samples are frozen when the sample densities are measured. The UTF samples investigated here were thawed by the heat of the solvent extraction. There was no water source at this point for imbibition to occur. Further, sample tube weights taken immediately after sampling and just before lathing were exactly the same showing neither water loss or gain in the the interim.

Imbibition is more likely to occur in the interbedded shales (Hvorslev, 1949). After sampling, clays or clay shales, maintain a negative pore pressure in response to the total stress change. The clays are cohesive with little porosity change since the effective stress is maintained by developing the negative pore pressure. This negative pore pressure commonly provides a gradient for fluid flow resulting in water imbibition under normal circumstances. However the low permeabiltiy of the adjacent oil sand,the lack of prolonged exposure to drilling fluid, and enclosure by the sample liner restrict imbibition in the interbedded shales of oil sand deposits. (This may not be true if a water sand is present.) Table 6.5 provides affirmation of this by showing shale log density values slightly lower then the shale samples. This difference can be explained by the zone of influence of a density log being greater then thin shale interbeds. Density values of thicker clay zones are accurately reflected in density logs.

6.6.4 The Density Log

The density log is a depth versus density plot processed from the raw output of a density logging tool. The dual spaced density logging tool emits gamma rays into the formation as it is pulled up the borehole on a wireline. The gamma rays collide with electrons in the formation and lose energy. This is known as Compton scattering. Short-spaced and long-spaced detectors measure gamma rays returning to the tool from the formation. Using two detectors spaced differently from the source of gamma rays allows a correction for borehole rugosity and mudcake. The count rates from the tool are used to calculate the density of a formation. This is based on density being related to the electron density of a formation. The electron density index of a substance is related to the true bulk density by the following formula:

$$\rho_e = \rho\ 2\ \frac{\Sigma\ Z's}{\text{molecular weight}} \qquad (6.5)$$

where ρ_e = electron density index

ρ = actual bulk density

Z = atomic number of the elements

Equation 6.5 can be adjusted to account for multiphase soils such as oil sand by knowing the content of each phase.

Thus, the basic density tool response is affected by the density of the formation and the $2\ \frac{\Sigma\ Z's}{\text{molecular weight}}$. The entire conversion from long and short-spaced detector rates to the density given in the log usually accounts for higher $2\ \frac{\Sigma\ Z's}{\text{molecular weight}}$ values in low density formations (coal) and the lower $2\ \frac{\Sigma\ Z's}{\text{molecular weight}}$ values found in the higher density formations (such as shale and oil sand) (Schlumberger, 1987, Samworth, 1979). When a formation deviates significantly from its assumed $2\ \frac{\Sigma\ Z's}{\text{molecular weight}}$ value in its specific density range, then a correction is necessary to obtain the true density of the formation from the log. For oil sands, this deviation is not significant enough to cause the disparity shown between the no gas density values and the density log. Actually, based on Schlumberger's equations, the geophysical density log should be reading slightly lower for rich oil sand.

6.6.5 Core-Log Disturbance Evaluation

At present, either the log is incorrect or one or more of the assumptions used in back calculating the no gas density is wrong. Apart from the differences in the core-log density values over a range of depths lies the problem of matching a density log reading for a given sample. This includes depth correction and subjectivity in choosing the exact density value on low sloping portions of the density log. However, this subjectivity can be eliminated by applying statistical analysis to the discrete values of the geophysical density log as long as the core depths are accurate. Using geophysical density log data to determine the in situ density of samples leads to excessively high estimations of disturbance since the density log values are too high. Thus, the use of the density log for sample disturbance evaluation is unnecessary and overly pessimistic. In any case, when evaluating oil sand sample disturbance it should be noted as to the method of determining the in situ density as the log and no gas core densities are not in agreement. It is concluded that sample disturbance evaluation should be based on the sample no gas density from extraction results.

Table 6.1 Syncrude sample results

		Ave Max		Ave Min					Density	Porosity			Medium Sand		Fine Sand		Silt and Clay			
Sample	Depth	Liner	Density	Liner	Bitumen	Water	Solid	Porosity	(No Gas)	(No Gas)	ID	IDD	Sieve	Sieve	Sieve	Sieve	Sieve	Sieve	Core Dia	Description
Numbe	(m)	Density	(g/cc)	Density	(%)	(%)	(%)	(%)	(g/cc)	(%)	(%)	(%)	#20	#40	#60	#100	#200	#325	(mm)	Rich Oil Sand
S5-1	39.1	2.00	1.72	1.92	14.1	4.2	81.7	47	2.05	37	27	16	100	99.93	83.96	12.59	6.78	5.80	63	Rich Oil Sand
S5-2	39.1	2.00	1.79	1.92	15.4	2.8	81.8	45	2.05	37	22	13	99.98	99.95	66.52	6.32	3.01	2.48	63	Rich Oil Sand
S6-1	40.6	2.00	1.73	1.92	15	3.6	81.5	47	2.04	38	25	15	98.56	92.61	61.88	7.20	3.21	2.58	63	Rich Oil Sand
S6-2	40.6	2.00	1.71	1.92	14.6	2.8	82.6	47	2.07	36	31	17	99.06	96.09	55.34	6.80	3.03	2.60	63	Rich Oil Sand
Christensen Modified Core Barrel																				
Reasons for low densities:			-improper lead distance																	
			-liners not placed in dry ice																	
			-high gas expansion potential																	

Table 6.2 Syncrude core average maximum and minimum liner densities and I_{Dr} range

Tube #	Core Dia (cm)	Ave Max Liner Density (g/cc)	Ave Min Liner Density (g/cc)	Tube IDD Range (%)
1	6.31	1.76	1.69	14 to 18
2	6.31	1.90	1.83	7 to 11
3	6.31	1.98	1.9	3 to 7
5	6.31	2.00	1.92	2 to 6
7	6.31	1.83	1.75	11 to 15
8	6.31	1.82	1.75	11 to 15
	Average	1.88	1.81	8 to 12
1	10.21	1.86	1.74	9 to 15
2	10.21	1.88	1.75	8 to 15
	Average	1.87	1.75	9 to 15
Notes:	-Tube IDD range calculated assuming S=0.82 from extractions			
	on tubes 5 and 6			
	-Modified Christensen core barrel core diameter 6.31 cm			
	-Standard Craelius core barrel core diameter 10.21 cm			

Table 6.3 UTF coring results

Sample Number	Depth (m)	Ave Min Liner Density	Density (g/cc)	Ave Max Liner Density	Bitumen (%)	Water (%)	Solid (%)	Porosity (%)	Density (no gas) (g/cc)	Porosity (no gas) (%)	IDD (%)	Medium Sand Sieve #20	Medium Sand Sieve #40	Fine Sand Sieve #60	Fine Sand Sieve #100	Silt and Clay Sieve #200	Silt and Clay Sieve #325	Core Dia (mm)	Description		Stratigraphic Unit	ID (%)
AT6-7-1	139.60		2.04		14.9	1.4	83.7	0.36	2.10	0.34	2.9	100.00	100.00	99.77	42.36	6.49	3.23	66	Rich Oil Sand, slabbed		D	5.6
AT6-7-2	139.70		2.01		13.5	4.0	82.5	0.38	2.07	0.36	2.9	100.00	100.00	98.76	63.83	28.39	12.65	66	Rich Oil Sand, slabbed		D	5.1
AT6-7-3	139.80		1.96		9.7	6.4	83.9	0.38	2.11	0.34	7.1	100.00	100.00	99.73	97.39	73.47	56.00	66	Interbedded, slabbed	X	D	13.7
AT6-7-4	140.00		1.98		8.6	7.6	83.8	0.36	2.10	0.34	5.7	100.00	100.00	99.80	95.34	73.18	56.44	66	Interbedded, slabbed	X	D	11.8
AT6-7-5	140.15		2.11		8.3	7.1	84.6	0.33	2.13	0.32	0.9	100.00	100.00	98.76	83.77	65.07	53.01	66	Interbedded, slabbed	X	D	1.5
AT6-7-6	140.30		1.98		10.6	5.9	83.5	0.38	2.09	0.34	5.3	99.84	99.42	95.05	59.47	41.47	31.35	66	Interbedded, slabbed	X	D	10.6
AT6-7-7	140.40		2.19		0.7	11.4	87.9	0.28	2.22	0.27	1.4	100.00	100.00	99.81	98.42	95.32	89.94	66	Shale, slabbed	X	D	3.8
AT6-7-8	140.50		2.15		2.1	9.6	88.3	0.29	2.23	0.26	3.6	100.00	99.96	99.54	96.25	92.57	85.67	66	Shale, slabbed	X	D	10.7
AT6-7-9	140.70		1.80		6.5	12.1	81.4	0.45	2.04	0.39	11.8	99.78	98.52	93.34	63.86	31.03	21.08	66	Mixed up shale and oil sand, slabbed	X	D	19.6
AT6-7-10	141.05		1.84		7.2	11.1	81.7	0.43	2.05	0.37	10.2	99.69	99.44	96.18	77.71	37.84	22.36	66	Mixed up shale and oil sand, slabbed	X	D	17.2
AT6-10-11	150.06		1.97		14.7	3.0	82.3	0.39	2.06	0.36	4.4	100.00	99.97	96.63	23.03	4.15	2.65	66	Rich Oil Sand, slabbed		E	8.0
AT6-10-12	150.30		1.93		15.7	1.5	82.8	0.40	2.06	0.35	7.2	100.00	99.98	96.42	20.21	3.77	2.53	66	Rich Oil Sand, slabbed		E	12.8
AT6-10-13	150.60		<2.09		14.4	2.5	83.1	0.35	2.08	0.35	0.0	100.00	100.00	98.68	26.97	3.66	2.36	66	Rich Oil Sand, slabbed		E	0.0
AT6-10-14	150.85		1.95		14.9	2.8	82.3	0.40	2.06	0.36	5.3	100.00	100.00	98.49	25.66	3.76	2.76	66	Rich Oil Sand, slabbed		E	9.7
AT6-10-15	151.10		1.85		14.9	2.8	82.3	0.43	2.06	0.36	10.2	100.00	100.00	98.36	23.03	3.13	2.26	66	Rich Oil Sand, fracture along entire length, slabbed		E	18.3
AT6-11-16	151.30		1.96		14.9	2.4	82.7	0.39	2.07	0.36	5.3	100.00	100.00	98.01	26.34	4.31	3.54	66	Rich Oil Sand		E	10.0
AT3-13-1	141.63	1.93	1.95	2.01	9.1	3.4	87.5	0.36	2.21	0.27	11.8	100.00	99.96	86.45	27.05	16.81	13.72	63	Medium Oil Sand	X	D	31.2
AT3-13-2	141.85	1.93	2.01	2.01	14.3	1.4	84.3	0.36	2.12	0.33	5.2	99.94	98.66	88.48	13.35	6.36	4.45	63	Rich Oil Sand		D	10.3
AT3-13-3	142.07	1.93	2.04	2.01	14.0	2.6	83.4	0.36	2.09	0.34	2.4	100.00	97.93	50.94	6.76	3.21	2.58	63	Rich Oil Sand		D	4.8
AT3-13-4	142.40	1.93	1.99	2.01	12.7	3.2	84.1	0.37	2.11	0.33	5.7	99.63	95.56	91.25	13.61	5.17	3.80	63	Rich Oil Sand, some coal		D	11.9
AT3-13-5	142.65	1.93	2.01	2.01	13.3	3.1	83.6	0.37	2.10	0.34	4.3	100.00	98.71	77.02	10.65	2.23	1.61	63	Rich Oil Sand		D	9.1
AT3-13-6	142.97	1.93	1.94	2.01	14.4	2.6	83.0	0.39	2.08	0.35	6.7	99.99	98.85	70.83	11.23	4.26	3.44	63	Rich Oil Sand		D	12.6
AT3-19-1	151.33	1.97	1.97	2.05	14.7	1.8	83.5	0.38	2.09	0.34	5.7	100.00	99.96	96.87	38.52	6.15	2.76	63	Rich Oil Sand		E	11.5
AT3-19-2	151.64	1.97	2.00	2.05	14.1	2.6	83.3	0.37	2.09	0.35	4.3	99.98	99.82	91.14	21.43	4.78	3.43	63	Rich Oil Sand		E	8.1
AT3-19-3	151.91	1.97	2.08	2.05	14.6	1.9	83.7	0.35	2.10	0.34	1.0	100.00	99.99	97.19	23.78	2.72	1.72	63	Rich Oil Sand		E	1.9
AT3-19-4	152.10	1.97	1.77	2.05	12.6	1.2	86.1	0.43	2.17	0.30	18.4	100.00	99.99	96.27	41.44	11.28	7.83	63	Rich Oil Sand, prep dist, 3mm clay seam		E	43.2
AT3-19-5	152.50	1.97	1.97	2.05	14.8	3.2	82.0	0.39	2.06	0.37	4.4	100.00	100.00	98.94	26.48	2.72	1.43	63	Rich Oil Sand		E	7.2
AT3-19-6	152.67	1.97	1.97	2.05	15.0	2.7	82.3	0.39	2.06	0.36	4.4	100.00	99.96	96.84	28.13	5.09	3.43	63	Rich Oil Sand		E	8.0
AGI1-3-1	143.44	1.80	1.90	1.93	12.9	2.6	84.5	0.40	2.12	0.33	10.4	99.98	99.91	97.17	27.78	5.26	2.11	102	Rich Oil Sand		D	21.7
AGI1-3-2	143.71	1.80	1.97	1.93	13.6	1.7	84.7	0.37	2.13	0.32	7.5	99.97	99.76	94.56	17.01	5.79	3.54	102	Rich Oil Sand		D	15.9
AGI1-3-3	144.06	1.80	1.96	1.93	14.0	1.9	84.1	0.36	2.11	0.33	7.1	99.97	99.63	81.22	9.42	3.51	2.94	102	Rich Oil Sand		D	14.4
AGI1-3-4	144.35	1.80	2.01	1.93	14.1	2.4	83.5	0.37	2.10	0.34	4.3	99.99	99.97	90.85	13.50	2.34	1.59	102	Rich Oil Sand		D	7.8
AGI1-3-5	144.61	1.80	2.06	1.93	11.9	2.8	85.3	0.34	2.14	0.31	3.7	99.93	98.65	77.90	20.45	8.81	7.00	102	Rich Oil Sand		D	8.7
AGI1-7-1	150.09	1.82	1.94	1.95	15.1	5.1	79.8	0.42	2.00	0.40	3.0	100.00	99.94	98.88	22.42	4.48	2.90	102	Rich Oil Sand		E	4.7
AGI1-7-2	150.32	1.82	1.94	1.95	14.5	1.6	83.9	0.39	2.10	0.34	7.6	99.95	99.81	98.50	22.00	3.78	2.33	102	Rich Oil Sand		E	15.6
AGI1-7-3	150.59	1.82	1.98	1.95	14.3	2.4	83.3	0.38	2.09	0.35	5.3	100.00	99.95	97.20	22.77	3.71	2.54	102	Rich Oil Sand		E	10.0
AGI1-7-4	150.80	1.82	1.96	1.95	14.9	1.8	83.2	0.39	2.09	0.35	6.2	99.98	99.93	97.23	16.13	2.76	1.91	102	Rich Oil Sand		E	11.5
AGI1-7-5	150.98	1.82	1.98	1.95	14.6	2.9	82.6	0.39	2.07	0.36	4.3	100.00	99.93	96.16	17.48	3.06	2.23	102	Rich Oil Sand		E	7.9
AGI1-7-6	151.32	1.82	1.98	1.95	14.8	1.4	83.8	0.36	2.10	0.34	5.7	100.00	99.98	99.71	18.70	1.78	1.19	102	Rich Oil Sand		E	11.5
AT7-2-5	143.08	1.90	2.00	1.95	15.1	3.6	81.3	0.39	2.04	0.38	2.0	99.98	99.85	96.65	17.89	4.28	2.77	96	Rich Oil Sand		D	3.0
AT7-2-4	143.43	1.90	2.00	1.95	14.4	2.2	83.4	0.37	2.09	0.34	4.3	100.00	100.00	99.69	49.36	10.58	4.80	96	Rich Oil Sand with 1 mm Shale Seams		D	8.4
AT7-2-3	143.62	1.90	1.99	1.95	13.9	2.3	83.7	0.37	2.10	0.34	5.2	100.00	99.69	98.46	27.24	9.61	6.48	96	Rich Oil Sand with 1 mm Shale Seams		D	10.3
AT7-2-2	143.82	1.90	2.02	1.95	9.6	4.5	85.9	0.35	2.16	0.30	6.5	100.00	99.99	99.77	69.54	32.52	24.90	96	Medium Oil Sand with 4 mm Shale Seams	X	D	14.6
AT7-2-1	143.97	1.90	1.98	1.95	13.2	2.8	84.0	0.37	2.11	0.33	6.2	100.00	99.91	99.37	51.66	10.29	9.69	96	Rich Oil sand, fractured		D	12.2
AT7-9-6	151.53	1.90	2.00	1.95	14.7	2.1	83.2	0.37	2.09	0.35	4.3	100.00	99.97	94.33	16.31	2.13	1.53	96	Rich oil sand		E	7.9
AT7-9-5	151.78	1.90	1.96	1.95	15.1	0.9	84.0	0.37	2.11	0.33	6.2	99.98	99.91	93.70	15.13	2.48	2.03	96	Rich oil sand		E	12.2
AT7-9-4	152.07	1.90	1.99	1.95	13.0	6.0	80.9	0.39	2.03	0.36	2.0	100.00	99.96	94.17	16.02	2.88	2.10	96	Rich oil sand		E	3.0
AT7-9-3	152.32	1.90	1.98	1.95	14.1	1.8	84.1	0.37	2.11	0.33	6.2	100.00	99.82	90.19	15.07	2.58	1.96	96	Rich oil sand		E	12.5
AT7-9-2	152.59	1.90	1.92	1.95	14.7	1.3	84.0	0.39	2.11	0.33	9.0	100.00	99.72	89.36	14.85	2.17	1.74	96	Rich oil sand		E	17.8
AT7-9-1	152.87	1.90	1.94	1.95	14.1	3.3	82.6	0.40	2.07	0.36	6.3	100.00	99.76	91.01	18.18	3.02	3.15	96	Rich oil sand		E	11.4

Notes:

>10% Bitumen - Rich
6-10% Bitumen - Medium
<6% Bitumen - Lean
Sample numbers: XXX-Y-Z
XXX = hole number
Y= tube number
Z = sample number from specific tube

Ave Max Liner Density = net core weight in liner/(net core length x pi x (inner diameter of bit)**2/4)
Ave Max Liner Density = net core weight in liner/(net core length x pi x (inner diameter of liner)**2/4)

X signifies > 25% silt and clay size or <10% bitumen
X implies rich oil sand

Core Dia (mm)		IDD average (%)	IDD average rich oil sand (%)	IDD radial expansion (%)
66	standard Christensen 4 5/8's core barrel	5.3	4.6	13.0
63	modified Christensen 4 5/8's core barrel	6.2	5.7	3.9
102	standard Craelius SK6L core barrel	5.9	5.9	6.5
96	modified Craelius SK6L core barrel	5.3	5.2	2.6
	Total IDD average	5.7	5.4	

Table 6.4 Syncrude Christensen, Pitcher core results

Sample Numbe	Density (g/cc)	Bitumen (%)	Water (%)	Sand (%)	Interval (m)	D10 (mm)	Log Insitu Density	Ave Sample Density	Ave BC insitu density	IDD bc %
p3-1	1.99	12.4	2.5	85.1	18.6-19.1		2.12	1.99	2.14	7
p4-2	1.95	13.3	2.3	84.4	19.7-20.5	0.84	2.12	1.97	2.12	8
p4-3	1.98					0.13				6.6
p5-1	1.92	13.9	4.5	81.6	20.5-21.2	0.09	2.13	1.92	2.08	6.1
p5-2	1.92	13.3	2.8	83.9		0.12				8.8
p5-3	1.95	14.5	1.8	83.7		0.09				7.2
p5-4	1.90	13.5	4	82.5		0.10				8.2
p6-1	1.88	15.3	4.6	80.1	21.6-22.3	0.11	2.13	1.92	2.04	6.3
p6-2	1.96	14.2	2.6	83.2		0.11				6.1
p6-5	1.92	11.3	7.9	80.8		0.13				5.2
p7-3	1.93	13.9	4.1	82	22.3-23	0.08	2.2	1.93	2.06	6.1
p7-4	1.94	15.6	2.5	81.9		0.09				5.5
p7-5	1.92	14.4	3.4	82.2		0.09				6.8
p8-1	1.95	12.4	3.5	84.1	23.1-23.9	0.09	2.18	1.9	2.1	7.6
p8-2b	1.82	7.1	8	84.9						14.7
p8-3	1.92	14	2.8	83.2		0.08				8
p8-4	1.89	14.7	3.6	81.7		0.10				7.7
p9-2	1.81	12.8	2.4	84.8	30-30.5		2.12	1.81	2.13	15.1
p11-2	1.79	15.8	1.9	82.3	31.2-32		2.12	1.75	2.03	13.2
p11-3	1.73	14.6	4.6	80.8		0.15				14.6
p11-5	1.72	14.6	4.6	80.8						15.1
p14-3	1.94	14.1	2.2	83.7	33.3-34.1		2.05	1.94	2.1	7.6
c26-1	1.91	14	2.7	83.3	22.1-22.4	0.11	2.16	1.91	2.09	8.6
c27-2t	1.96	15.6	1.3	83.1	22.9-23.7	0.08	2.19	1.95	2.08	6
c27-2c	1.94	15.6	1.3	83.1						6.9
c28-2t	1.90	16.2	2.1	81.7	25.3-26.1		2.15	1.92	2.05	7.2
c28-2c	1.93	16.2	2.1	81.7						5.8

Christensen bit ID = 14.923 cm Christensen inner tube id = 15.56 cm

p=pitcher core barrel Average density = 1.93 g/cc for pitcher barrel

c=Christensen core barrel Average density = 1.93 g/cc for Christensen core barrel

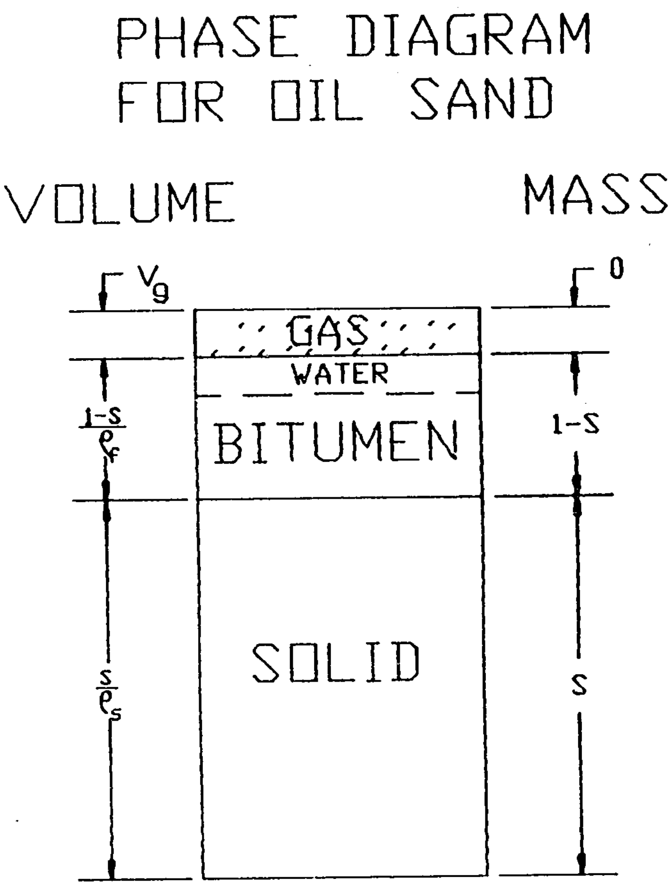
bc=back calculated Pitcher barrel core size 73 mm

ng=no gas The pitcher barrel allows no reduction in density due to radial gas expansion.

