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# Horizontal Core Acquisition And Orientation For Formation Evaluation

**Robert A. Skopec** **Oryx Energy Company, Dallas**
**Monte M. Mann** **Diamant Boart Stratabit, Houston**
**Doug Jeffers** **Scientific Drilling International, Midland**
**Susan P. Grier** **Core Laboratories, Dallas**

## ABSTRACT

The increase in horizontal drilling activity has produced a need for improved coring technology. The development of a reliable horizontal (medium radius) coring and orientation system has greatly improved the acquisition of information necessary for formation evaluation and reservoir engineering. A concerted effort between Oryx Energy Company and service companies has resulted in newly developed hardare and methods for obtaining horizontal core sections. Horizontal coring presents for the first time an opportunity to directly examine the lateral evolution of rock facies, reservoir heterogeneity, vertical fracture spacing, and fluid distribution. These data are essential to understanding horizontal well behavior and are particuarly useful in reservoir modeling. Reservoir description is the foundation for designing, operating and evaluating the performance of a horizontal wellbore.

## INTRODUCTION

Oryx Energy Company has successfully recovered horizontal core from highly fractured carbonate rocks in south and west Texas. Acquisition of representative reservoir rock during drilling is the most tangible technique for gaining direct knowledge of the subsurface.

Data obtained from horizontal core are a prerequisite for developing realistic projections of reservoir performance, as well as definition of highly complex pore systems. Characterization of the fracture network geometry and degree of connectivity is essential to understanding transient and steady-state fluid flow. When a reservoir is being developed with horizontal well-

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bores, a considerable amount of geological information is needed for calculating its volumetric potential and quality. Production is optimized in fractured reservoirs when the horizontal wellbore intersects the fractures in a direction perpendicular to their surfaces. Lateral evolution of facies and fracture orientation is most reliably obtained from core material. Horizontal wells can also be highly effective in reservoirs where conventional wells have low productivity, where productivity is limited by water and gas coning, and in thick continuous sands containing heavy oil and bitumen where steam-assisted gravity drainage is possible.[1]

Wireline logs cannot be used as a substitute for the information gained from core material. Conventional logs such as the nuclear, electrical, and sonic tools can be easily run in horizontal wells; however, they exhibit very little character and are insensitive to fractures. Advances have been made in fracture delineation with electrical imaging and acoustic waveform logs. Difficulties arise with these devices in distinguishing open and mineralized fractures. There is distortion of fracture azimuth/aperture, and they can be sensitive to borehole rugosity. Acoustic logs often exhibit cycle skipping, making it impossible to define fracture porosity. In many instances, well conditions may prohibit well logging altogether, and the cost of running speciality logs can be quite high.[2]

Comprehensive formation evaluation in horizontal wells is best accomplished through the integration of core and log analysis. Pressure transient data and geophysical methods are also useful in examining large-scale reservoir properties. All sources of data are essential to provide a basis for developing a viable reservoir model.

Very few references to horizontal coring exist in the literature.[3, 4, 5] Elf Aquitaine has reported extraction of core from oil-bearing limestone reservoirs at Lacq, France; Castera Lou, France; and Rospo Mare, in the Italian Adriatic.[4]

Operators in the United States have been slow to adopt horizontal coring, and many insist on coring the formation of interest vertically and re-entering the borehole for completion of the horizontal section. This method is problematic due to the thin nature of many fractured reservoirs targeted for horizontal drilling.

In the past, the Petroleum Industry has suffered from poor coring performance, resulting in high costs of obtaining core from indurated and fractured formations.[6] The primary reason for poor recovery was the frequent jamming of the rock in the coring assembly. This problem has been largely overcome by the use of flexible fiberglass inner barrels and multiple core-catcher assemblies. On four horizontal coring projects, Oryx Energy Company has achieved a recovery rate of almost one hundred percent efficiency by utilizing shorter core sections and improved inner and outer barrel stabilization. For orientation purposes, a slip scribe is used in conjunction with an Electronic Multishot Instrument (EMI). The EMI is a solid-state survey device which utilizes an array of accelerometers for determination of inclination. Magnetometers are used to determine orientation with respect to geographic north. Many of the problems associated with camera surveys have been alleviated through the use of EMI technology. To operate the EMI in a horizontal configuration, it was necessary to develop specialized equipment. A newly designed rotatable nonmagnetic blade centralizer, enhanced running gear, and a high frequency shock absorber must be used to obtain accurate core orientation data.

Perfect alignment of the knives cutting the core (slip scribe) and the survey instrument is necessary to obtain accurate core orientation data. All of the methods previously used for alignment have been proven to cause significant error. To assure positive alignment of the coring assembly, a Laser Alignment System (LAS), patent pending, has been invented and used successfully. Also, specialized horizontal core handling procedures have been developed to insure accurate core orientation data.

It must be stressed that core alone is not the answer to all formation evaluation problems. The value of the core data is a direct function of its integrity upon retrieval and the cooperation among the core acquisition and analysis team. Without a carefully conceived coring and orientation plan, the core material could render itself useless. Difficulties are also evidenced in determining the criteria necessary to define a core point. Mud log shows can be very subtle in horizontal wells, and drilling parameters must be relied upon to identify high porosity zones. Well control problems inherent to horizontal drilling can preclude safe coring conditions.

The objective of this paper is to provide a background on the efficient retrieval of oriented horizontal core and the measures needed to obtain accurate orientation data.

## HORIZONTAL CORE ACQUISITION

### Bottom Hole Coring Assembly (BHCA)

The following core assembly guidelines apply to medium-radius lateral drilling with build rates approximating 10-20°/100 ft (174-349 mrad/30m)[7] (Figure 1). These methods are also highly recommended for long-radius directional drilling with rates of 1°-6°/100 ft (17.4-104.7 mrad/30m).

Short radius coring has been attempted; however, this method severely limits the length of core obtainable due to high build rates of 1°-3°/drilled foot (69.8-174.5 mrad/0.3 m). Additional rig time and economics make short radius coring unfavorable.[8]

Drilling oil and gas bearing fractures in the presence of lost circulation can pose safety problems when coring. Gas kicks are common in fractured reservoirs, and trip gas is a constant threat when pulling the coring assembly. High quality mud logging can aid in resolving subtle changes when drilling laterally if adequate mud returns and/or gas shows are evident. With the advent of positive displacement mud motors and polycrystalline diamond bits in horizontal drilling, drill cuttings offer little evidence of productive zones because of their poor quality. Often when drilling is underbalanced, return oil serves as the sole criteria for selection of the core point. When drilling overbalanced, maintaining a minimum mud weight above formation pressure will improve core recovery and minimize flushing of the core. Drilling fluids should be designed to optimize drilling parameters while minimizing formation (core) damage.

Specific objectives for horizontal coring include:

1) Efficient recovery of core sections.
2) High recovery rates.
3) Quality core material.
4) Accurate orientation data.
5) Maintenance of borehole angle.
6) Comprehensive core analysis.

## Inner Barrel and Core Head

Fibertube (fiberglass) inner barrels were used to facilitate core entry and improve coring efficiency. Fiberglass has a low coefficient of friction, is extremely durable, and is flexible enough to prevent jamming. Fiberglass is the inner barrel of choice in horizontal coring for reducing friction during core entry. Fiberglass can be cut at the wellsite and is used as a core preservation container.

The core head, which was designed for hard rock, has a full round profile (regular gauge) ridge-set natural diamond bit for high rates of penetration and added stabilization. A short bit-throat design was used to minimize friction force and avoid jamming. Typically, 4 in (10 cm) - diameter core is obtained in 30 ft (9 m) sections with 8-1/2 in (22 cm) bits. A slip scribe core catcher assembly with tungsten-carbide chamfered knives placed at 0, 134 and 206 degrees (0,2.34 and 3.60 rad) was used for scribing and orientation purposes. Slip scribe components are coated with tungsten carbide grit to facilitate positive core catching (Figure 2).

## Stabilization

The BHCA portion of the drill-string affects the trajectory of the bit and, consequently, the wellbore.[9] Side forces at the bit can cause the BHCA to build or drop angle, depending on the design of the outer barrel stabilizers. The inclination of the horizontal wellbore must be maintained to a tolerance of no greater than ±1-2°/100 ft (17.4-34.9 mrad/30m) during coring to prevent excessive doglegs. All coring was performed from the rotary table to avoid complications often encountered with mud motors. Low rotary speeds (40-50 RPM) were used to avoid core damage, barrel jams, and to prevent excessive inner barrel rotation.