For an in situ density of 2.10 g/cc the liner density due to radial gas expansion alone would be reduced to 1.94 g/cc (IDD=8%)

Table 6.5 UTF Core-Log Density Comparison

Hole	Depth Drillers/Corrected (m)	Log Density (g/cc)	No Gas Density (g/cc)	Log Density /No Gas Density	Comments
AT6	139.5-141.2/139.1-140.7	2.12	2.09	1.01	rich oil sand
		2.17	2.11	na	interbedded
		2.19	2.23	na	shale
		2.02	2.05	na	mixed oil sand-shale with coal, bioturbated
	150.0-151.5/149.8-151.3	2.20	2.07	1.06	rich oil sand
AT3	141.55-143.15/NA	2.17	2.12	1.02	rich oil sand, some medium oil sand
	151.25-151.90/NA	2.13	2.10	1.01	rich oil sand, small fines present
AGI1	143.44-144.81/NA	2.18	2.12	1.03	rich oil sand, depth questionable
	150.09-151.32/NA	2.15	2.08	1.03	rich oil sand
AT7	143.08-143.97/NA	2.16	2.10	1.03	rich oil sand
	151.53-152.87/NA	2.12	2.09	1.01	rich oil sand



$$\rho = \frac{1}{V_g + \frac{(1-S)}{\rho_f} + \frac{S}{\rho_s}}$$

TO CALCULATE ρ_{ng} ASSUME $V_g = 0$

$$\rho_{ng} = \frac{1}{\frac{(1-S)}{\rho_f} + \frac{S}{\rho_s}}$$

Figure 6.1 Calculation of ρ_{ng}

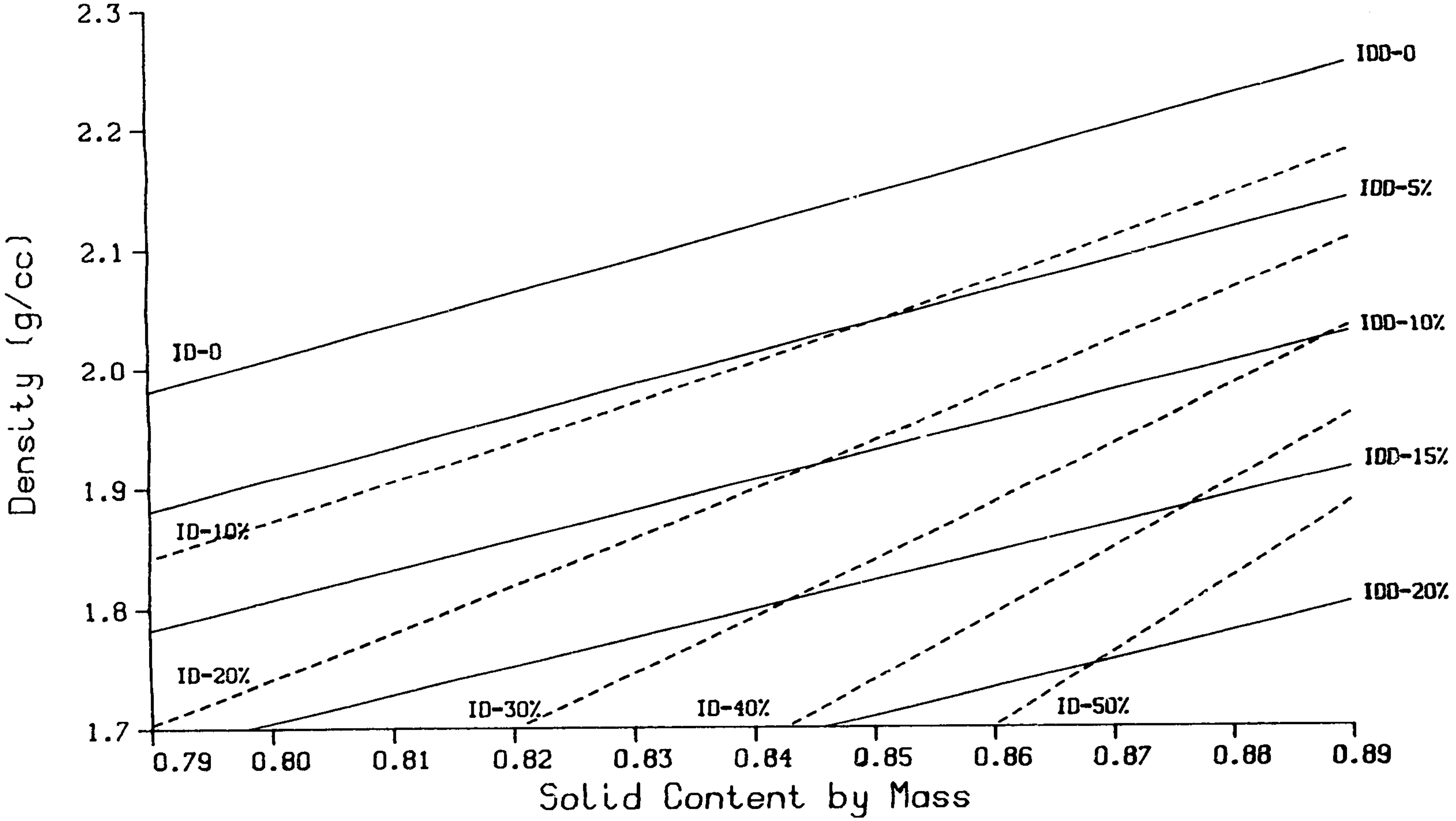


Figure 6.2 Input parameters solids and density and their relationship to disturbance indicators I_D and I_{DD}

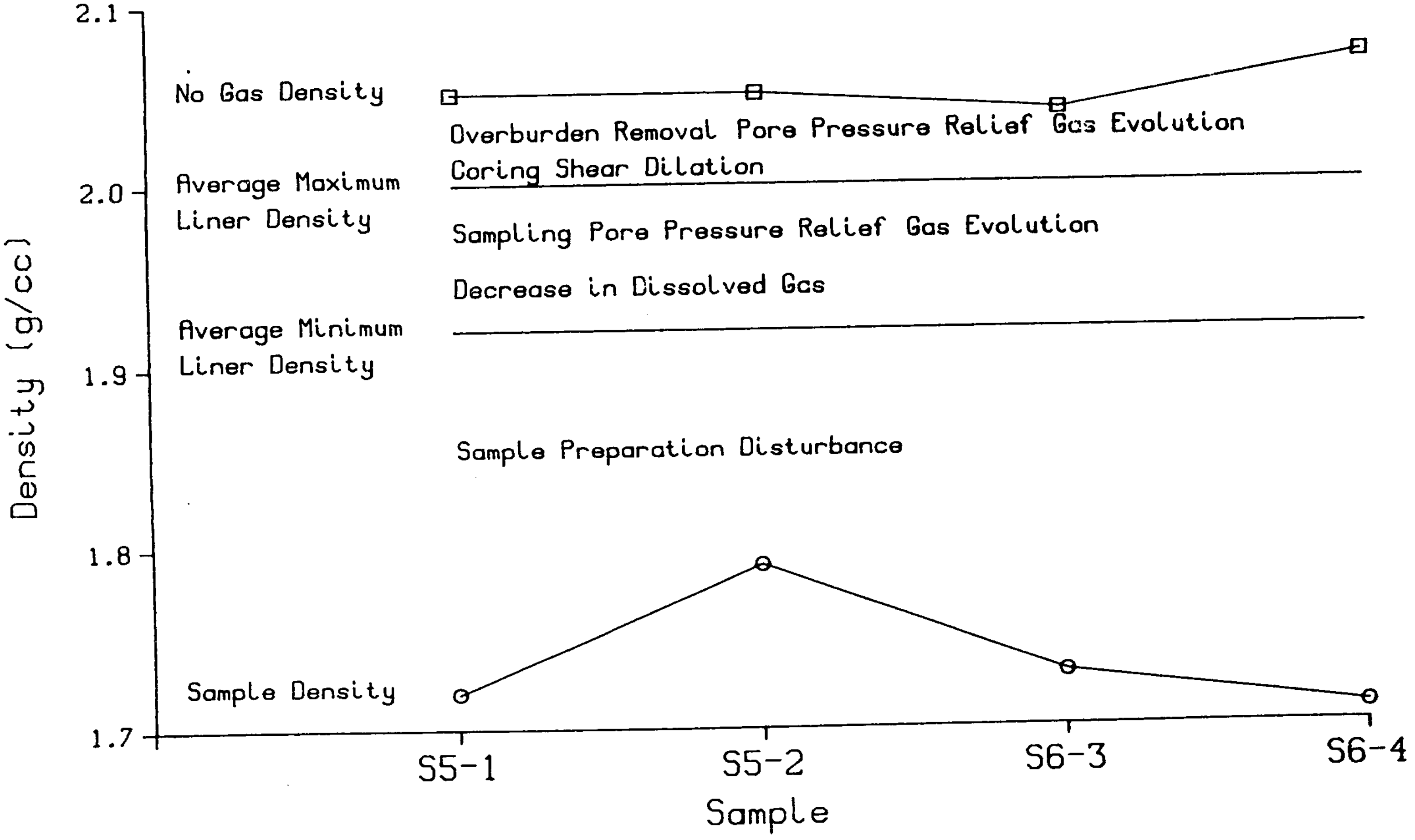


Figure 6.3 Densities comparison Syncrude data rich oil sand

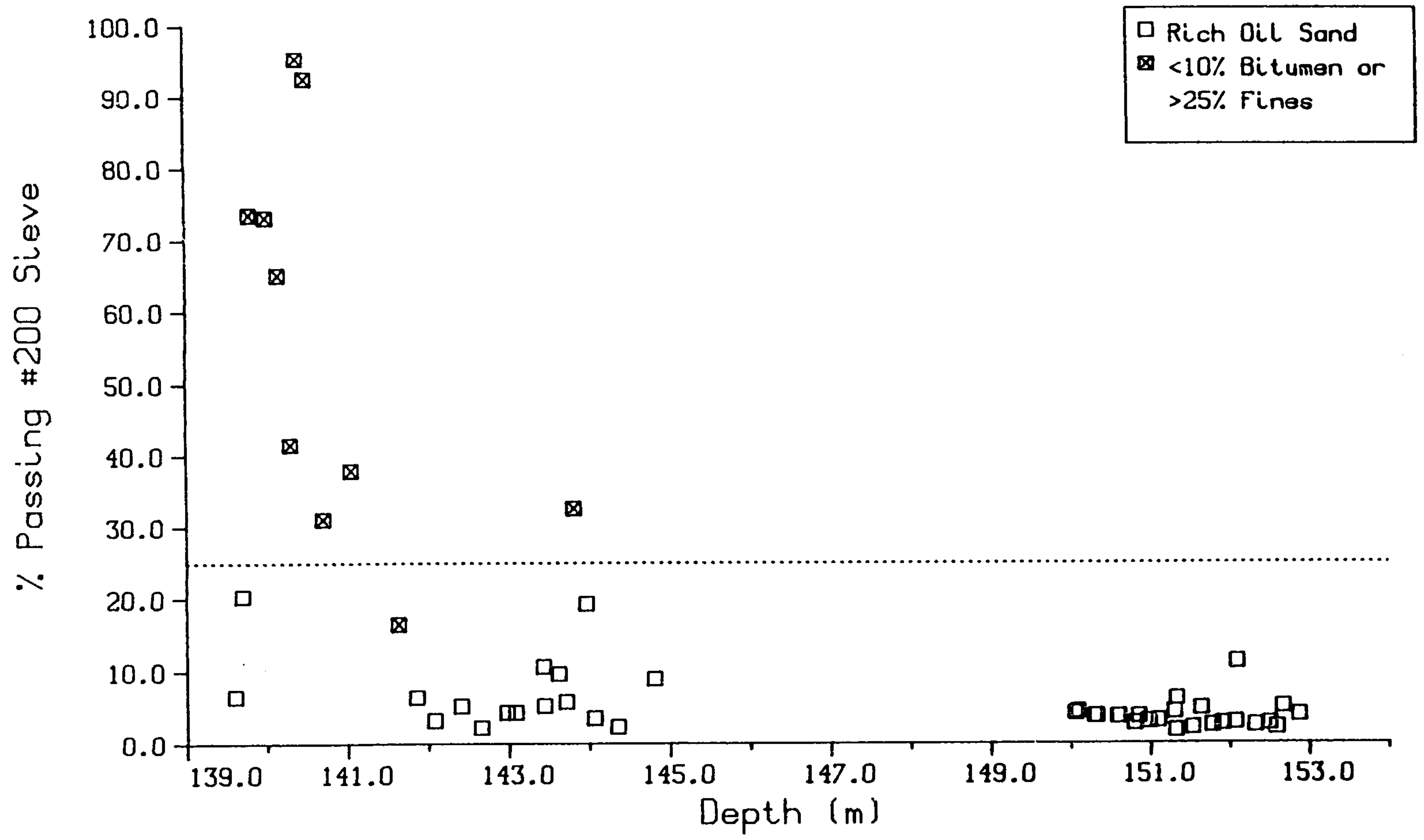


Figure 6.4 Depth versus % fines UTF data

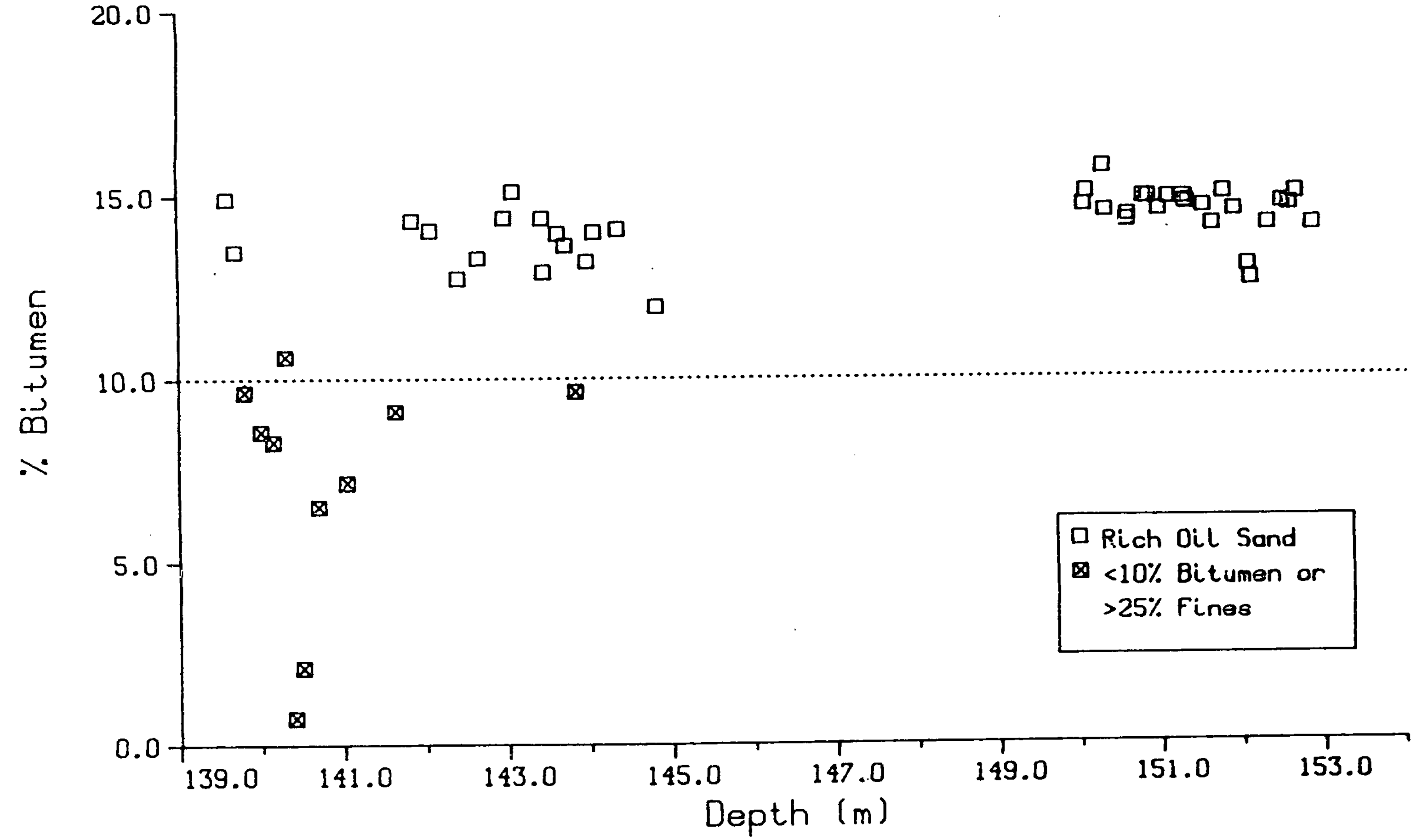


Figure 6.5 Depth versus % bitumen UTF data

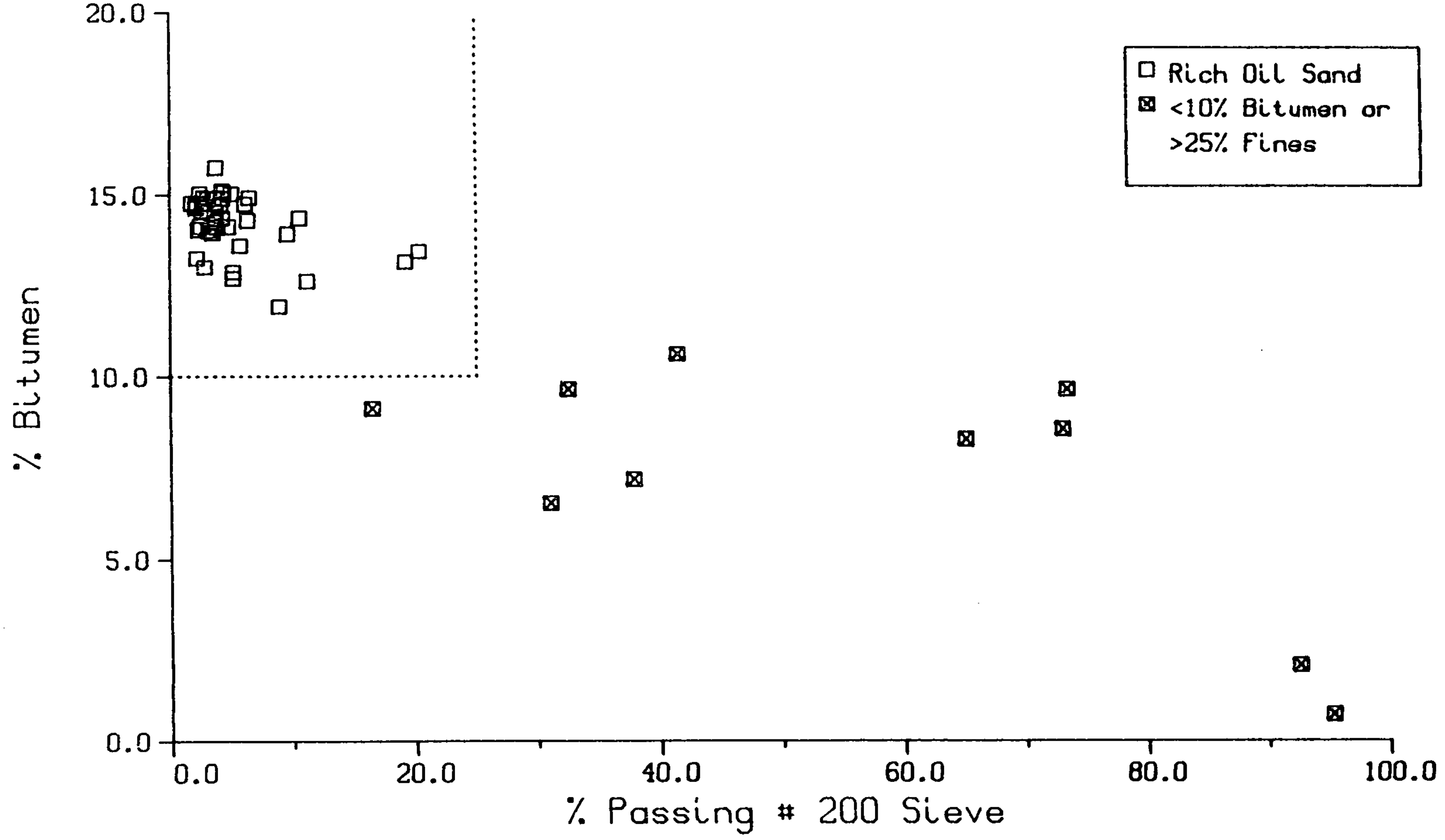


Figure 6.6 Fines versus % bitumen UTF data

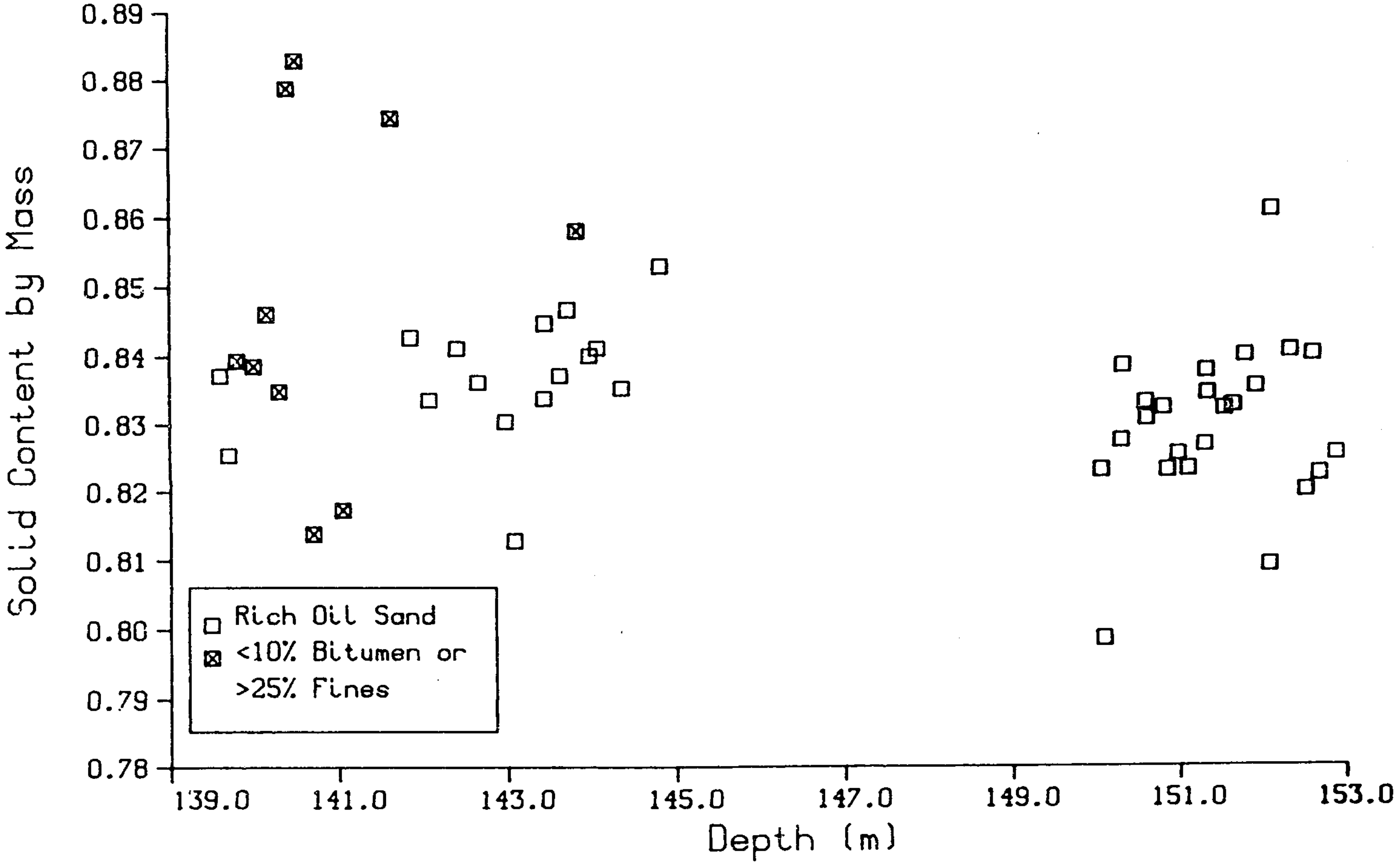


Figure 6.7 Depth versus solid content UTF data

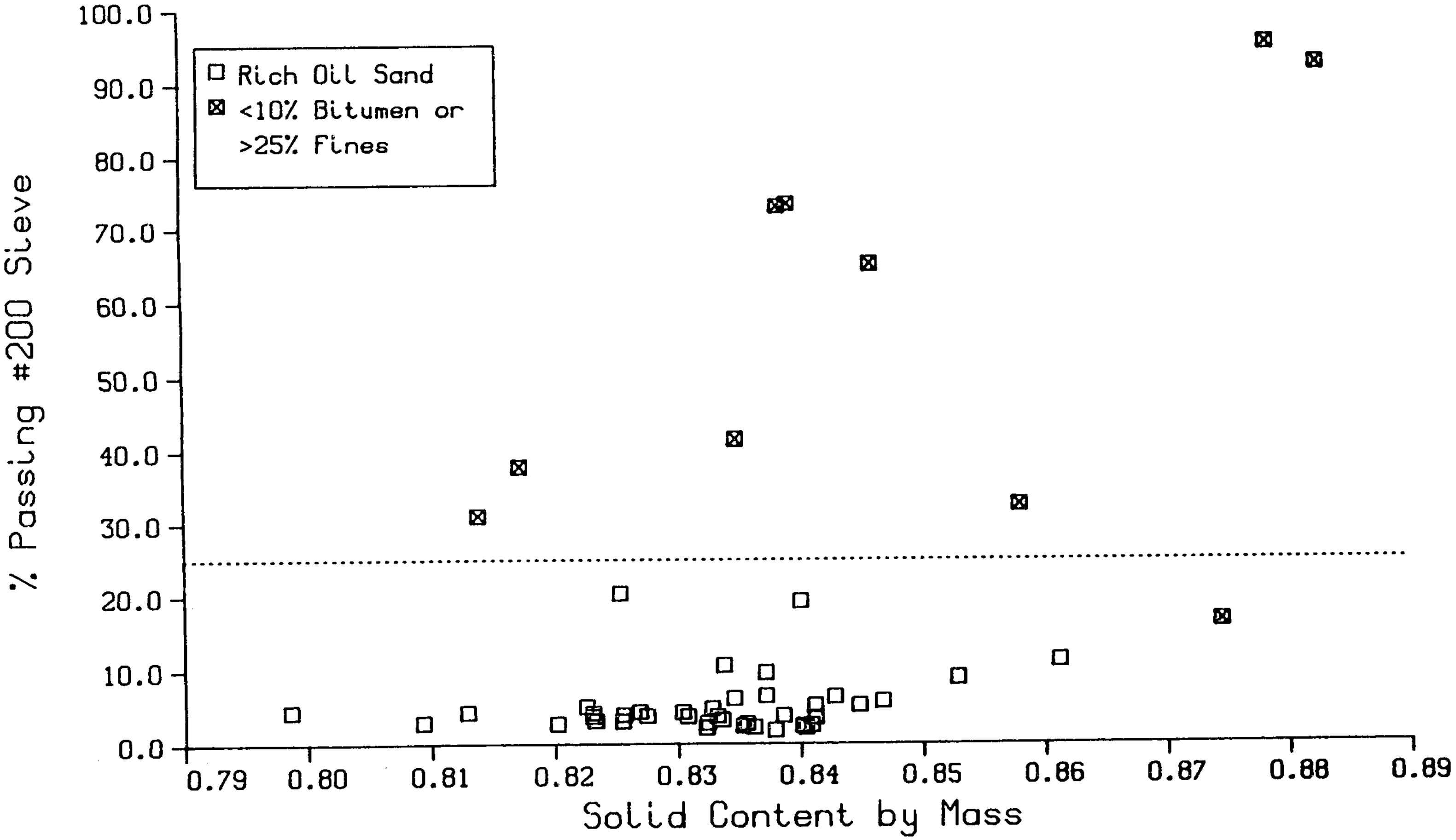


Figure 6.8 Solid content versus % fines UTF data

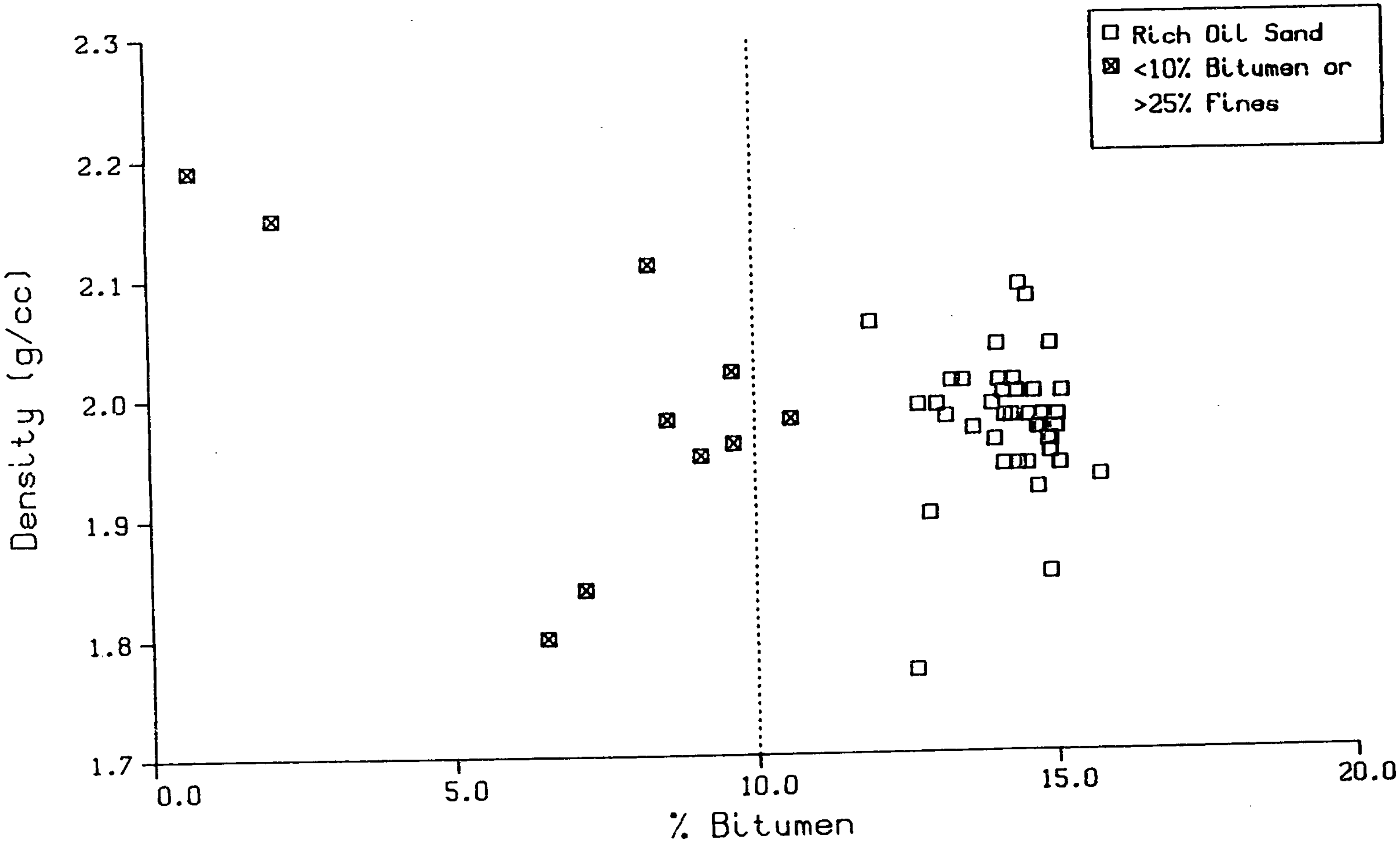


Figure 6.9 Bitumen content versus density UTF data

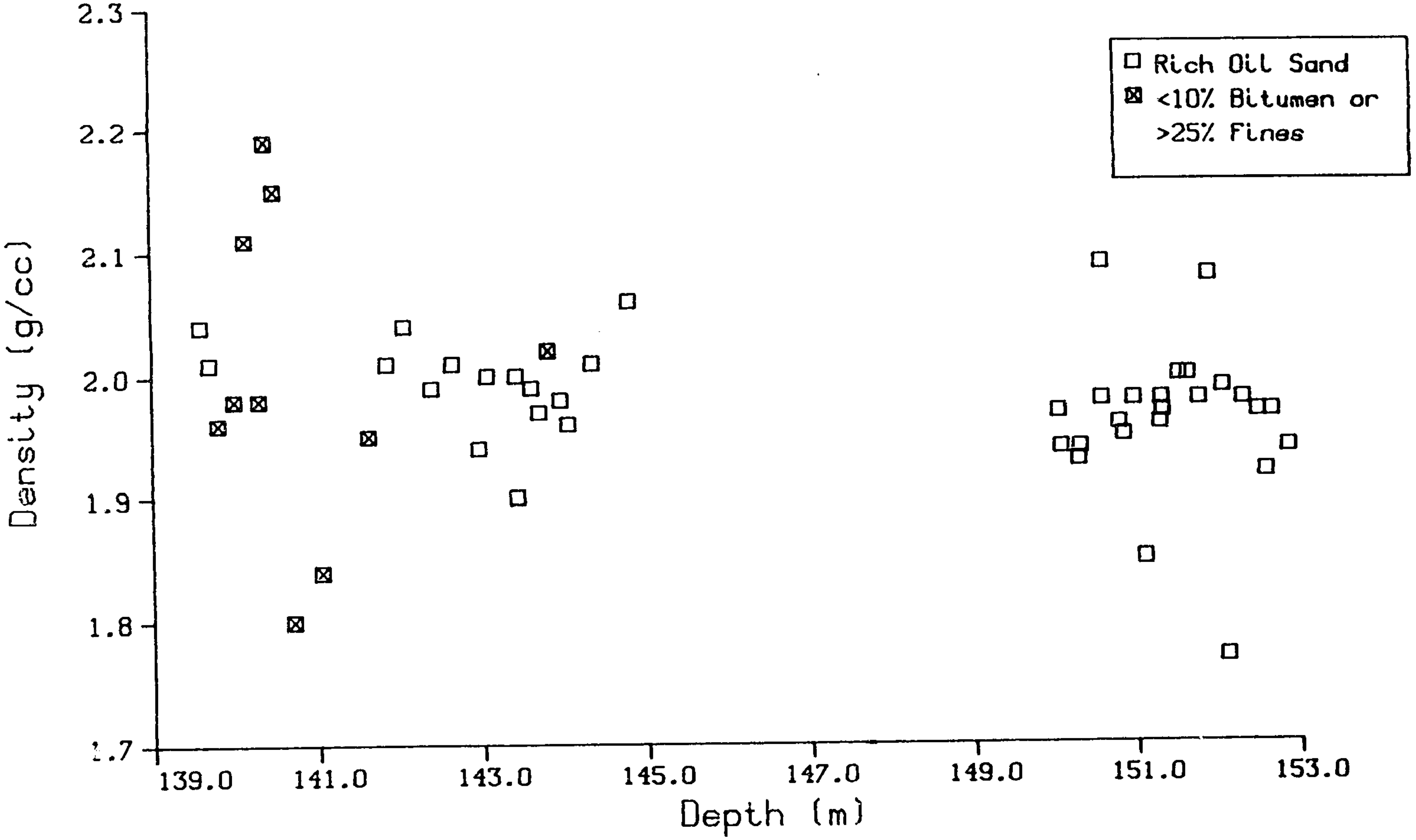


Figure 6.10 Depth versus density UTF data

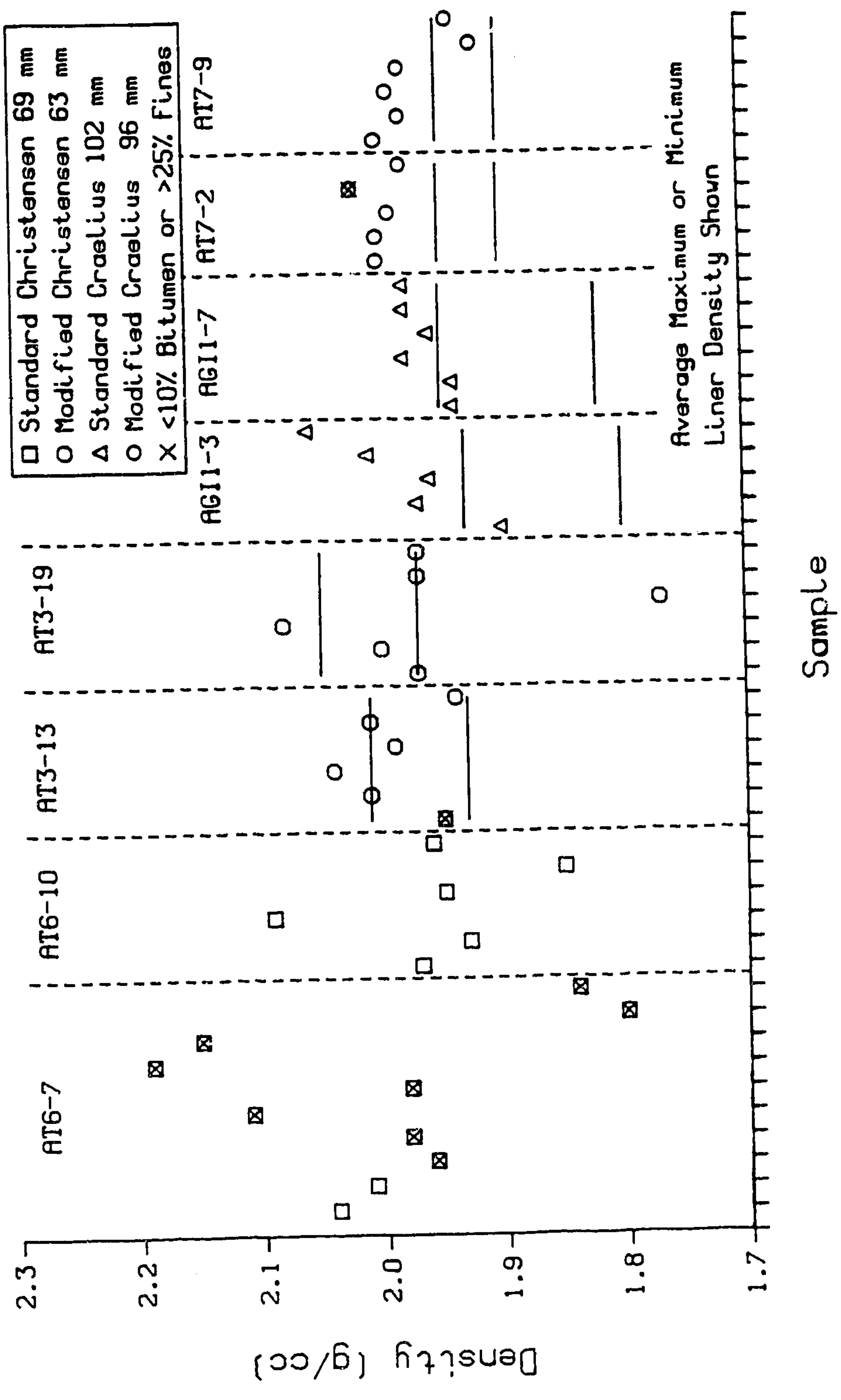


Figure 6.11 Liner densities comparison UTF data

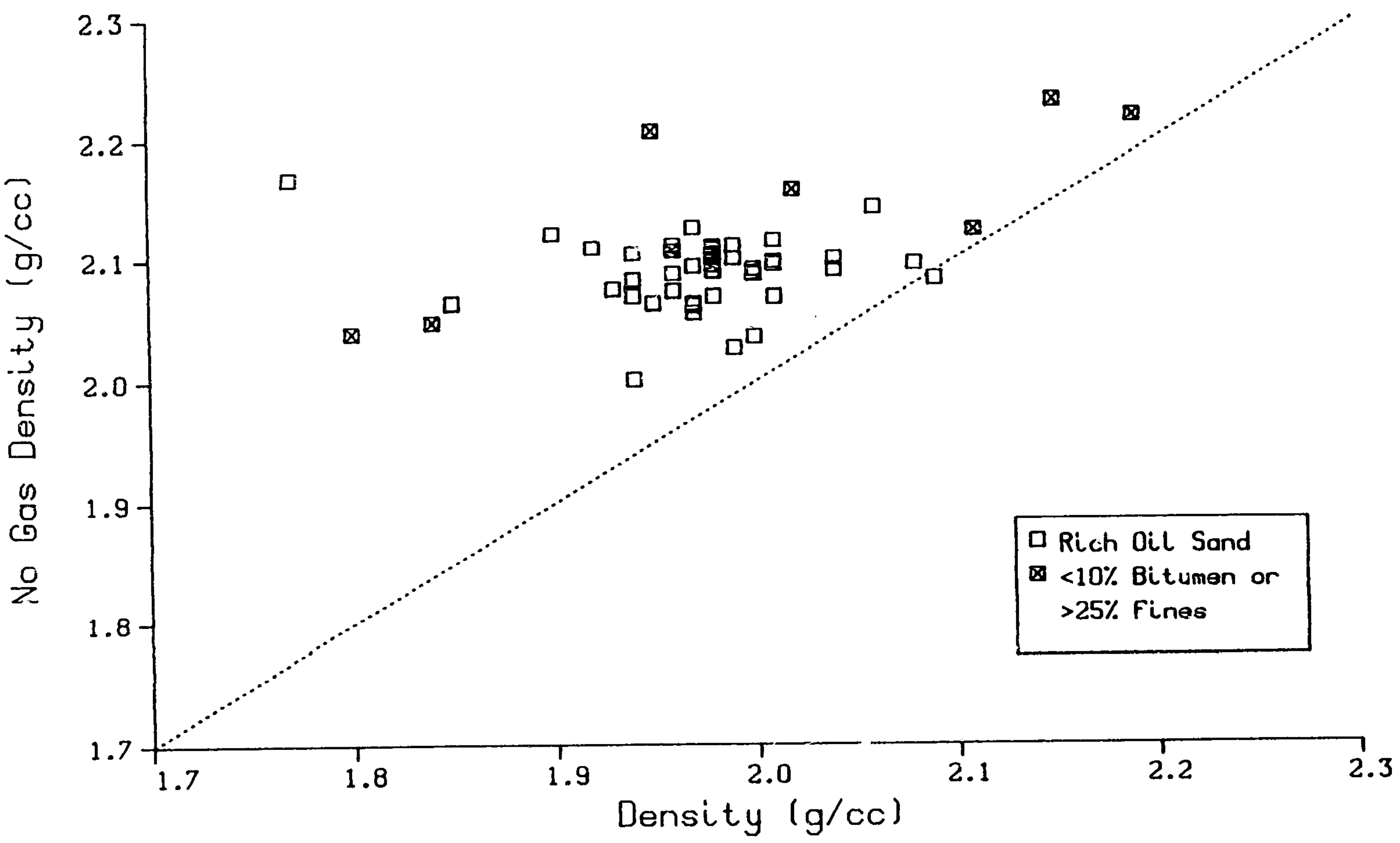


Figure 6.12 Density versus no gas density UTF data

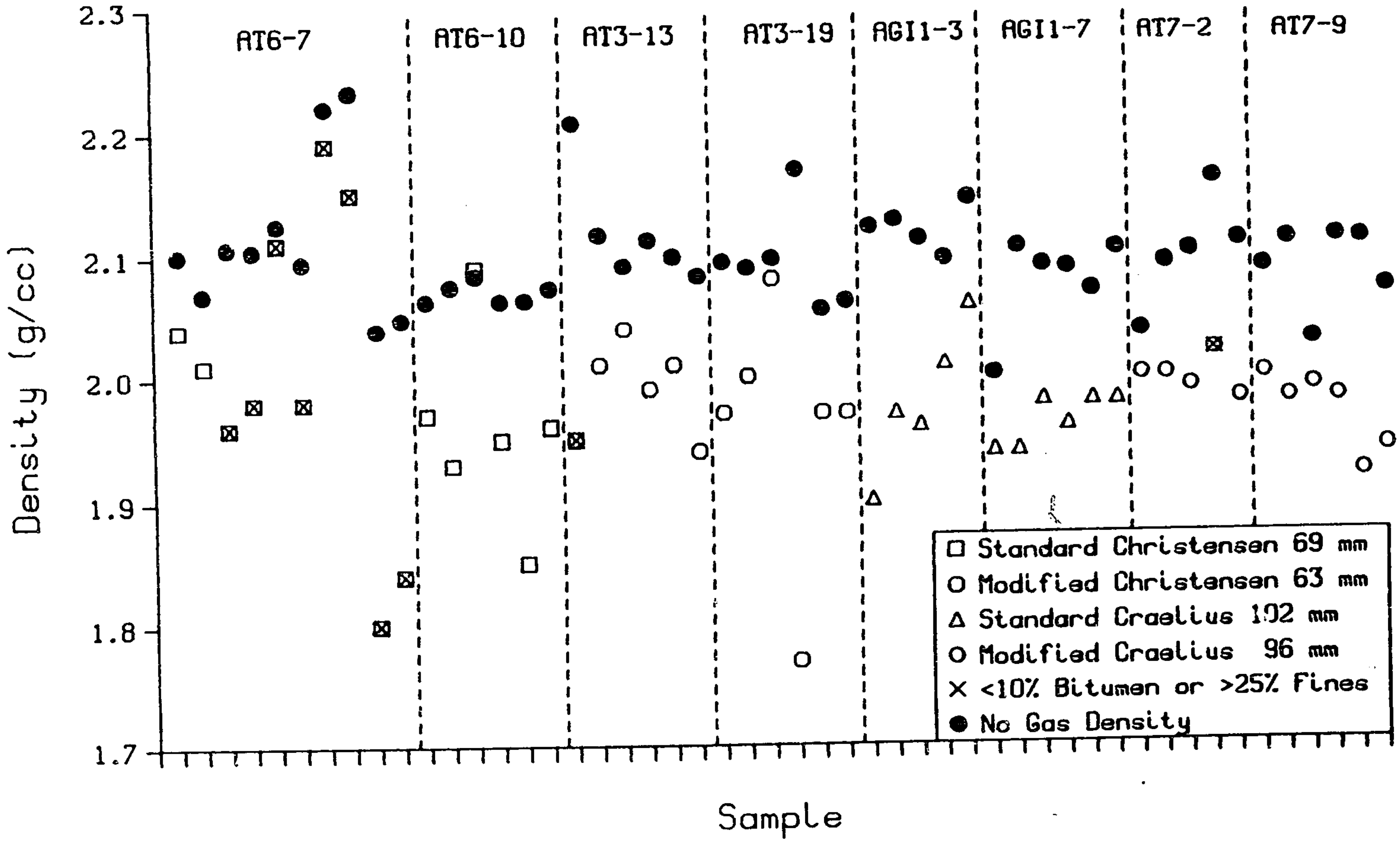


Figure 6.13 Densities comparison UTF data

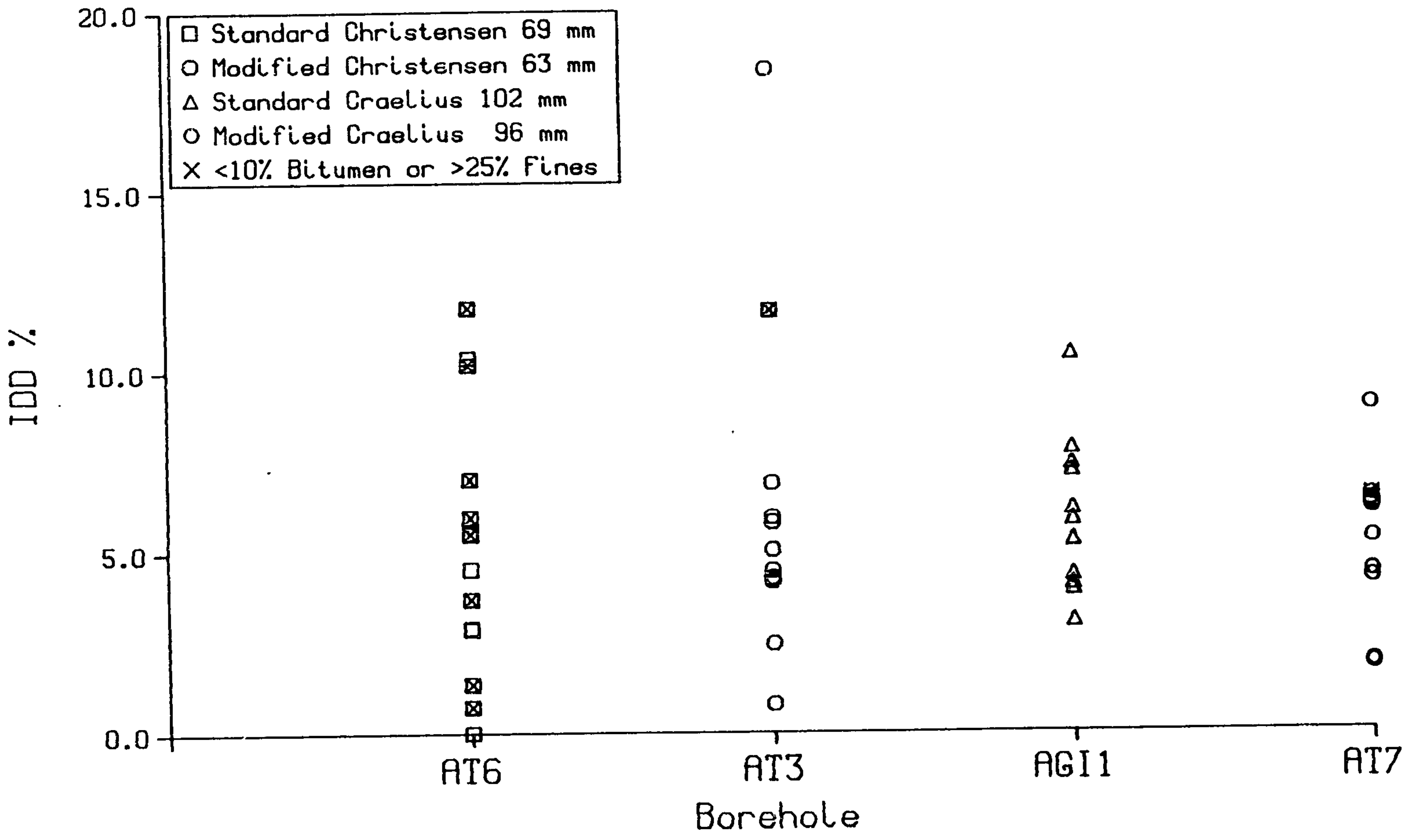


Figure 6.14 Borehole versus index of disturbance density UTF data

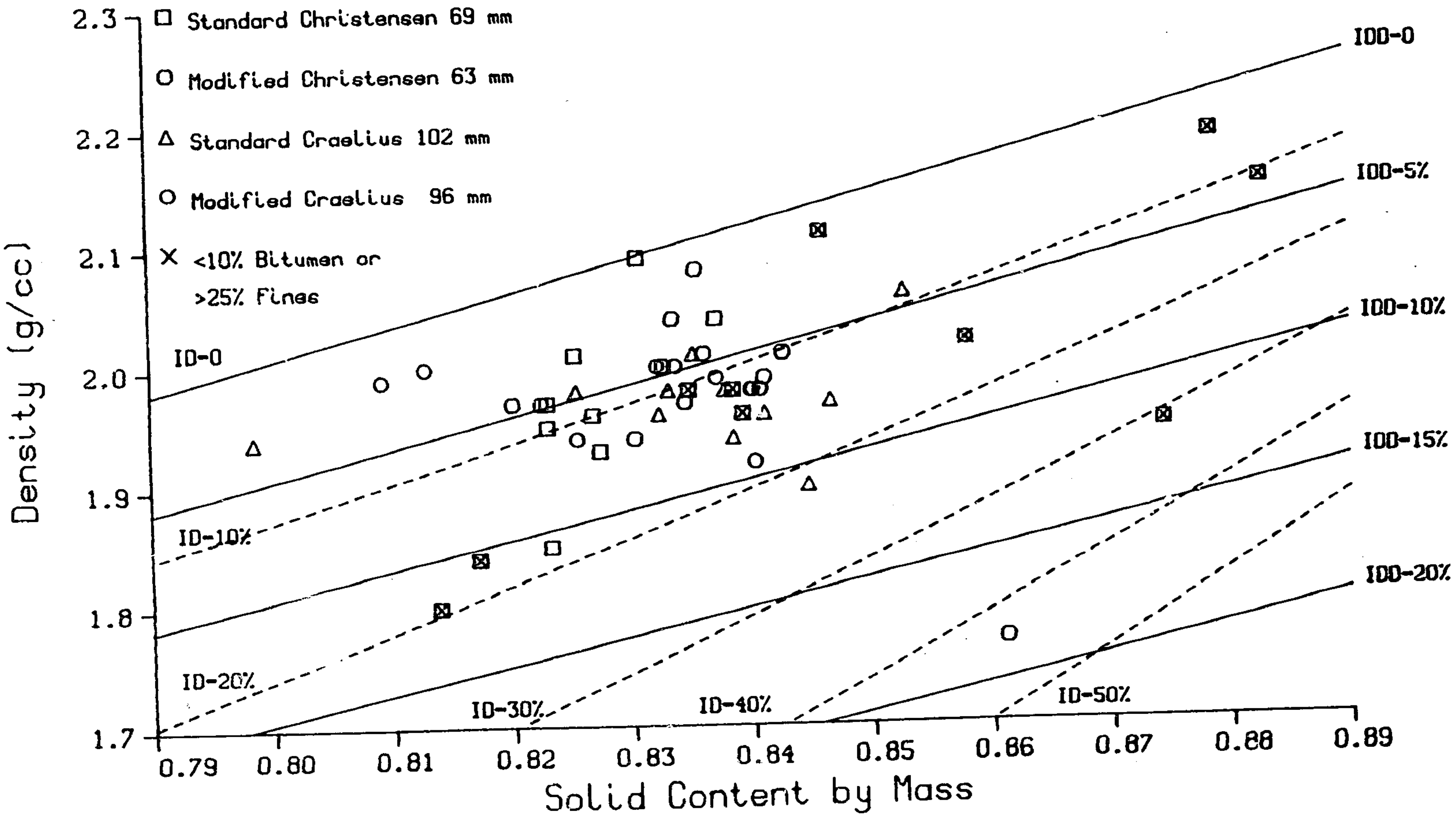


Figure 6.15 Solid content versus density UTF data

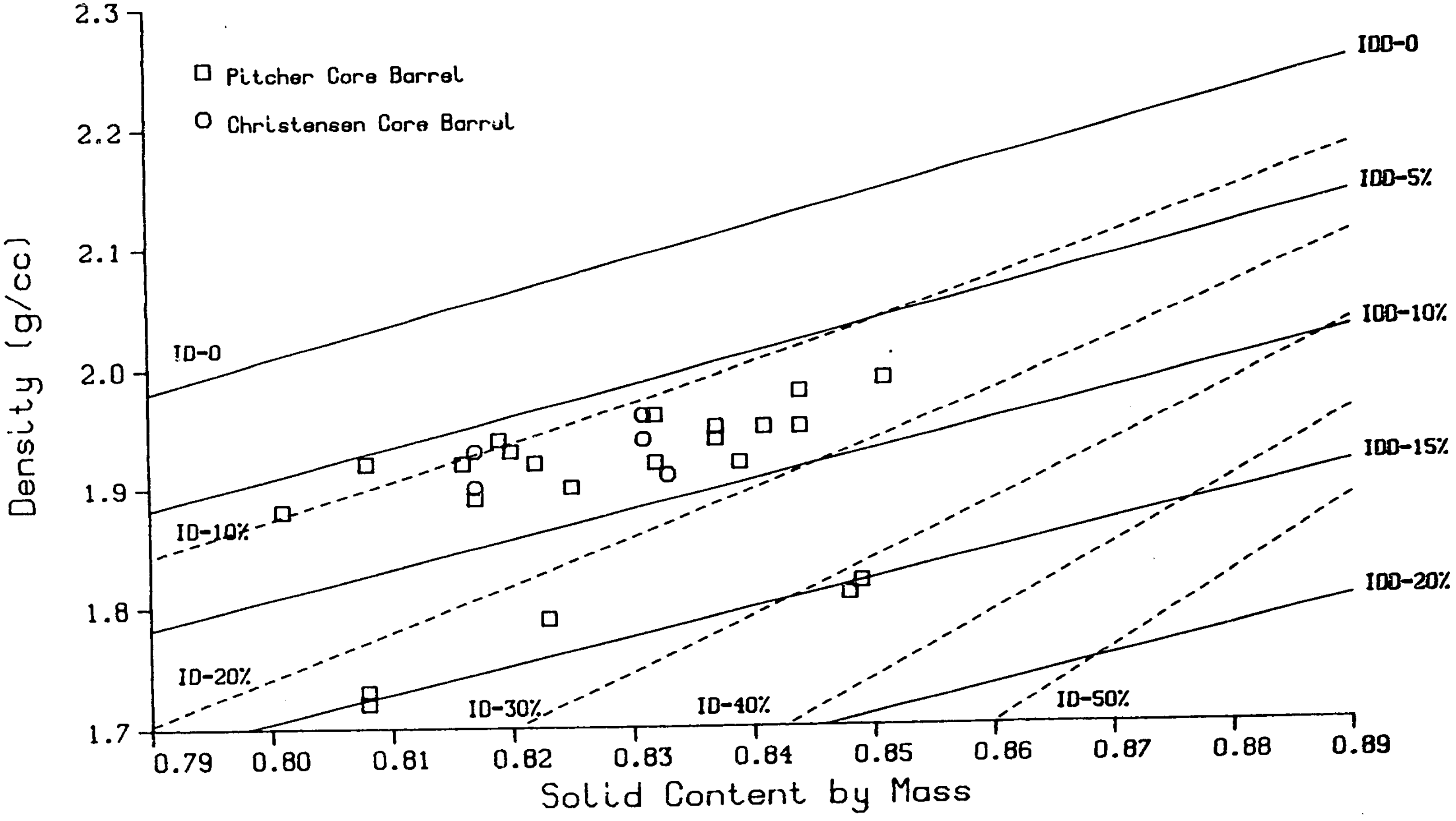


Figure 6.16 Solid content versus density Branco Syncrude samples

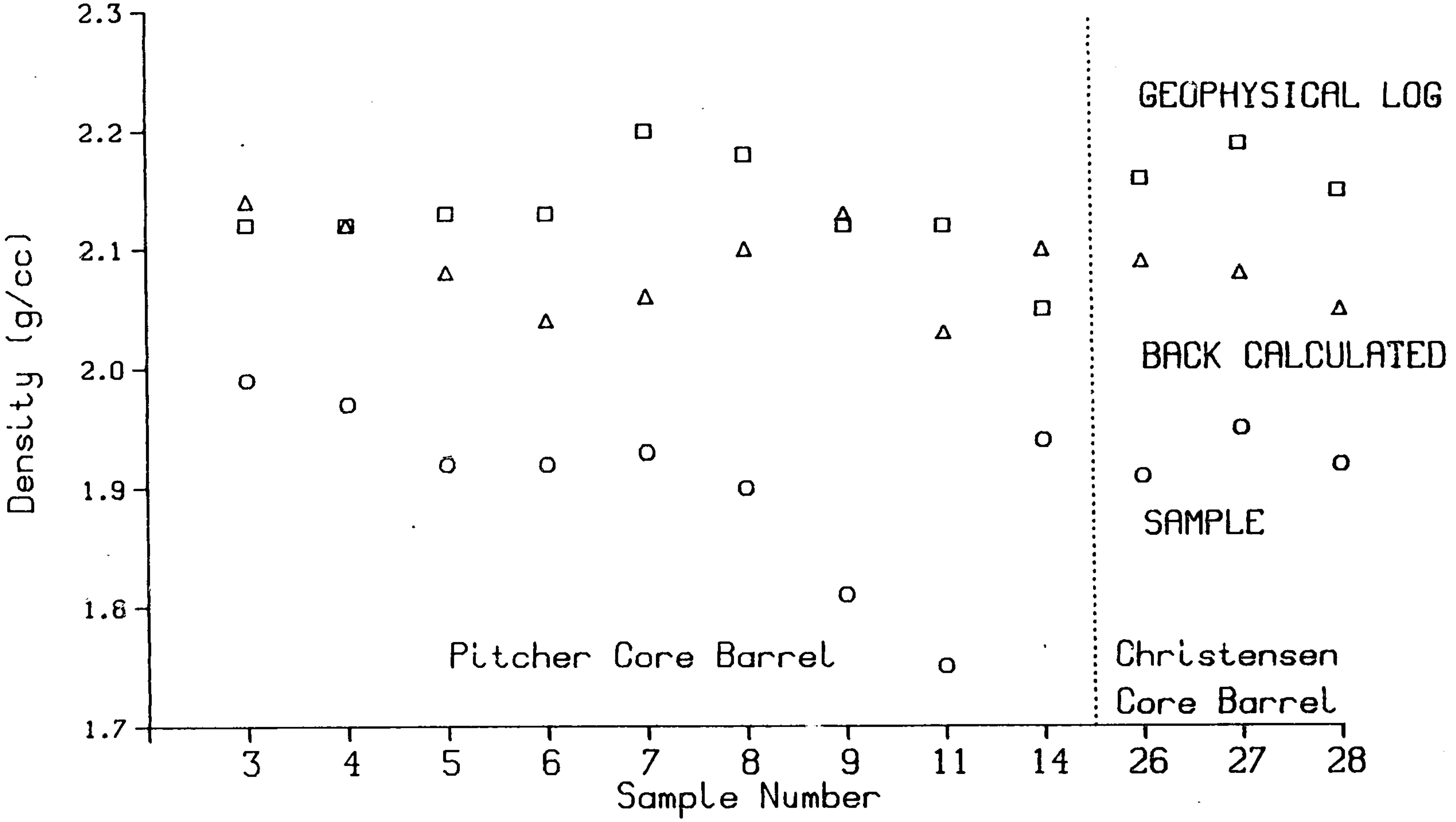


Figure 6.17 Branco Syncrude samples core-log density comparison

Due to the unavailability of copyright permission, figure 6.18, Branco Syncrude data geophysical log (Branco, 1988) has been removed. This figure contained gamma ray and bulk density logs taken at Syncrude of Canada Ltd. for the borehole that Branco (1988) sampled.

Plate 6.1 AT6 slabbed tube at room temperature showing gas disturbance along slabbed face

7. Discussion on Sample Disturbance and Further Recommendations

7.1 Sample Disturbance of Athabasca Oil Sands

The object of undisturbed sampling is to get a core of soil or rock with minimal disturbance from its in situ condition. Various authors have outlined quality classifications. Table 7.1 summarizes four such classifications and the appropriate quality class is designated for oil sand core. Thus it is seen that undisturbed oil sand sampling is really a misnomer particularly for oil sands. The main restriction on the level of quality is that the soil structure and density change and result in uncharacteristic strength and deformation properties. There are two reasons for the density decrease:

1. Gas evolution on pore pressure decrease causing the effective stresses to reduce below zero.
2. Dense sands loosen on sampling for both rotary and driving type samplers (Hvorslev, 1949, Marcuson and Franklin, 1979, Griffin, 1973, Marcuson, Cooper and Bieganousky, 1977, Seko and Tobe, 1977, Mori and Koreeda, 1979).

Gas evolution results in bubble formation and small fractures as the core pore volume increases along preferential zones. The volume increase continues until the gas can be drained by the fractures and the joining of gas bubbles to form drainage paths (Peacock, 1988). Gas evolution damage depends on the quantity of gas in solution. This quantity is variable and is dependent on pore pressure, groundwater conditions and fluid properties. Dilation of the locked structure of oil sands occurs during the coring phase where the individual blanks of a Stratapax bit cut a core by shearing action, and when the bit as a whole transmits torque and vertical forces to the core. Dilation also occurs due to net effective stress relief during formation of the borehole and after the core is cut.

Generally the overburden is drilled out and coring starts in the Clearwater Formation. The hole is cased only through the overburden. Slough from the sides of the borehole can accumulate in the tops of a sample (see plate 4.5). Slough is distinguishable from less disturbed core by its loose nature. On a wireline coring system the drill rods must be lifted in the hole to break the connection at the surface to retrieve the middle tube. Fluid circulation is stopped on wireline retrieval and usually not resumed until coring. Poor circulation practices and poor mud conditioning lead to slough formation in oil sand. The slough is highly disturbed, low density core. In Athabasca oil sand coring, kim mud is added to the water together comprising the drilling mud. Kim mud disperses the bitumen and keeps the equipment clean. The density of the mud is 1.0 g/cm^3 and little or no mud cake forms on the core and sides of the borehole. A layer of bitumen actually forms on these surfaces. When the middle tube is removed conventionally by pulling the drill string a pressure drop is induced. The drill rods may jar against the sides of the borehole transmitting a shock to the core in the core barrel. Circulation before coring is very important in removing any slough from the borehole. Overcoring frequently occurs whether it is due to less than accurate measuring on the part of the driller or slough build up. Overcoring is more likely to happen when using the modified barrels because the middle tube is cored full and not just 1.5 m of core is taken. The mud levels in the borehole are kept hydrostatic. This is necessary to prevent blow outs, maintain borehole integrity and to circulate the drilling fluid. In situ pore pressures are usually less than hydrostatic in the Athabasca area introducing effective stress drops in the vicinity of the borehole. When cutting the core is complete the core is broken off. The middle tube is pulled up and the core catcher provides the reaction to break off the core towards the bit. This is a tensile failure further dilating oil sand near the bottom and top of consecutive cores. As the core enters the middle tube the core catcher must be spread open. This scrapes the sides of the core. As the core enters the middle tube the liner and core move relatively and frictional forces on the core are developed and can be complicated by pieces of core jamming. The driller controls the degree of disturbance that occurs due to these factors. His influence is great and core quality is directly related to the expertise a driller and his crew exhibit in the coring and handling of the core samples.