A slick assembly (bit with drill collars) caused the inclination of the well to drop during coring at a rate of 0.3°/30 ft (5.24 mrad/9 m) (Figure 3). In an attempt to improve upon the slick assembly, a two-point concentric stabilization was tried. Stabilizers were sized 1/4 in (0.6 cm) undergauge, positioned near the bit and at 30 ft (9 m) from the bit. This BHCA dropped angle at rates more severe than the slick design, 0.7°/30 ft (12.2 mrad/9 m). Optimum conditions were achieved with a dual-stabilizer BHCA, with a 1/8 in (0.3 cm) undergauge near-bit stabilizer and a 1/2 in (1.2 cm) undergauge stabilizer at 30 ft from the bit (Figure 4). Results from this BHCA indicate that the inclination of the well dropped at an acceptable rate of approximately 0.1°/30 ft (1.74 mrad/9 m), and essentially acted as a hold assembly (Table 1). Core sections are cut early in the lateral section when maintaining the borehole angle is easiest and assembly torque is at a minimum. Besides improving recovery, adequately stabilized barrels will preserve the mechanical integrity of the core, making it more useful to the core analyst. Shorter core sections of 30 ft (9 m) were taken due to the radius of curvature (10°/100 ft, 174 mrad/30m) of the well at the kickoff point and the stiffness of the drill collars. For build rates greater than 12°/100 ft (208 mrad/30m), the rigid cylinder equation will need to be examined to determine the optimum core barrel length.

Inner barrel stabilization is critical in horizontal coring operations. The forces of gravity cause the inner barrel to decentralize, which increases the risk of jamming. To prevent bowing, a bronze fluted bushing is milled and fitted directly to the fiberglass inner barrel (Figure 5). A core head modification that included the addition of a radial roller bearing assembly has also improved inner barrel stabilization (Figure 2). Composite inner barrel centralizers were proven to be unsuitable for horizontal coring.

## Coring Parameters

By optimizing the design of the BHCA, gravity effects can be overcome in horizontal coring. Coring parameters are more difficult to monitor when drilling laterally. The rate of penetration is less important than obtaining quality core sections. To avoid coring complications, light Weight-On-Bit

(WOB) and low rotary speeds are used to minimize bending of the relatively flexible core barrel. Reducing drilling parameters also results in better scribe quality and lessens the chances of spiraling the core. Low flow rates are used to reduce disturbance of the core.

After coring, *tripping-out* of the borehole should be slow, particularly through the build angle section. The drill-string must be *chained-out* to prevent rotation of the core barrel. Pup joints are used to insure a full kelly and eliminate the need for connections during coring.

When coring horizontally, it is difficult to ascertain when the core bit is in contact with the formation due to the inaccuracy of the WOB indicator. At the start of the coring process, lighter weights are required, and this further reduces the certainty of when coring begins. For this reason, pump pressure is the most reliable indicator for monitoring the coring progress.

Depth versus time is correlated at the surface by the coring engineer and orientation surveyor. A stop watch is started simultaneously with the multishot instrument, and depth is correlated to 0.1 ft (3.05 cm) from the geolograph. Depth misalignment errors can occur when coring is stopped to circulate drilling fluid, when the core barrel is jammed or when the bit loses contact with the formation. During these times, the surveyor must pay close attention to drilling parameters. The core depth and drillers' depths should be compared by *strapping-out* of the borehole. A core gamma ray trace can also be used for exact depth correlation if wireline logs are run.

## HORIZONTAL CORE ORIENTATION

Many of the formations targeted for horizontal drilling are fractured. Horizontal core orientation data are used by explorationists for basin analysis and prospect delineation. Reservoir engineers use these data for modeling to determine drainage patterns and reservoir volumes. Completion and stimulation programs can also be optimized if fracture orientation data are available.

In 1988, Oryx Energy Company indicated to various service companies the need to improve core survey quality. The new generation of magnetic surveying instrumentation was well-proven in Measurement While Drilling (MWD) operations.

Many of the problems associated with using an Electronic Multishot Instrument (EMI) in coring were easily corrected, while others only required the close cooperation of the surveyor and core analyst.