When the middle tube and core have been brought to the surface the tube is moved around. The steel shoes on the bottom of the tube are removed and excess core is bagged. The excess core must be broken off. When coring 1.50 m lengths with standard core barrels the core is usually pushed up to fill the liner. There is always some annular clearance between the core as cut and the inner diameter of the liner. This clearance is significant in standard coring with the 4 5/8's Christensen barrel to allow bending moments to be set up in the core as the plastic liner is moved around. Also standard thin liners and their flexible nature increases disturbance as the liners themselves are handled. The modified liners have smaller annular clearances reducing volumetric expansion and providing more core support. The 6.35 mm thickness of the modified liners provides support and reduces tube bending during handling. Tube bending occurs even after the sample has been frozen and is being prepared for testing. The core in the plastic liners are capped with plastic caps or taped up with duct tape and sealed with plastic bags. Resin may be used to seal the ends also (see plate 7.1). Resin sealing should be seriously considered when gas tests are to be performed on the core or if freezing is not to be done. The capped and marked plastic liners and core are placed in dry ice in insulated boxes (see plate 7.2) resulting in a decrease in temperature to -80^{0}C. The bitumen phase shrinks on temperature lowering. The sand grains composed of quartz change little but the water phase expands 9% when it turns to ice than it contracts with a further decrease in temperature. Lowering the core temperature increases the viscosity of the bitumen phase. At -20^{0}C and lower the core has significant tensile strength. Lower core temperature also limits bubble formation, lowers the diffusion rate of dissolved gas and increases the solubility of gas in the bitumen and water phases (Peacock, 1988). Clays and the nature of their attachment in the pore throats are affected by the temperature change. This can affect permeability results. Although there is only a small amount of water in oil sands and any volume increase on freezing is less than the volume decrease of the bitumen phase this does not rule out the possibility of the solidified water causing a pore volume increase. Water in oil sands occurs in envelopes around the sand grains. The sand grains form a locked structure. Unless complete water migration occurs during the freezing of the water, the sand grains will be forced apart by the levering action of the ice crystals. The ice levering affect combined with gas evolution at low temperature can magnify the volume increase due to ice expansion. Water migration is affected by fines content, the presence of bitumen and newly developed air spaces. The unsaturated void space due to core expansion may provide room for the increased ice volume.

Even a saturated, rich oil sand core with a 5% water content will only experience an I_{DD} of less than 1% due to ice expansion assuming that no ice levering has occurred and the volume of the bitumen has remained constant. There have been no studies to the author's knowledge on the affects of extreme temperature lowering on oil sands core.

The core also experiences temperature changes. The in situ temperature in the Athabasca area is about $7^{0}C$. The temperature of the drilling fluid is highly variable and depends on the ambient temperature. The drilling fluid either warms of cools the core. After coring dry ice lowers the temperature, then as in the case of the UTF core the core was placed in the freezer truck where the temperature was $-20^{0}C$. After transportation to Edmonton the core was stored in a cold room still at $-20^{0}C$. Prior to sample preparation the core was placed in dry ice to reduce the effects of frictional heat increases caused by sawing tubes and lathing the core.

Chemical changes like oxidation are occurring in the core. Temperature lowering reduces the speed of these chemical changes such as sulphate production by bacteriological oxidation or direct chemical oxidation (Carrigy and Wallace, 1985). As Hvorslev (1949) points out core should be weighed to check for signs of disturbance during storage. The core is subjected to shocks from before it is even cored during the advance of the borehole to that particular core, from the sampling process, handling, transportation by truck to the laboratory and subsequent handling and test preparation. Even with all the precautions taken there is evidence of creep and the oil sands usually expand to fill any annular area in the liner and any spaces in the top retainer at the ends of the modified liner.

Response to pore pressure decrease varies within the core and is dependent on the grain size. Oil sands, are heterogeneous by nature with varying clay content and bands of shale and silt interspersed throughout. On sampling negative capillary pressure in the fine grained portions can cause fluid migration from adjacent core or drilling fluid remaining in the tube (Hvorslev, 1949). This fluids migration is reduced when the temperature of the core is quickly lowered. In the slabbed core from the UTF it was noticed that some sections of the slabbed core bled bitumen (plate 7.3). This phenomena was not bitumen migration towards finer grained zones able to maintain capillary pressure since it did not occur in all such zones. The bleeding was attributed to zones of localized cementation where the soil structure did not expand with the bitumen phase on thawing causing oversaturation of the bitumen and its coating the outside of the core (Rottenfuser, 1987).

An indicator of disturbance is typically recovery, or more specifically net recovery (Hvorslev, 1949). That is comparing the amount cored by measuring the kelly bar movement on coring with a graduated stick and marker with the core recovered as determined by measuring any spaces in the top of the liner and measuring the length of any core sticking out of the liner. This does not account for slough which can take up several centimeters in the tops of the liners but since it is at the very top of the liner and not used for testing purposes its only affect is if it is mistakenly added to the geology of the core. Another problem with examining recoveries is that the core may break off at different points. Core may break off any where from just below the core catcher to the bottom of the bit. Also the core may drop down a bit in the liner and break off in a position that was previously well above the core catcher. Many cases can be found in the drilling logs where core recovery is low followed by excess recovery on the next run simply because the excess core was from the last run. If core is left over from the last run chances are some of the core will be washed away particularly in cases where the middle tube fails to exactly fall over the already cut core on its return to the hole.

In gaseous oil sands recovery can exceed 100% and is due to core expansion by gas evolution in the pore space. The amount of expansion depends on the volume of gas in solution and the coring and sample handling procedures.

7.2 Further Recommendations for Undisturbed Oil Sand Sampling

In oil sand sampling where high quality samples are desired the following recommendations may be used together or in part depending on the final use of the samples. Modified plastic liner sealing can be accomplished by gluing into the tops of the liners a plate or plastic fitting in the offset part of the end retainer, and gluing one end cap to the bottom of the liner. Alternatively the end caps and if necessary vacant tube spaces can be filled with sealing compound. The above will provide an air tight seal and may eliminate the requirement for freezing.

At all stages of core handling there is a tendency to allow the core an opportunity to suffer heat induced disturbance by making a judgement on the speed of thawing. Under no circumstances should core be removed from a -20°C freezer unless it is placed in an insulated box and covered in dry ice. A completely fractured plastic liner from AGI 1 was testimony to improper handling. Careful handling of the core cannot be stressed enough. Handling disturbance creates fractures and reduces the amount of core available for testing.

When preparing samples from core for extraction tests the results are affected by the method of collecting the samples. Channel samples homogenized from the center of the area concerned should be used for extraction tests and grain size analysis. Precautions should be taken to prevent water loss from core samples before extractions are run. A core subjected to a strength test will have its water content changed and not be representative for an extraction analysis. In this case lathe shavings or sawn pieces of the core from adjacent sections of core have to be used for extraction. Visual homogeniety should be at least verified.

Various densities should be taken if possible. Maximum and minimum tube densities from in tube core weights can bracket core densities and provide an indication of sample disturbance. In investigations concerned with sample disturbance at various stages of the sample handling process, densities can be taken of full core tubes, cut tube sections, and of unlathed and lathed core. This is not necessary for every core sample as long as the sample handling procedure remains constant.

Oil sand sampling and sample handling procedures can vary depending on the end use of the samples. Thus it is important that there is someone present during sampling that is cognizant of the tests to which the core will be subjected. This generally ensures better samples and the test results can be reviewed with consideration to any sampling difficulties.

Table 7.1 Oil sand sample quality designation

Author	Description of oil sand core sample	Comments
Hvorslev (1949)	representative	same strata but soil structure disturbed
Idel, Muhs and von Soos (1970)	quality class 3	grain size distribution and water content are accurate but the dry density is not
Kallstenius (1971)	C III	soil composition and rough estimation of desired qualities only possible
Rowe (1972)	quality class 3b	remoulded properties and greater than 90% recovery but less than 100%

Plate 7.1 Sealing tube ends with resin

Plate 7.2 Insulated boxes with dry ice and core

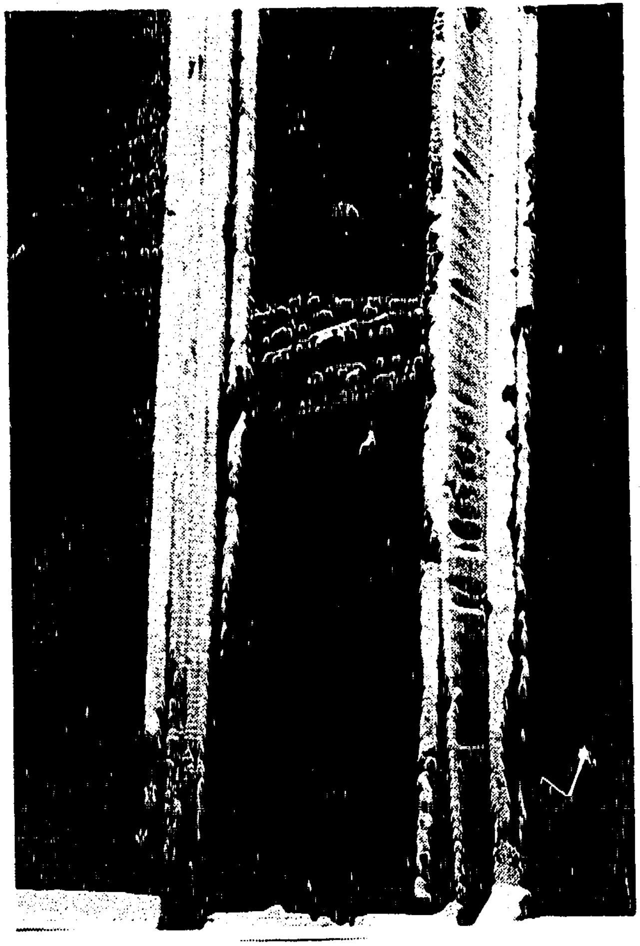


Plate 7.3 Localized bitumen bleeding in UTF slabbed core

8. Reevaluation of High Quality Samples

Based on a plot of maximum principle stress ratio versus I_D, Plewes (1986) concluded that an I_D of less than 14% indicated a sample exhibiting near in situ strength and stress-strain behaviour. Plewes used the same oil sand samples from the Saline Creek outcrop as did Agar (1984) and the sampling procedures are described earlier. Plewes assumed a constant in situ porosity of 33% for all of his Saline Creek samples in calculating I_D values. The 33% porosity value was the average based on geophysical density logs taken earlier (Smith et al, 1978). Thus each I_D value is really just a porosity value. His samples exhibit considerable variation. The no gas porosity which is a close estimate of the in situ porosity ranges from 29 to 40% (table 8.1). A plot of back calculated I_D versus I_D calculated assuming an in situ porosity of 33% is shown in figure 8.1. The I_D values calculated by Plewes are too large because the in situ porosity was not constant and was greater than 33% as shown by the no gas porosities. Plewes conclusion that 14% I_D or less indicates a high quality sample is really a statement that a porosity of 37.6% or less in a rich oil sand sample will exhibit near in situ geomechanical behaviour.

Figure 8.2 evaluates the quality of Plewes' Saline Creek outcrop samples. The I_{DD}'s are all less than 10% and on average 4.1%. The Saline Creek outcrop samples were in general high quality.

Dusseault and Van Domselaar (1982) state that samples with I_D values less than 10% can be considered high quality. This value is based on a culmination of previous experience. Their I_D values were calculated from geophysical log densities. This is an inaccurate method of calculating I_D. In any case an I_D value of 10% is approximately equal to an I_{DD} of 5% (figure 6.2) indicating a maintenance of 95% of the no gas (insitu) density. Since the no gas density values are less than geophysical density log values, a 10% I_D cut off value is consistent with a lower than 5% I_{DD} value. While this is indeed high quality, it must be remembered that geomechanical properties are affected differently by disturbance. Each investigator must evaluate the effects of disturbance on the properties of interest with the samples available. Stress-strain relationships are very sensitive to disturbance while shear strength values are less sensitive. Permeability is related to porosity which is greatly affected by disturbance. Any property, no matter how accurately measured from samples should be related to the in situ condition where the lithological variability must be appreciated.