## Electronic Multishot Instrument (EMI)

The Combination High Accuracy Magnetic Probe (CHAMP*) EMI tool was used for all horizontal core orientation. The EMI is a solid-state self-contained directional surveying device that measures tool attitude in relation to the earth's magnetic and gravitational fields. The gravity sensor array consists of three orthogonal accelerometers: Z, along the tool axis; X, perpendicular to the Z axis in line with the T-slot at the end of the tool; and Y, perpendicular to both the X and Z axis (Figure 6). The magnetic sensor array consists of three orthogonal fluxgate magnetometers which are configured parallel to the axes of the accelerometers. Collected raw data consist of accelerometer outputs, magnetometer outputs, probe temperature, battery voltage, and calibration data.[10]

The accelerometer array is used to derive inclination, high-side toolface, and the vertical resultant in azimuth. Magnetometer data are used to calculate azimuth and magnetic toolface. Several toolface reports can be acquired by the EMI probe. High side, magnetic only, and gravitational-magnetic toolface data are most important in coring operations. The magnetic only and gravitational-magnetic toolface data rely on the use of stationary (steel) shots taken at the beginning and end of coring. These stationary shots are used for EMI vibration (offset) corrections. The most critical data obtained in horizontal coring come from the gravitational-magnetic toolface. This information is reliable in high angle/horizontal boreholes and uses borehole azimuth as its frame of reference. Calculated data for a typical core survey are given in Table 2.

Since the EMI is a magnetic device, the data must be corrected for magnetic declination. The EMI is carefully positioned to minimize magnetic interference. The geodetic location of the well, volume of magnetic material above and below the EMI, and borehole azimuth/inclination influence the total magnetic signal.[9] When coring horizontally, borehole inclination and azimuth are

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affected because of their alignment with the Z axis component. To overcome this effect, two 30 ft (9 m) Non-Magnetic Drill Collars (NMDC) made of austenitic steel were used to isolate the EMI.[11] Spacing of the EMI was optimized by comparing measured and calculated values of magnetic field strength. Comparison of the magnetic components and borehole azimuth values from the MWD survey and EMI probe serves as a means of cross-checking data quality prior to coring. This measure also assures that spacing of the EMI within the NMDC is optimized. Exact placement of the EMI is accomplished with non-magnetic variable length spacer bars. The EMI can withstand temperatures up to 257°F (125°C) and pressures of up to 20,000 PSI (137.9 MPa). The EMI will continuously record up to 1,023 data sets in non-volatile memory. Data sets (shots) are taken every two minutes while coring, which can be equated to a range of five to ten shots per foot of horizontal core cut. This high density of data is used to more accurately correlate any breaks (fractures) in the core to depth seen as sudden changes in the toolface measurement.[12] The frequency at which data are collected can be preprogramed per coring requirements. Data collection can also be delayed to place the probe dormant during *tripping*. The instrument is software configurable. By downloading to a personal computer, core orientation parameters are optimized. Corrections to surface-recorded time versus measured depth, as well as magnetic interference can be made readily at the wellsite. A diagram of the downhole tool and computer interface is shown in Figure 7.

Prior to 1985, conventional photomechanical surveys were used to orient core. These instruments added significant risk to the drilling operation and the data were usually questionable. Photomechanical surveys utilize cameras that record images with a plumb bob-compass device. The following problems exist with running photomechanical surveys:[10,12]

1) Unreliability of probe, compass sticking, and film problems.
2) Drilling must be stopped to take survey data, and potential for getting stuck in borehole.
3) Core breakage when core head *torques-up* after taking survey data.
4) Increased risk of jamming when taking survey data.
5) Low density of data, usually one survey every 3-5 ft (1-2m) (especially an issue in fractured rock).

Paleomagnetics is an effective method for the orientation of vertical core sections; however, it was not considered as a viable technique for orienting fractured horizontal core. A minimum of eight to twelve samples must be plugged from each two to three foot (0.6-0.9m) continuous core section. This high sampling frequency precludes any full-diameter core testing which is extremely useful in formation evaluation. Paleomagnetic core orientation can also be adversely affected by Chemical Remnant Magnetism introduced during the diagenesis of the rock unit.

The EMI has solved many of the operational errors associated with downhole core orientation. In order to increase the accuracy of the horizontal core orientation survey, many hardware enhancements were needed.

## EMI Enhancements

The EMI probe is highly accurate. Inclination is read to ± 0.1° (1.74 mrad). Direction is accurate to ±0.1° (1.74 mrad) with a potential error of ± 0.25° (4.36 mrad) multiplied by Sin (inclination), and tool face is read to ±0.25° (4.36 mrad) with a potential error of ±0.25 (4.36 mrad) multiplied by Sin (inclination). The EMI is subjected to a pre- and post-survey calibration check to insure sensor performance and survey accuracy.