Table 8.1 Plewes Saline Creek samples

Sample Number	Density (g/cc)	Water (%)	Bitumen (%)	Solid (%)	ID Plewes (%)	ID bc (%)	IDD (%)	Density no gas (g/cc)	Porosity no gas (%)
SC-83-22D	1.99	1.3	13.4	85.3	9.1	15.9	7.2	2.14	31
SC-83-22U	2.01	1.6	13.1	85.3	6.7	13.9	6.3	2.14	31
SC-84-1	2.02	1.7	14.8	83.5	10.3	6.9	3.6	2.10	34
SC-84-3A	2.00	2.6	15.8	81.6	16.1	3.7	2.2	2.05	37
SC-84-3B	1.99	2.6	15.8	81.6	17	4.5	2.7	2.05	37
SC-84-4A	1.97	3.2	15.9	80.9	20.9	4.6	2.8	2.03	38
SC-84-4B	1.97	3.2	15.9	80.9	20.9	4.6	2.8	2.03	38
SC-84-5A	2.00	3.3	14	82.7	13.6	6.5	3.6	2.07	36
SC-84-5B	1.95	3.3	14	82.7	18.5	10.8	6.0	2.07	36
SC-84-8A	1.99	2	12.6	85.4	9.1	16.3	7.3	2.15	31
SC-84-8B	1.97	2	12.6	85.4	10	18.4	8.3	2.15	31
SC-84-10	2.01	3.6	12.2	84.2	9.4	10.0	4.9	2.11	33
SC-84-13	2.02	2.1	15.2	82.7	12.4	4.7	2.6	2.07	36
SC-84-14A	1.97	5.1	13.4	81.5	20	5.9	3.6	2.04	37
SC-84-14B	1.94	5.1	13.4	81.5	22.1	8.4	5.0	2.04	37
SC-84-15A	2.02	1.2	16.5	82.3	13	3.7	2.1	2.06	36
SC-84-15B	1.99	1.2	16.5	82.3	16.4	6.3	3.6	2.06	36
SC-84-17	1.97	2.1	16.1	81.8	19.1	6.7	3.9	2.05	37
SC-84-22	2.04	2.8	14.1	83.1	9.7	4.0	2.1	2.08	35
SC-84-23	1.99	3.3	15.8	80.9	19.7	3.0	1.8	2.03	38
SC-84-24	1.96	3.5	16.2	80.3	23.6	4.0	2.6	2.01	39
SC-84-25A	2.01	3.8	12.9	83.3	12.1	7.2	3.8	2.09	35
SC-84-25B	2.00	3.8	12.9	83.3	12.4	8.1	4.3	2.09	35
SC-84-29	1.93	2	14.8	83.2	19.4	14.2	7.5	2.09	35
SC-84-30	1.93	4	13.9	82.1	21.5	10.8	6.2	2.06	36
SC-84-31	1.93	2.3	16.4	81.3	23.6	8.7	5.3	2.04	38
SC-84-33	2.01	3.9	13.7	82.4	14.2	4.8	2.7	2.07	36
SC-84-34	2.06	1.9	14.8	83.3	6.7	2.7	1.4	2.09	35
SC-84-39	2.03	1.4	15.8	82.8	10.3	4.1	2.2	2.08	35
SC-84-40A	1.96	2.6	15.8	81.6	19.7	7.0	4.2	2.05	37
SC-84-40B	1.99	2.6	15.8	81.6	17.6	4.5	2.7	2.05	37
SC-84-43	1.95	2.7	17.4	79.9	24.1	4.0	2.6	2.00	40
SC-84-49	1.89	3.1	14.4	82.5	24.5	15.5	8.6	2.07	36
SC-84-51	1.95	1.6	16.9	81.5	21.5	7.6	4.5	2.04	37
SC-84-52	2.03	4.2	9.4	86.4	2.7	16.2	6.7	2.18	29
SC-84-53	1.95	2.7	17.8	79.5	26.1	3.2	2.1	1.99	40
SC-84-55A	1.96	2.4	16.3	81.3	20.6	6.3	3.8	2.04	38
SC-84-55B	2.00	2.4	16.3	81.3	17.3	3.0	1.8	2.04	38
SC-84-60	1.97	2	15.3	82.7	16.4	9.1	5.0	2.07	36
SC-84-110	1.98	3.2	14.3	82.5	16.7	7.7	4.3	2.07	36
SC-84-115A	1.96	2.2	15.5	82.3	18.8	8.8	5.0	2.06	36
SC-84-115B	1.95	2.2	15.5	82.3	19.7	9.7	5.5	2.06	36
SC-84-117	2.00	2.9	15.7	81.4	16.4	3.3	2.0	2.04	38

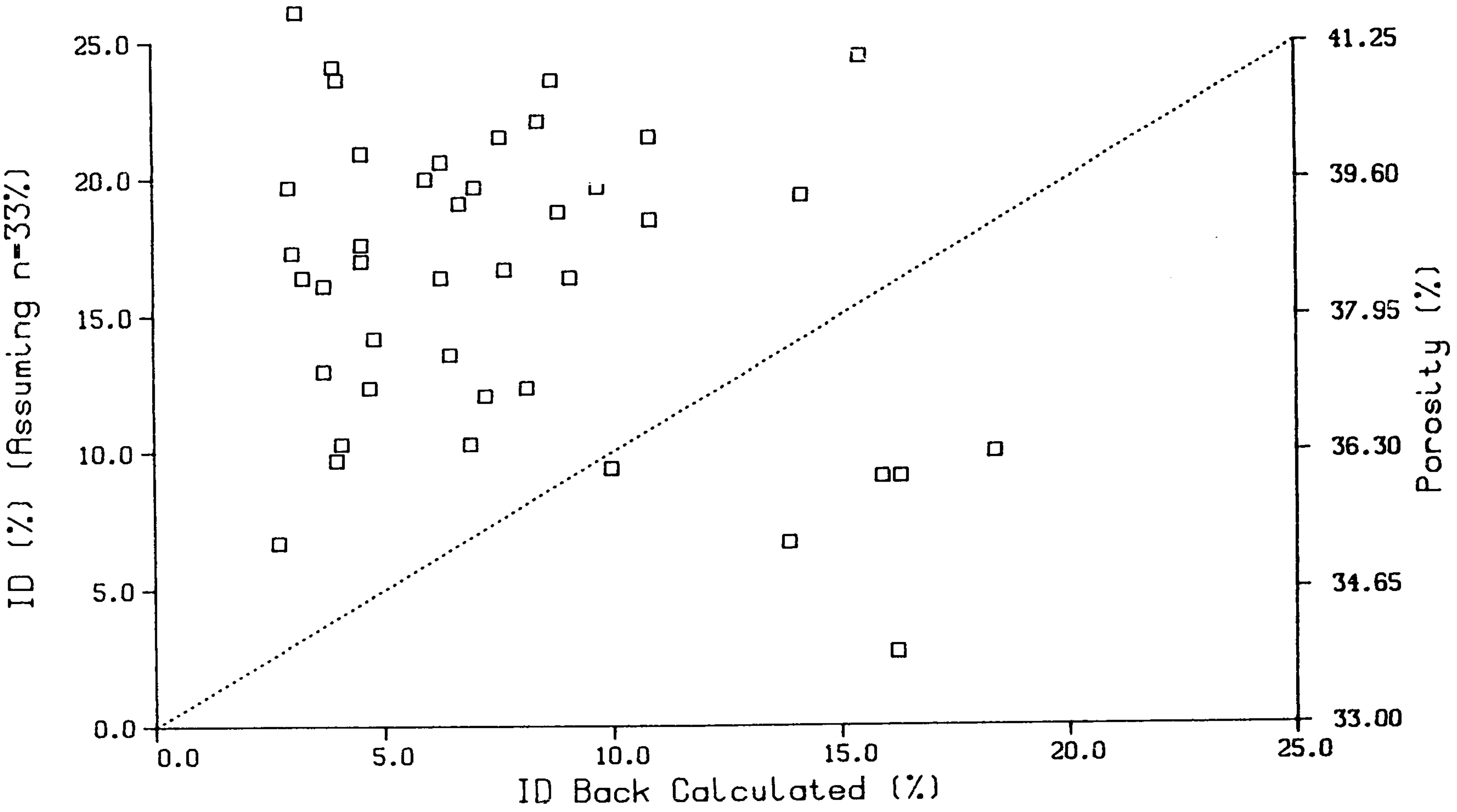


Figure 8.1 Core-log comparison of I_D Plewes Saline Creek samples

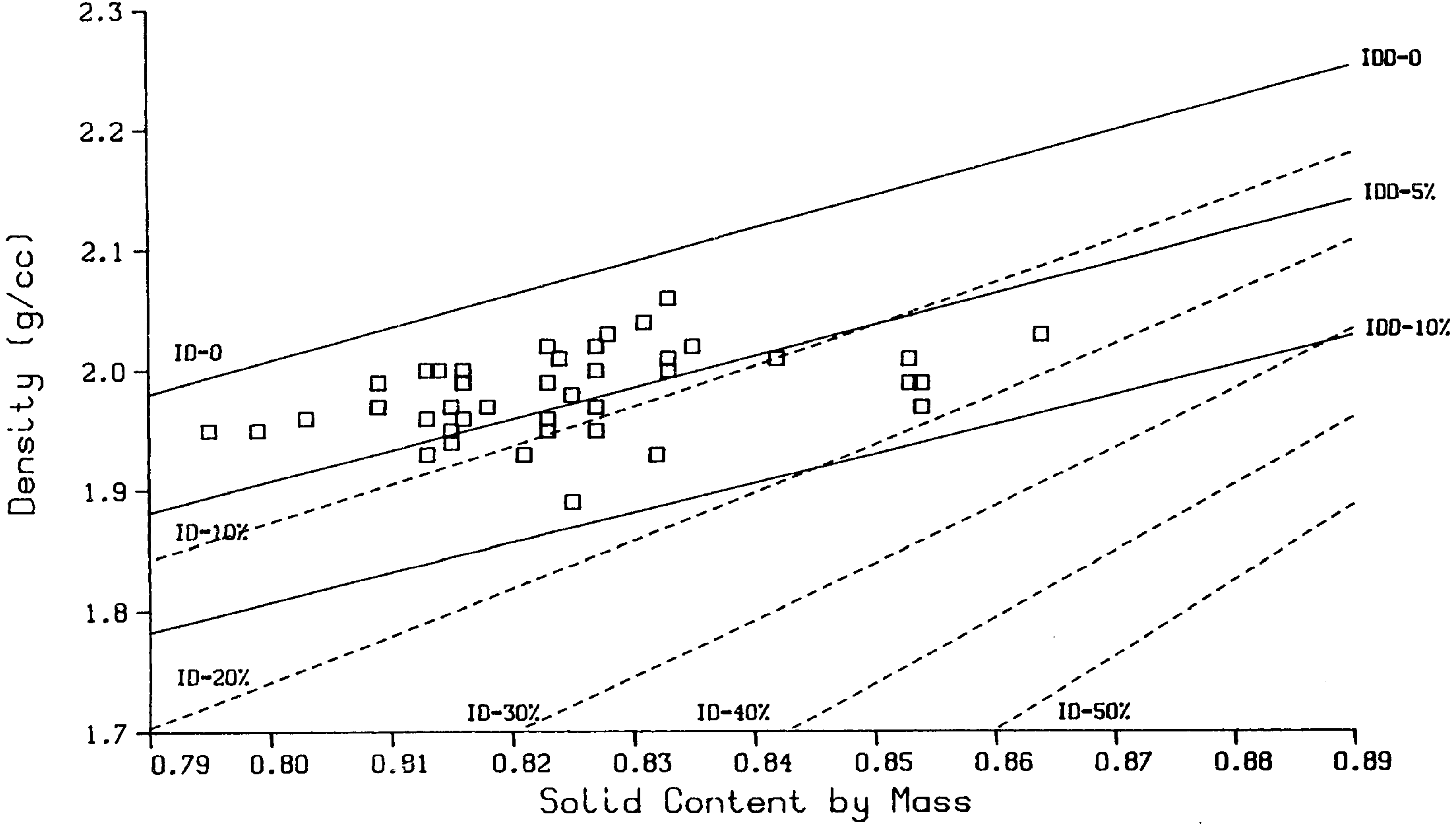


Figure 8.2 Solid content versus density Plewes Saline Creek samples

9. Conclusions and Recommendations for Future Research

9.1 Conclusions

The main conclusions are described in the following sections.

9.1.1 Respecting Natural Geologic Variation

Simple calculations have shown that large variation in in situ density occur in oil sand due to varying solid content. The magnitude of this measured variation also depends on the length of sample homogeniezed for oil, water and solids determination. The reason for testing affects the choice of a length to be extracted. For petrophysical parameters large lengths on the order of a half meter or more would be appropriate. For most geotechnical tests where samples are typically under 100 mm in length, greater lithological extremes and variations are possible and should be evaluated.

9.1.2 Oil Sand Sample Disturbance Evaluation

Geophysical logs are invaluable when used in conjunction with coring for lithology determination and reservoir evaluation. However, geophysical density logs should not be used to evaluate sample disturbance. Geophysical density logs tend to be erratic and thus chosing an appropriate value to match with a sample is difficult and subjective. Back calculated no gas density values are generally lower than density log values, thus using density logs for estimates of in situ density artificially increases estimations of sample disturbance. Oil sand samples are routinely extracted to determine the oil, water and solid content. Extraction results combined with sample densities are all that is required to quantify sample disturbance.

Sample disturbance is best quantified by I_{DD} not I_D. I_{DD} is a nondimensional parameter relating the difference in density of a sample with gas in its voids to a perfect gasless sample. I_D is a secondary parameter relating the nondimensionalized porosity difference between a sample and its saturated condition. I_D is based on porosity which in turn is calculated from the primary values of sample density and solid content just as I_{DD}. I_D is more affected by varying solid content than I_{DD} and its meaning is less direct.

The most effective method of presenting data for sample quality evaluation is in the form of a solid content versus density plot. Levels of I_{DD} should be marked off on the plot. $I_{DD}=0$ provides an upper bound on sample quality.

9.1.3 In Situ Density and Porosity of Rich Athabasca Oil Sand

Fluid gain or loss in properly handled oil sand samples is improbable therefore the extraction solid and fluid contents should be accurate. This information alone allows estimation of in situ porosity and density. For clean Athabasca oil sands with solids contents ranging from 0.80

to 0.86, the corresponding in situ density range would be 2.00 to 2.16 g/cm^3 and in situ porosity range would be 30 to 40%.

9.1.4 Oil Sand Sampling Recommendations

Recommendations have been put forward for improved oil sand sampling. Freezing of oil sand samples is not new but its importance is being better understood. Freezing may be more critical for some types of testing. Another simple but effective sampling technique is the weighing and measuring of the core while it is still in the liner. These values can yield average maximum and minimum core liner densities. Weights also can check on core records regarding recovery. Maximum and minimum liner densities can provide information regarding sample quality, recovery and lithology.

9.1.5 Samplers Performance

Based on Branco's research work and usage of the Pitcher core barrel and a standard Christensen double tube core barrel, neither barrel provided superior or high quality samples in the gaseous rich Syncrude oil sands. Branco's sampling procedures are described earlier and his sample handling techniques may have eliminated any advantage the Pitcher barrel would appear to have over an unlined Christensen core barrel.

No conclusive evaluation was possible in the comparison of the standard and modified core barrels based on the UTF results. Average I_{DD} disturbance values for all four forms of the two core barrels were within about 1%. The low in situ gas content of the oil sand allowed all the core barrels to obtain high quality samples. Minor sample handling disturbance may have overshadowed the small differences in sample quality among the core barrels.

9.2 Recommendations for Future Research

1. Adequate reasons for the core-log discrepancy should be found. Reasons for the difference would increase the value of existing data and improve analytical results in geotechnical and petrophysical applications.
2. To add to the confidence of core extraction results it is recommended that water imbibition of Athabasca oil sand be investigated. Geophysical logs and tritium drilling fluid can be used to check core flushing (Britton, 1984).
3. The effects of freezing on core should be investigated, in particular, bitumen tensile strength and viscosity at low temperatures, water temperature induced volumetric changes and pore clay disturbance and its effects on permeability.
4. Develop methods to determine in tube core densities from x-ray imaging or other techniques for oil sand and associated stratigraphy.
5. Quantify the total gas volume in oil sand samples and incorporate into disturbance potential.

6. Quantification of the effect bitumen viscosity has on oil sand geomechanical properties. This may be done by a series of variably timed strength tests on oil sand core. In conjuction, extraction of the bitumen phase under confining stress would allow comparison of porosity values and soil skeleton strength tests from regular procedures. A preserved sand skeleton would have the bitumen effects removed. The time factor and its effect on various failure and deformations an oil sand body may experience should be considered. The bitumen viscosity may affect strength tests of varying duration and temperature (Agar, 1984).
7. Anisotropies in oil sands and their effects on geomechanical properties should be investigated.
8. When another coring program presents itself, the modified core barrels should be put into use. If the core taken is gaseous and handled carefully, a conclusive evaluation of the effectiveness in reducing sample disturbance of the modifications may be reached.

9.3 Epilogue

Presently the production of oil from oil sand deposits in Alberta is increasing, assuring the Western World a secure supply of oil at a reasonable price. Research projects can help by improving the understanding of the resource enabling its optimal development. Resource development filters through the economy providing economic prosperity not only for those directly involved but for the entire nation.

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Appendice A: Core Catcher Design Program, Input and Output Files

The following is a documented Fortran IV program to aid in core catcher design. Inut and output files are listed after the source code.

```
      DIMENSION TITLE(20)
      REAL  A,C,F,G,H,I,J,K,L,N,Z,X,Y,IDD,IDR,D,B,R,P,O,Q,S,PI
      INTEGER MFLAG,WFLAG
C THIS FORTRAN IV PROGRAM CALCULATES THE DROP OF A CORE AS THE CORE
C CATCHER (SPLIT RING) IS ACTIVATED WHEN THE CORE IS MOVING OUT THE
C BOTTOM OF THE TUBE OF A CORE BARREL.  UNITS OF THE DROP
C ARE THE SAME AS THOSE USED FOR THE CORE CATCHER AND CORE LIFTER
C CASE GEOMETRY AS INPUT.  ALSO THE PROGRAM TELLS HOW THE SPLIT RING
C WORKS, OUTPUTS ANGLES OF TAPER Z,X, AND Y (AS DESCRIBED IN THE
C DEFINITIONS), AND CALCULATES THE INDEX OF DISTURBANCE AS DEFINED
C BY DUSSEAULT AND VAN DOMSELAAR (1982) DUE TO RADIAL EXPANSION
C AND LONGITUDINAL EXPANSION. RADIAL EXPANSION IS DUE TO THE
C SOIL SKELETON EXPANDING RADIALLY TO FILL THE SPACE BETWEEN THE
C LINER AND THE CORE AS CUT.  LONGITUDINAL EXPANSION IS ASSUMED
C TO OCCUR TO FILL THE SPACE LEFT AS THE CORE DROPS TO ACTIVATE
C THE CORE CATCHER.
C INPUT FILE:
C LINE     DESCRIPTION
C 1           TITLE (8A10) THAT IS A MAXIMUM OF 80 CHARACTERS
C 2           A,C (2F10.3)
C 3           F,G (2F10.3)
C 4           H,I (2F10.3)
C 5           J,K (2F10.3)
C 6           L,N (2F10.3)
C DEFINITIONS
C CONSTANTS:
C      A=MAXIMUM INSIDE DIAMETER IN CORE LIFTER CASE (TOP)
C      C=MINIMUM INSIDE DIAMETER IN CORE LIFTER CASE (BOTTOM)
C      F=LONGITUDINAL DISTANCE BETWEEN A AND C
C      G=TOP OUTSIDE DIAMETER OF UNRESTRAINED SPLIT RING
C      H=TOP INSIDE DIAMETER OF UNRESTRAINED SPLIT RING
C      I=BOTTOM INSIDE DIAMETER OF UNRESTRAINED SPLIT RING
C      J=BOTTOM OUTSIDE DIAMETER OF UNRESTRAINED SPLIT RING
C      K=HEIGHT OF SPLIT RING
C      L=SLOT IN UNRESTRAINED SPLIT RING
C      N=CORE DIAMETER
C      Z=ANGLE OF TAPER FROM VERTICAL OF CORE LIFTER CASE
C      X=ANGLE OF OUTSIDE EDGE FROM VERTICAL OF SPLIT RING
C      Y=ANGLE OF INSIDE EDGE FROM VERTICAL OF SPLIT RING
C VARIABLES:
C      D=DEPTH FROM TOP OF TAPER IN CORE LIFTER CASE TO TOP OF SPLIT
C         RING
C      B=INSIDE DIAMETER IN CORE LIFTER CASE AT DEPTH, D
C      R=TOP OUTSIDE DIAMETER OF SPLIT RING
C      P=TOP INSIDE DIAMETER OF SPLIT RING
C      O=SLOT IN SPLIT RING WIDTH
C      Q=BOTTOM INSIDE DIAMETER OF SPLIT RING
C      S=BOTTOM OUTSIDE DIAMETER OF SPLIT RING
C      IDR=INDEX OF DISTURBANCE DUE TO RADIAL EXPANSION OF THE CORE
C            TO FILL THE LINER OF DIAMETER C
C      IDD=INDEX OF DISTURBANCE DUE TO CORE EXPANDING TO FILL THE
C            SPACE CREATED BY THE CORE DROPPING IN THE LINER AS THE
C            CORE CATCHER IS ACTIVATED
C FLAGS:
C      MFLAG=1    TOP OF SPLIT RING STICKS IN CORE LIFTER CASE UPON
C                    CATCHING CORE
C      MFLAG=2    BOTTOM OF SPLIT RING STICKS IN CORE LIFTER CASE
```

```
C                   UPON CATCHING CORE
C      WFLAG=1    TOP OF SPLIT RING CATCHES CORE
C      WFLAG=2    BOTTOM OF SPLIT RING CATCHES CORE
C      WFLAG=3    TOP AND BOTTOM OF SPLIT RING CATCHES CORE
C A NEGATIVE DISPLACEMENT, E IMPLIES THE CORE IS LARGER THEN THE
C AVAILABLE AREA THAT THE SPLIT RING CAN DISPLACE, SHALL NEGATIVE
C VALUES OF E MAY BE DESIRED
      PI=3.1416
C READ IN TITLE
      READ(5,10)TITLE
C READ IN CORE LIFTER CASE AND SPLIT RING DATA
      READ(5,11)A,C
      READ(5,11)F,G
      READ(5,11)H,I
      READ(5,11)J,K
      READ(5,11)L,N
C CHECK IF CORE CAN PASS THROUGH A CLOSED SPLIT RING
      IF((H* PI-L)/PI.GT.N.AND.(I*PI-L)/PI.GT.N) GOTO 1000
      IF(H.GE.I) GOTO 1
C TOP OF SPLIT RING CATCHES CORE, NOTE IT IS ASSUMED THAT THE SPLIT
C RING IS RIGID AND THE SLOT WIDTH REMAINS CONSTANT ACROSS ITS
C LENGTH
      P=N
      WFLAG=1
C NEW GAP WIDTH O
      O=L+PI*(P-H)
C INSIDE DIAMETER AT BOTTOM OF CORE CATCHER
      Q=I+(O-L)/PI
1     IF(I.GT.H) GOTO 3
C BOTTOM OF CORE CATCHER CATCHES CORE
      Q=N
      WFLAG=2
C TOP AND BOTTOM OF SPLIT RING CATCHES CORE
      IF(I.EQ.H) WFLAG=3
C NEW GAP WIDTH O
      O=L+PI*(Q-I)
C INSIDE DIAMETER OF SPLIT RING
      P=H+(O-L)/PI
C OUTER DIAMETER OF SPLIT RING AT ITS TOP
3     R=P+G-H
C OUTER DIAMETER OF BOTTOM OF SPLIT RING
      S=Q+J-I
C POINTER SET AT DIAMETER OF TOP OF SPLIT RING
      B=R
C DROP LENGTH TO TOP OF SPLIT RING
      D=F*(A-B)/(A-C)
      MFLAG=1
C CORE CATCHER DROP=E
      E=D
C SET D TO DEPTH AT BOTTOM OF SPLIT RING
      D=E+K
C B=INSIDE DIAMETER OF CORE LIFTER DASE AT D
      B=A-D/F*(A-C)
      IF(S.LT.B) GOTO 5
C B SET AT OUTER DIAMETER AT BOTTOM OF SPLIT RING
      B=S
C DEPTH TO SPLIT RING BOTTOM
      D=F*(A-B)/(A-C)
      MFLAG=2
C DEPTH TO SPLIT RING TOP
      E=D-K
C CALCULATE ANGLES IN DEGREES
5     Z=ATAN((A-C)/2/F)*180./PI
      X=ATAN((G-J)/2/K)*180./PI
      Y=ATAN((I-H)/2/K)*180./PI
```

```
C CALCULATE INDEX OF DISTURBANCE DUE TO CORE DROPPING AND LEAVING
C A GAP IN THE TOP OF THE LINER (IDD) AND DUE TO RADIAL EXPANSION
C (IDR)
C THE INDEX OF DISTURBANCE CALCULATED ASSUMES AN INSITU POROSITY
C OF 0.30 AND A CORE LINER LENGTH OF 60 INCHES
C THE VALUE OF C IS ASSUMED TO BE THE INSIDE DIAMETER OF THE
C PLASTIC LINER
        IDD=(1.0/0.3-1.0)/(1.0+1.0/(E/(60.0-E)))*100.0
        IDR=(1.0/0.3-1.0)/(1.0+1.0/((C**2-N**2)/N**2))*100.0
C OUTPUT TITLE
        WRITE(6,10)TITLE
C OUTPUT VALUES
        IF(WFLAG.EQ.1) WRITE(6,20)
        IF(WFLAG.EQ.2) WRITE(6,21)
        IF(WFLAG.EQ.3) WRITE(6,22)
        IF(MFLAG.EQ.1) WRITE(6,30)
        IF(MFLAG.EQ.2) WRITE(6,31)
        WRITE(6,40)E
        WRITE(6,50)IDD
        WRITE(6,60)IDR
        WRITE(6,70)Z
        WRITE(6,80)X
        WRITE(6,90)Y
10      FORMAT(20A4)
11      FORMAT(2F10.3)
20      FORMAT('TOP OF SPLIT RING CATCHES CORE')
21      FORMAT('BOTTOM OF SPLIT RING CATCHES CORE')
22      FORMAT('ENTIRE LENGTH OF SPLIT RING CATCHES CORE')
30      FORMAT('TOP OF SPLIT RING STICKS IN CORE LIFTER CASE UPON',
       >' CATCHING CORE')
31      FORMAT('BOTTOM OF SPLIT RING STICKS IN CORE LIFTER CASE',
       >' UPON CATCHING CORE')
40      FORMAT('LONGITUDINAL CORE DISPLACEMENT= ',F10.4)
50      FORMAT('INDEX OF DISTURBANCE DUE TO LONGITUDINAL CORE',
       >' DISPLACEMENT= ',F10.4,'%')
60      FORMAT('INDEX OF DISTURBANCE DUE TO RADIAL EXPANSION= ',
       >F10.4,'%',/,'IDS CALCULATED ASSUMING 30% INSITU POROSITY',
       >' AND A LINER LENGTH OF 60 INCHES')
70      FORMAT('ANGLE Z= ',F10.3,' DEGREES')
80      FORMAT('ANGLE X= ',F10.3,' DEGREES')
90      FORMAT('ANGLE Y= ',F10.3,' DEGREES')
100     FORMAT('CORE TOO SMALL')
        STOP
1000   WRITE (6,100)
        STOP
        END
```

Input file:

```
SK6L FINAL DESIGN UNITS=INCHES
4.100       3.820
2.0          4.001
3.738       3.738
3.844       1.5
0.3          3.770
```

Output file:

```
SK6L FINAL DESIGN UNITS=INCHES
ENTIRE LENGTH OF SPLIT RING CATCHES CORE
BOTTOM OF SPLIT RING STICKS IN CORE LIFTER CASE UPON CATCHING CORE
LONGITUDINAL CORE DISPLACEMENT=       0.1000
INDEX OF DISTURBANCE DUE TO LONGITUDINAL CORE DISPLACEMENT=       0.3889%
INDEX OF DISTURBANCE DUE TO RADIAL EXPANSION=       6.0681%
IDS CALCULATED ASSUMING 30% INSITU POROSITY AND A LINER LENGTH OF 60 INCHES
ANGLE Z=        4.004 DEGREES
ANGLE X=        2.996 DEGREES
```

```
ANGLE Y=         0.0    DEGREES

Input file:
SK6L ORIGINAL DESIGN UNITS=INCHES
4.315       4.050
2.925       4.273
3.988       3.988
4.136       1.575
0.4          4.02
Output file:
SK6L ORIGINAL DESIGN UNITS=INCHES
ENTIRE LENGTH OF SPLIT RING CATCHES CORE
BOTTOM OF SPLIT RING STICKS IN CORE LIFTER CASE UPON CATCHING CORE
LONGITUDINAL CORE DISPLACEMENT=       0.0475
INDEX OF DISTURBANCE DUE TO LONGITUDINAL CORE DISPLACEMENT=       0.1849%
INDEX OF DISTURBANCE DUE TO RADIAL EXPANSION=       3.4439%
IDS CALCULATED ASSUMING 30% INSITU POROSITY AND A LINER LENGTH OF 60 INCHES
ANGLE Z=         2.594  DEGREES
ANGLE X=         2.490  DEGREES
ANGLE Y=         0.0    DEGREES

Input file:
4-5/8'S FINAL DESIGN UNITS=INCHES
2.815       2.535
2.0          2.716
2.453       2.453
2.559       1.5
0.2          2.485

Output file:
4-5/8'S FINAL DESIGN UNITS=INCHES
ENTIRE LENGTH OF SPLIT RING CATCHES CORE
BOTTOM OF SPLIT RING STICKS IN CORE LIFTER CASE UPON CATCHING CORE
LONGITUDINAL CORE DISPLACEMENT=       0.1000
INDEX OF DISTURBANCE DUE TO LONGITUDINAL CORE DISPLACEMENT=       0.3889%
INDEX OF DISTURBANCE DUE TO RADIAL EXPANSION=       9.1137%
IDS CALCULATED ASSUMING 30% INSITU POROSITY AND A LINER LENGTH OF 60 INCHES
ANGLE Z=         4.004  DEGREES
ANGLE X=         2.996  DEGREES
ANGLE Y=         0.0    DEGREES

Input file:
4-5/8'S ORIGINAL DESIGN UNITS=INCHES
3.191       2.837
1.975       3.120
2.704       2.736
2.910       1.390
0.26         2.70

Output file:
4-5/8'S ORIGINAL DESIGN UNITS=INCHES
TOP OF SPLIT RING CATCHES CORE
BOTTOM OF SPLIT RING STICKS IN CORE LIFTER CASE UPON CATCHING CORE
LONGITUDINAL CORE DISPLACEMENT=       0.2000
INDEX OF DISTURBANCE DUE TO LONGITUDINAL CORE DISPLACEMENT=       0.7780%
INDEX OF DISTURBANCE DUE TO RADIAL EXPANSION=       21.9914%
IDS CALCULATED ASSUMING 30% INSITU POROSITY AND A LINER LENGTH OF 60 INCHES
ANGLE Z=         5.121  DEGREES
ANGLE X=         4.320  DEGREES
ANGLE Y=         0.659  DEGREES
```

Appendix B: UTF Coring Logs

Table B.1 AOSTRA wellsite core description hole no. AGI1

Core Run Number	Cut(m)	Rec(m)	Drillers Depth		Tube No.	Depth of Geol. Des.	Lithological (Geological) Description	Remarks
			From	To				
1	1.65	0.00	141.81	143.45		ns		no tube put in freezer
2	0.25	0.19	143.45	143.70		143.93	black, fine grained R.O.S., rare	no tube put in freezer
							large mica grains	0.18m bagged 143.52-143.70
3	1.65	1.99	143.70	145.35	3	145.30	black fine grained R.O.S. with	core swelling badly
							black-dark grey clay laminations	0.44m bagged 144.91 to 145.30
4	1.65	1.66	145.35	147.00	4	147.00	black fine grained R.O.S. with	0.14m core bagged 146.76-147.0
							small clay laminations	core swelling
5	1.50	1.77	147.00	148.50	5	148.50	black fine grained R.O.S.	0.25m bagged 148.25-148.5
6	1.50	1.70	148.50	150.00	6	150.00	as above	0.18m bagged 149.82-150.0
7	1.50	1.62	150.00	151.50	7	151.50	as above, traces of wet grey	0.10m core bagged 151.4 to
							inconsolidated quartzose sand	151.5
8	1.50	1.59	151.50	153.00	8	153.00	black fine grained R.O.S., rare	0.07m core bagged
							mica grains	152.93 -153.0
9	1.50	1.43	153.00	154.50	9	154.50	as above	0.14m core bagged
								154.36 - 154.5
10	1.50	1.50	154.50	156.00	10	156.00	as above	
11	1.50	1.49	156.00	157.50	11	157.50	as above	0.14m core bagged
								157.36 - 157.49
12	1.50	1.59	157.50	159.00	12	159.00	as above	0.05 m core bagged
								158.95 - 159.0
13	1.50	1.69	159.00	160.50	13	160.50	as above	0.17m core bagged
								160.33 - 160.5
14	1.50	1.40	160.50	162.00	14	161.90	grey silty claystone, well indurated hard	core not frozen in order
							brown patches (frozen after sampling)	to sample basal Km shale
15	1.50	0.74	162.00	163.50	15	162.70	wet, fine grained, black L.O.S. to M.O.S.	reservoir below basal Km shale
								is often wet
16	1.00	1.14	163.50	164.50	16	163.70	wet fine grained L.O.S./rig chattered	core catchers on Craelius
							as if coal above limestone--rubble zone?	would not hold limestone
Total	22.70	21.46					Date: 87 08 15 Core Diameter 102 mm	
							Percentage Recovery 94.5%	

Table B.2 AOSTRA wellsite core description hole no. AT7

Core Run Number	Cut(m)	Rec(m)	Drillers Depth		Tube No.	Depth of Geol. Des.	Lithological (Geological) Description	Remarks
			From	To				
1	1.65	0.31	142.00	143.65	none	142.31	cemented siltstones, some bitumen	no tube - catcher in liner
							saturated sands	0.31m bagged 142.0 - 142.31
2	0.40	1.05	143.65	144.05		143.90	L.O.S., some mica grains	
3	1.65	0.29	144.05	145.70	none	144.34	indurated V.L.O.S. some silt	no tube .16/.13m bagged
								0.29m bagged 144.05 - 144.34
4	1.65	0.00	145.70	147.35	none		nr	
5	0.50	0.07	147.35	147.85	none	147.38	L.O.S. shale partings burrows	0.07 m bagged 147.31 - 147.38
6	1.00	0.20	147.85	148.85	none	148.05	black fine grained M.O.S.	take out plastic catcher in liner
								0.20m bagged 147.85 - 148.05
7	1.50	1.66	148.85	150.35	7	150.35	black fine grained R.O.S.	w/o plastic catcher, core swelling
								0.14m excess 150.21 - 150.35
8	1.50	1.61	150.35	151.85	8	151.85	competent, black hard micaceous R.O.S.	core swelling
								0.11m bagged 151.74 - 151.85
9	1.50	1.92	151.85	153.35	9	153.35	black fine grained R.O.S.	core swelling
								0.40m bagged from end of run
10	1.50	1.68	153.35	154.85	10	154.85	black fine grained R.O.S.	core swelling
								0.38m bagged 154.47 - 154.85
11	1.50	1.04	154.85	156.35	11	155.89	as above very soft	0.11m excess bagged
								155.78 - 155.89
12	1.00	1.08	156.35	157.35	12	157.35	black poorly sorted micaceous	0.07m bagged 157.28 - 157.35
							R.O.S. wet large mica grains	
13	1.50	0.60	157.35	158.85	13	157.95	black fine grained R.O.S.	0.23m bagged 157.72 - 157.95
14	1.50	0.15	158.85	160.35	none	159.00	hard, black to brown, micaceous L.O.S.	0.15m bagged 158.85 - 159.0
							coaly stringers, small pyrite nodules	
15	1.50	0.25	160.35	161.85	none	160.60	interbeds: wet fine grained M.O.S. hard	0.25m bagged 160.35 - 160.6
							grey argillaceous siltstone rare	
							pyrite traces	
16	1.50	0.32	161.85	163.35	none	162.17	as above	0.32m bagged 161.85 - 162.17
							Date: 87 09 19 Core Diameter 96 mm	

Table B.3 AOSTRA wellsite core description hole no. AT2

Core Run Number	Cut(m)	Rec(m)	Drillers Depth		Tube No.	Depth of Geol. Des.	Lithological (Geological) Description	Remarks
			From	To				
1	1.50	1.37	123.00	124.50	1		very fine grained claystone btm of Kc between 124.5 and 126.0	Clearwater (Kc)
2	1.50	0.97	124.50	126.00	2		coarse grained sand quartz, chert and lithic fragments	Wabiskaw
3	1.50	1.38	126.00	127.50	3		wet very fine grained, soft weak dark grey sandstone, quartz, chert and microlithic fragments	0.08m bagged
4	1.50	1.50	127.50	129.00	4		wet, fine grained sandstone, dark grey claystone laminae	
5	1.50	0.00	129.00	130.50			no recovery for 3 runs unable to pick up core bit plugged	
6	1.50	0.00	130.50	132.00				
7	1.50	0.00	132.00	133.50				
8	1.50	1.13	133.50	135.00	5	133.85	very hard cemented band at base of core, sandstone with traces of bitumen and clay bands very fine grained	0.08m bagged
9	1.50	1.50	135.00	136.50	6	136.50	wet, fine grained sandstone with fine grained dark clay interlaminae	0.12m bagged
10	1.50	1.33	136.50	138.00	7	137.83	lean oil sand, fine grained	
11	1.50	1.55	138.00	139.50	8	139.50	black, indurated medium oil sands with shale interbeds	0.04m bagged
12	1.50	1.43	139.50	141.00	9	140.93	hard siltstone bands interbedded with black rich oil sands	
13	1.65	1.63	141.00	142.65	10	142.63	rich oil sand, black, with hard siltstone band	0.07m bagged
14	1.65	1.55	142.65	144.30	11	144.20	black, rich oil sands	0.05m bagged
15	1.50	1.57	144.30	145.80	12	145.80	black, rich oil sand interbedded with siltstone bands	0.07m bagged
16	1.65	1.54	145.80	147.45	13		black fine grained rich oil sand soft, wet	0.06m bagged
17	1.65	1.59	147.45	149.10	14	149.04	black, soft, wet fine grained medium to rich oil sands	0.10m bagged trace of brown wet soft quartzose sand
18	1.00	1.11	149.10	150.10	15	150.10	brown, hard, argillaceous, micaceous siltstone to very fine grained sandstone	0.14m bagged
19	1.65	1.50	150.10	151.75	16	151.60	hard, black rich oil sand competent	
20	1.00	0.97	151.75	152.75	17	152.72	black, fine grained rich oil competent	
21	1.65	1.57	152.75	154.40	18		black, fine grained rich oi l sand large mica flakes	0.08m bagged
Total	31.40	25.19					Date: 87 08 23 Core Diameter 63 mm	
							Percentage Recovery 80.2%	

Table B.4 AOSTRA wellsite core description hole no. AT3

Core Run	Cut(m)	Rec(m)	Drillers Depth		Tube	Depth of	Lithological (Geological) Description	Remarks
Number			From	To	No.	Geol. Des.		
1	1.20	1.50	133.00		1	134.20	dark grey to black claystone very	Jammed off due to junk downhole
							slightly silty	0.01m excess 132.5-133.0
				134.20				bagged
2	1.50	1.47	134.20		2	125.67	black to dark grey argillaceous fine	0.08m excess 125.59-125.67
							grained sandstone, glauconite,quartz chert	
				125.70				
3	1.50	0.10	125.70		no	?	grey-brown fine grained argillaceous	0.10m bagged, probably
					tube		sandstone claystone laminae small pyritic	from top of run
				127.20			lenses from top of run	
4	1.50	1.42	127.20		3	128.62	dark brown very fine grained argillaceous	0.10m bagged
							laminated sandstone with dark grey clay	128.52-128.62
				128.70			laminae	
5	1.65	1.57	128.70		4	130.27	dark grey hard silts, dark grey black clay	0.09m bagged
							laminae siltstone lenses, brown fine	130.18-130.27
				130.35			grained sand laminae	
6	1.65	1.57	130.35		5	131.92	dark grey well indurated argillaceous	0.09 bagged
							silts, pyrite lenses	131.83-131.92
				132.00				
7	1.65	1.58	132.00		6	133.59	dark grey-black wet, laminated fine	0.09 bagged
							grained argillaceous sandstone with clay	133.47-133.59
				133.65			laminae	
8	1.60	1.40	133.65		7	135.14	dark grey yellow pyritic siltstone	
				135.25				
9	1.60	1.58	135.25		8	136.83	grey micaceous silts Lean Oil Sands and	0.09m bagged
							very fine grained brown micaceous sand	136.74-136.83
				136.85			laminate	
10	1.60	1.50	136.85		9	138.35	interlaminated to interbedded grey	0.08m bagged
							siltstone,dark brown claystone and black	138.27-138.35
				138.45			fine grained medium rich oil sand	
11	1.60	1.58	138.45		10	140.01	dark grey wet fine grained micaceous	0.08m bagged
							lean oil sand to medium rich oil sand	139.93-140.01
				140.05			grey siltstone interbeds	
12	1.50	1.47	140.05		11	141.52	dark grey wet fine grained lean oil sand	
							with siltstone interbeds,micaceous	
				141.55				
13	1.60	1.65	141.55		12	143.15	wet, dark grey lean oil sand with dark	0.15m excess
							siltstone bands, indurated	143.0-143.15
				143.15				
14	1.60	1.58	143.15		13	144.73	dark grey to black medium rich oil sands	0.10m excess
							with hard dark grey siltstone bands,	144.63-144.73
				144.75			harder than above	
15	1.60	1.61	144.75		14	146.35	soft dark grey to black, medium to rich	0.11m excess
							oil sand, some thin siltstone interbeds	146.24-146.35
				146.35			large mica flakes	
16	1.60	1.61	146.35		15	147.95	hard dark grey medium rich oil sand with	0.11m excess
							siltstone interbeds large mica grains	147.84-147.95
				147.95			interbeds, about .25 cm	
17	1.65	1.62	147.95		16	149.57	black rich oil sand with very thin	0.12 bagged
							siltstone interlaminae, soft	149.48-149.60
				149.60				
18	1.65	1.63	149.60		17	151.23	black rich oil sands traces of siltstone	0.13 bagged
							large mica grains	151.12-151.25
				151.25				
19	1.65	1.63	151.25		18	152.88	black rich oil sand fairly hard large	0.13 bagged
							mica grains, no siltstone	152.77-152.9
				152.90				
20	1.60	1.45	152.90		19	154.35	black rich oil sand to very rich oil sand	0.07m bagged
							soft, clean quartz grains visible	154.43-154.5
				154.50				
Total	31.35	29.66					Date: 87 08 25 Core Diameter 63 mm	
							Percentage Recovery 94.6%	