The source(s) of error in running an EMI probe for core orientation purposes is (are) more appropriately related to the following factors:

1) static error - Usually caused by the misalignment of the EMI with the principal scribe knife.

2) dynamic error - Results from improper EMI centralization, coring induced vibration not dampened, and torque on the EMI assembly.

3) operator/laboratory error - Surveyor may be unfamiliar with proper orientation procedures. Core analysts are usually unfamiliar with survey data.

static error - This significant source of error has plagued the use of downhole surveying instruments since their inception. The quality of the survey data will be severely limited if the EMI is not positively aligned to the principal scribe knife in the core head which is used as the frame of reference for all subsequent core measurements.

Several techniques are used for alignment purposes; however, all have inherent error in their use. Chalk line, hoisting (protractor method), and bubble level alignment methods are subject to operator error and are prone to inaccuracies during poor weather conditions. The most common alignment system in use today utilizes an optical telescope for sighting purposes. The BHCA/EMI is laid in a horizontal position on a pipe rack. The telescope is then mounted directly over the principal scribe knife, and a target is attached to the survey instrument alignment rod. The target is usually a 3/8 in (1 cm) metal rod known as a *flag*. Most of the optical alignment systems in use today are in disrepair. Their use suffers greatly in the dark of night, especially if one considers the target is over 35 ft (11 m) from the telescope. It is also common practice to use this method on 60 ft (18 m) or longer coring and survey assemblies. Errors of up to 26° (454 mrad) have been noted using this method, and alignment quality has been found to be highly operator dependent. Errors as little as ± 5° (87.2 mrad) in the core barrel alignment process can translate to significant error in the core orientation.

Clearly, to improve the principal scribe knife-instrument alignment process, the development of a new method was imperative. The Laser Alignment System

(LAS), patent pending, was invented to overcome many of the problems associated with optical alignment techniques. The LAS incorporates a 2 mW (2 Joules/sec) Helium-Neon laser, in place of the telescope. Collimated light is transmitted to a mirrored target at the survey instrument in place of the *flag*. The optically polished mirror is fitted with a cross-hair reticle. The LAS has been proven to be accurate to ±1.0° (17.4 mrad). The alignment is highly reproducible, the LAS is easy to use, and the results are in excellent agreement between surveyors and coring engineers. The mirrored target also allows for a second check of the alignment accuracy by reflecting the incident beam to a protractor located just below the laser source (Figures 5, 8, and 9). The entire LAS process is performed on the pipe rack prior to lowering the BHCA/EMI into the borehole. A second generation of self-powered LAS hardware is being developed for harsh weather conditions and employs an audible target.

dynamic error - This source of error can be reduced significantly with EMI hardware enhancements and proper operating procedures. Dynamic error results from running the EMI in the borehole environment. Vibration, torque on the EMI assembly, and decentralization of the EMI are all examples of dynamic error sources.

A high frequency shock absorber has been developed to dampen the effects of vibration transmitted from the BHCA to the EMI. The shock absorber is located in the interior of the EMI barrel assembly between the instrument keyway and the T-slot alignment bar (Figure 7).

To use the EMI in horizontal coring, a special running gear (instrument assembly) was designed for support and centralization. As inclination in the borehole increases, magnetic interference increases necessitating the use of an extended non-magnetic running gear. The entire running gear must be held stationary in the NMDC which is rotating during coring. Rubber fingers are inappropriate in horizontal coring due to their inability to support the weight of a horizontal running gear. Drag on the NMDC is also quite high with rubber fingers. Rubber rotating fin centralizers can reduce drag; however, they are unable to support the weight of horizontal running gears. The problem of EMI horizontal centralization and drag was solved with nonmagnetic rotating blade centralizers of variable strengths and lengths (Figure 10).

An improved orientation cross-over from the running gear to the core barrel alignment rod also makes the alignment process simpler. It is worth noting that the running gear acts as a *drop ball* and diverts the drilling fluid from the inner barrel to the annulus between the inner and outer barrels. This requires the borehole to be clean and conditioned prior to coring.

In making up the BHCA and running gear, it is important that all joints be fully tightened. Standard procedure includes punch or chisel marks to be placed across each connection to identify any additional tightening (torque) which occurred downhole.[13] Normally, torque of the assembled hardware is low or nonexistent and creates an error of much less than 1° (17.4 mrad).[14] Assembly torque can be easily recognized by conducting an LAS check subsequent to coring.