Table B.5 AOSTRA wellsite core description hole no. AT6

Core Run Number	Cut(m)	Rec(m)	Drillers Depth From	Drillers Depth To	Tube No.	Depth of Geol. Des.	Lithological (Geological) Description	Remarks
1	2.00	1.03	123.00		1	123.33	dark grey claystone, traces of silt	had to make pick up run
							silty laminations	core badly damaged
				125.00	No			Clearwater Fm.
2	3.00	2.15	125.00		2	125.65	dark grey argillaceous siltstone lenses	Wabiskaw Mb.
							of fine grained dark green glauconitic sand	
				128.00	3	127.15	dark grey very fine grained argillaceous	
							sandstone, quartz chert mica glauconitic	
3	2.50	2.68	128.00		4	129.00	dark grey-brown argillaceous micaceous	McMurray Fm.
							fine grained sandstone	
				130.50	5	130.50	dark grey micaceous very fine grained	rare brown sandstone laminae
							argillaceous sandstone, lenses of siltstone	
4	3.00	3.00	130.50		6	132.00	dark brown very fine grained argillaceous	
							sandstone large mica-grains	
				133.50	7	133.50	dark brown argillaceous siltstone,	
							interbeds of dark brown sandstone	
5	3.00	3.04	133.50		8	135.00	dark grey argillaceous silty sandstone	
							micaceous slight oil stain	
				136.50	9	136.50	dark brown laminated, very fine grained	0.05m bagged 136.46-136.5m
							L.O.S.	
6	3.00	3.00	136.50		10	138.00	interbeds: brown very fine grained	
							argillaceous sandstone, siltstone	
				139.50	11	139.50	black soft wet fine grained R.O.S.	good reservoir
7	3.00	3.00	139.50		12	141.00	black soft wet fine grained U.O.S.,	core swelling
							lenses of brown wet quartzose sand	
				142.50	13	142.50	laminae of black fine grained U.O.S.	0.09m bagged 142.41 to 142.50m
							brown argillaceous siltstone, mica	
8	3.00	3.00	142.50		14	144.00	black, soft wet fine grained R.O.S.	core swelling
				145.50	15	145.50	as above	
9	3.00	3.00	145.50		16	147.00	black, fine grained moderately weak	core swelling
							M.O.S. to R.O.S.	
				148.50	17	148.50	as above clay laminae	0.09m bagged 148.41 to 148.50 m
10	3.00	3.00	148.50		18	150.00	black fine grained soft R.O.S.	core swelling
				151.50	19	151.50	hard, black fine grained R.O.S.	0.04m bagged 151.46 to 151.50
11	2.90	2.80	151.50		20	152.00	as above	
				154.40	21	154.30	black, soft fine grained V.R.O.S., trace	
							of brown quartzose sand	
Total	31.40	29.90						
							Date: 87 08 30 Core Diameter 60 mm	
							Percentage Recovery 95.2%	

Table B.6 AOSTRA wellsite core description hole no. AGI4

Core Run Number	Cut(m)	Rec(m)	Drillers Depth		Tube No.	Depth of Cent. Des.	Lithological (Geological) Description	Remarks
			From	To				
1	1.50	1.57	135.00	136.50	1	136.50	dark-brown, laminated very fine grained	0.10m bagged 136.4 - 136.5
							sandstone, U.O.S. laminae, micaceous	
2	1.60	1.47	136.50	138.10	2	137.97	as above though matrix is L.O.S.	0.11m bagged 137.86 - 137.97
3	1.60	1.53	138.10	139.70	3	139.63	black, laminated fine grained micaceous	0.04m bagged 139.59 - 139.63
							L.O.S.	
4	1.60	1.54	139.70	141.30	4	141.24	dark-brown, laminated, very fine grained	0.14m bagged 141.10 - 141.24
							L.O.S., U.O.S. lenses, large mica grains	
5	1.60	1.52	141.30	142.90	5	142.82	black, fine grained R.O.S.	0.04m bagged 142.78 - 142.82
6	1.60	1.57	142.90	144.50	6	144.47	black, soft, wet fine grained R.O.S.	0.10m bagged 144.37 - 144.47
7	1.60	1.62	144.50	146.10	7	146.10	black, hard, fine grained R.O.S., with	0.15m bagged 145.95 - 146.10
							grey silty argillaceous lenses	
8	1.60	1.47	146.10	147.70	8	147.57	black, fine grained R.O.S.	
9	1.50	1.57	147.70	149.20	9	149.20	as above	0.10m bagged 149.10 - 149.20
10	1.60	1.29	149.20	150.80	10	150.49	soft black fine grained R.O.S.	
11	1.30	1.27	150.80	152.10	11	152.07	soft black fine grained V.R.O.S.	0.18m bagged 151.89 - 152.07
12	1.60	1.62	152.10	153.70	12	153.70	black fine grained R.O.S.	0.14m bagged 153.56 - 153.70
13	1.60	1.62	153.70	155.30	13	155.30	hard, competent, black fine grained	trace of w/s at top of tube
							R.O.S.	0.15m bagged 155.15 - 155.30
14	1.60	1.48	155.30	156.90	14	156.78	as above	
15	1.60	1.56	156.90	158.50	15	158.46	black-brown fine grained mottled M.O.S.	0.16m bagged 158.30 - 158.46
							with argillaceous clasts	
16	1.60	1.60	158.50	160.10	16	160.10	hard black, fine grained V.R O.S.	0.12m bagged 159.90 - 160.10
17	1.60	1.62	160.10	161.70	17	161.70	black, soft fine grained R.O.S.	0.15m bagged 161.55 - 161.70
18	1.60	1.46	161.70	163.30	18	163.16	grey-green argillaceous micrite	
19	1.50	1.52	163.30	164.80	19	164.80		Dev. top 163.3m
								0.06m discard
Total	29.80	28.90					Date: 8710 07 Core Diameter 63 mm	
							Percentage Recovery 96.8%	

Table B.7 AOSTRA wellsite core description hole no. CI

Core Run Number	Cut(m)	Rec(m)	Drillers Depth From	Drillers Depth To	Tube No.	Depth of Geol. Des.	Lithological (Geological) Description	Cumulative Recovery
1	1.50	1.50	146.20	147.70	1	147.70	ss blk, good oil stn, soft, fine-medium well srtd.	1.5
2	1.50	1.58	147.70	149.20	2	149.20	ss: a/s	3.08
3	1.50	1.50	149.20	150.70	3	150.70	ss: blk good oil stn, soft-med, well srtd	4.58
4	1.50	1.50	150.70	152.20	4	152.20	ss: a/s - some clay near base	6.08
5	1.50	1.30	152.20	153.70	5	153.70	a/s	7.58
6	1.50	1.53	153.70	155.20	6	155.20	a/s micaceous	9.11
7	1.50	1.50	155.20	156.70	7	156.70	a/s	10.61
8	1.50	1.50	156.70	158.20	8	158.20	a/s	12.11
9	1.50	1.56	158.20	159.70	9	159.70	a/s	13.67
10	1.50	1.50	159.70	161.20	10	161.20	a/s	15.17
11	1.50	1.50	161.20	162.70	11	162.70	a/s w/ clay clasts	16.67
12	1.50	1.58	162.70	164.20	12	164.20	a/s	18.25
13	1.50	1.50	164.20	165.70	13	165.70	a/s w/ clay clasts	19.75
14	1.50	0.90	165.70	167.20	14	167.20	lst	20.65
15	0.90	0.66	167.20	168.10	15	-	a/s bedded	21.31
16	1.00	1.72	168.10	169.10	16	169.10	a/s bedded	23.03
17	1.40	1.34	169.10	170.50	17	170.50	a/s bedded	24.37
Total	24.30	24.37					Date: 87 10 15 Core Diameter 102 mm	
							Percentage Recovery 100.3%	

Appendix C: UTF Geophysical Logs

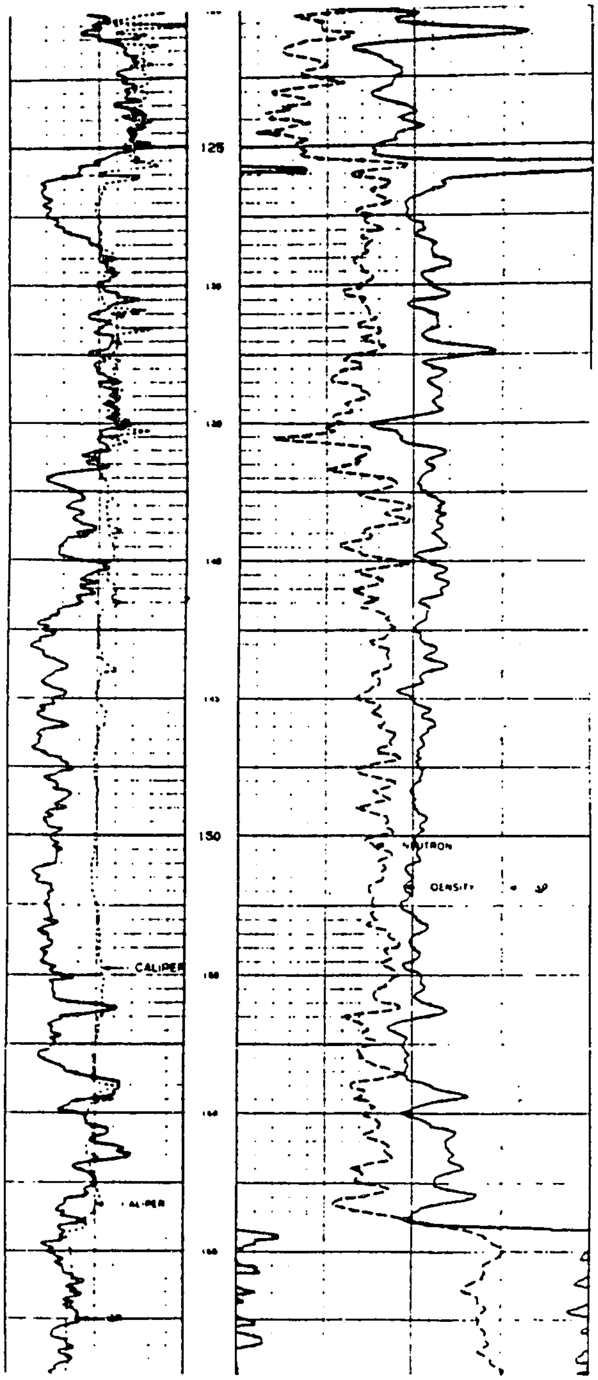

Figure C.1 Geophysical logs hole AGI1

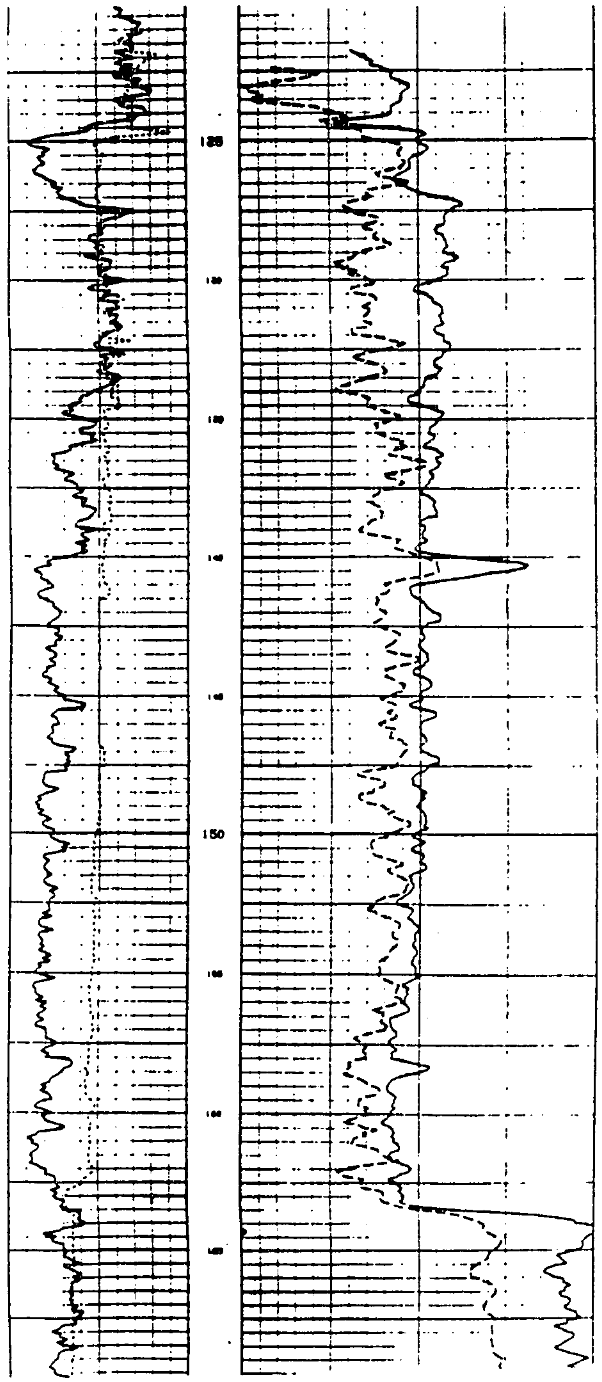

Figure C.2 Geophysical logs hole AT7

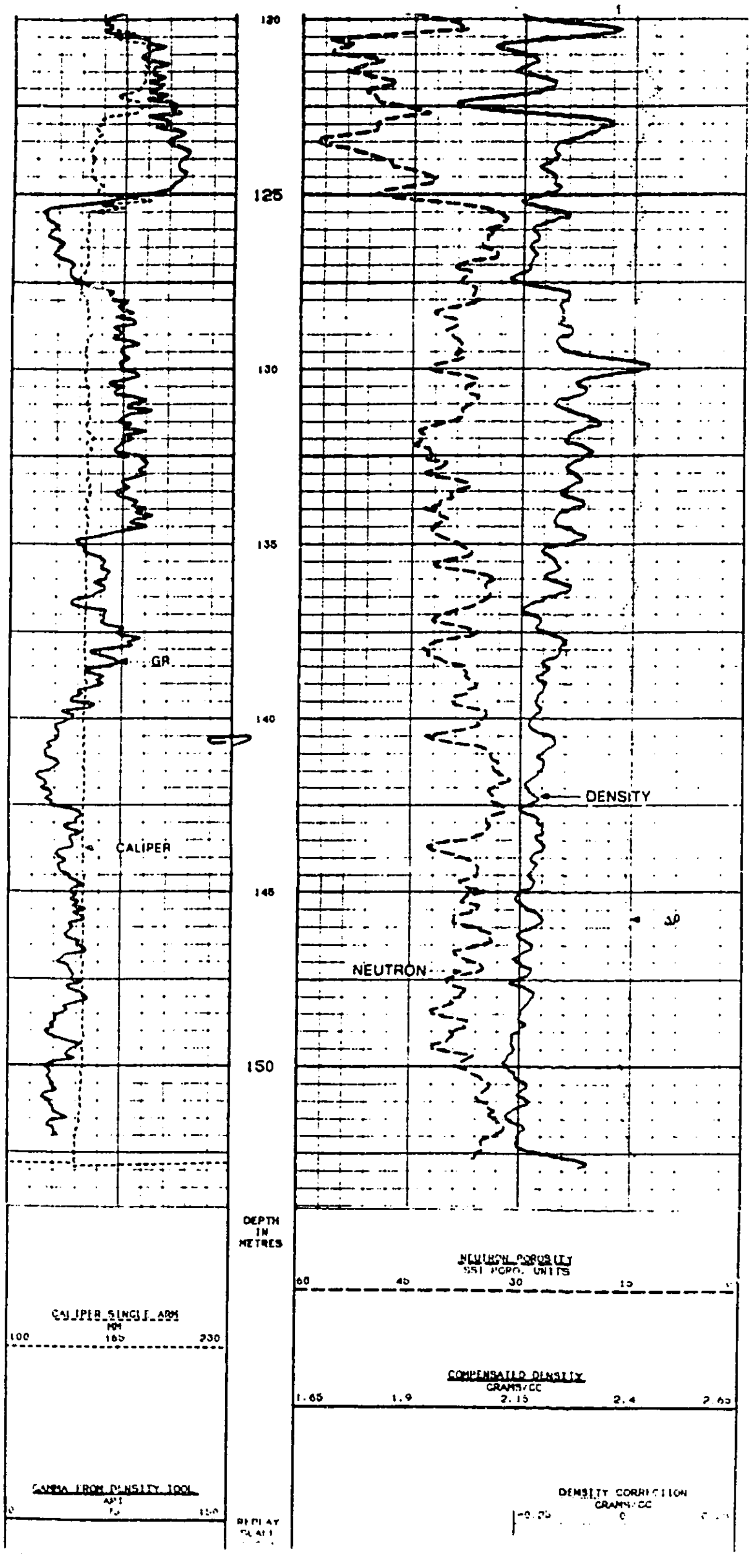

Figure C.3 Geophysical logs hole AT3

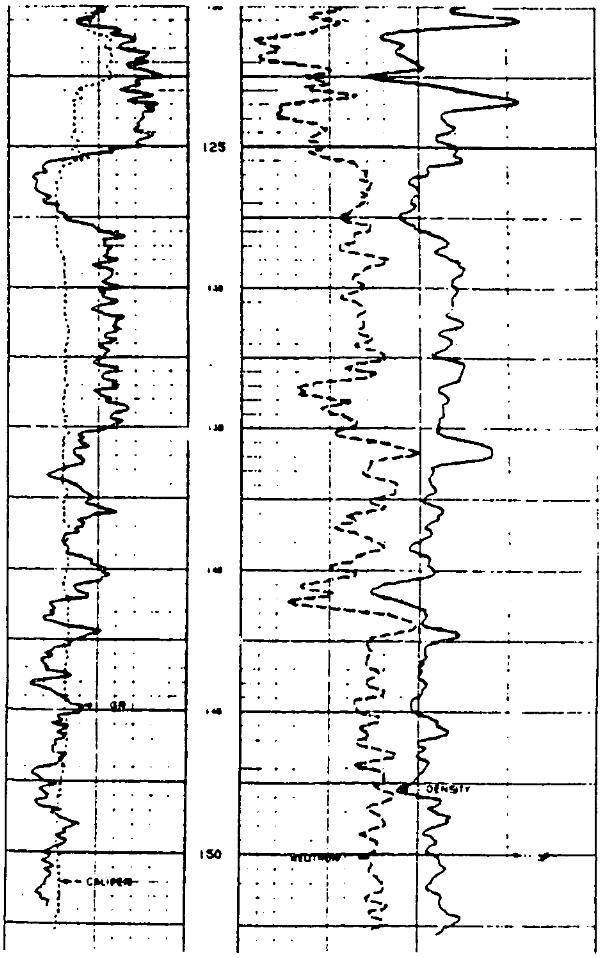

Figure C.4 Geophysical logs hole AT6

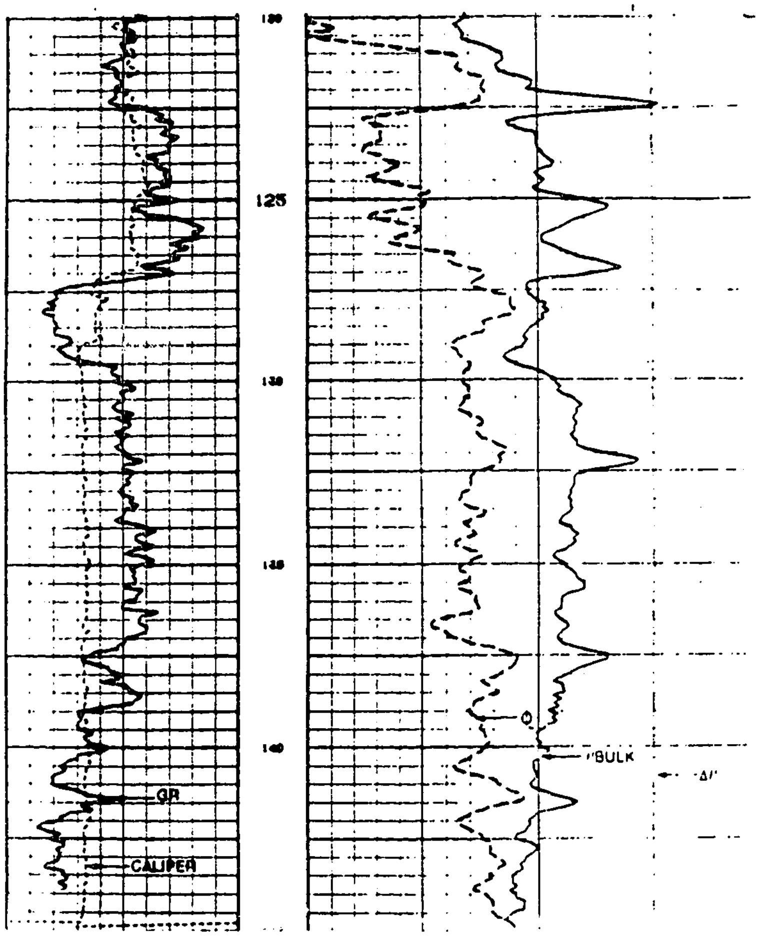

Figure C.5 Geophysical logs hole CI