<u>operator/laboratory error</u> - Operator error is the most difficult variable to control. Communication between the surveyor, core analyst, rig personnel, and oil company representatives is absolutely necessary in order to obtain quality core orientation data. This is particularly true in fractured rock where the surveyor must understand laboratory horizontal core orientation procedures. It is recommended that the surveyor assist the core analyst in the interpretation and application of EMI data. One of the largest sources of error in oriented core work is caused by not knowing which core piece corresponds to an EMI shot on the survey log. Depth misalignment errors are minimized if survey shots are timed and correlated to the geolograph. Note taking and documentation of drilling parameters at the wellsite is also necessary to evaluate EMI data quality.

The potential for error also exists in measuring planer features of horizontal core in the laboratory. Reproducibility error is generally on the order of ± 2 percent among skilled core analysts.[14] Laboratory instrumentation (Goniometer) error is not considered to be a major concern.

## Difficulties in Application of EMI Data to Core

The EMI data should be subjected to quality control and statistical analysis prior to its use in the laboratory. Anomalous shot points are easily discounted by comparison of baseline magnetic and gravitational total field strengths to actual shot data. Anomalous gravitational data are generally attributed to inner barrel rotation coincident in time with the shot. Less than ten percent of all data fall into this category. Evidence of unreliable shot data is also found when magnetic interference is a problem. This may be a result of incorrect NMDC or EMI spacing calculations. *Hot spots* in the NMDC, use of the EMI at very high latitudes, magnetic storms and certain formation minerals can also lead to errors in the acquisition of magnetic data.[9]

Scribe quality is one of the most important factors in core orientation.[15] The quality of the scribe and, consequently, the core orientation is a function of:

1) scribing hardware constraints - Poor knife quality or failure.

2) rock consolidation - Degree of rock consolidation or fracturing.

3) scribe rotation or discontinuity - Excessive inner barrel rotation, torque, or improper drilling parameters.

scribing hardware constraints - The scribe knives must be sharp and set to a tolerance which will aid in the catching of the core. Improper knife tolerance can lead to jamming, excessively wide scribes, and additional rotation of the inner barrel. The precision by which determination of the true principal scribe knife location can be made is dependent on the scribe depth and width of the cut on the core's surface. Errors in reading the scribe location can be appreciable.[14] Cases also exist where failure of the scribe knives occurred resulting in no grooves on the core.[2]

rock consolidation - Depth misalignment and poor scribe quality is a significant problem in excessively fractured and rubble zones. The reliability of core orientation data is reduced where core cannot be pieced together easily. EMI shot density should be increased if unconsolidated or fractured rock is anticipated. Scribe knives will spin within a rubble zone or at a fracture plane with significant aperture.

scribe rotation or discontinuity - During both vertical and horizontal coring, the scribe knives do not cut a straight groove down the length of the core. The principal scribe knife will turn to the right (clockwise) with the rotation of the drill string as depth increases. This curvature effect is evident when the scribe grooves spiral around the core. Scribe rotation is caused by torque transferred to the inner core barrel. Cores with significant groove rotation are difficult to orient accurately.[14] Spiraling or spinning of the knives at a particular footage must be documented in both the orientation data and the core. Lack of such data generally indicates either depth misalignment between the core and survey, incorrect reconstruction of the core itself, or erroneous survey data.

At least one type of scribe discontinuity is unique to horizontal coring. Drilling parameters such as WOB and pump pressure are difficult to stabilize when drilling horizontally in fractured formations. *Scribe skip* is one such phenomenon in which the groove line skips or jumps a discrete amount at a break in the core which fits together. *Scribe skip* ranging from a few degrees up to 86 degrees has been observed in horizontal cores. The skip observed in the core has also been documented by the orientation survey. The origin of the *scribe skip* is attributed to a loss of contact between the coring bit and the formation. When the bit loses contact, the core breaks off, and the knives spin with the barrel. Once the bit is again in contact with the formation, the knives are stabilized. The contact between the two pieces of core is often jagged, and the two pieces fit together.

To a lesser degree, *assembly torque* occurs when the core barrel, between the scribe knives and the running gear, twists slightly resulting in rotation of the EMI probe. Once the knives encounter a fracture or the bit loses contact with the formation, the barrel and, consequently, the EMI probe will snap back into alignment. *Assembly torque* is identified by comparing the amount of groove rotation of the core to that reported by the EMI. *Assembly torque* is most common in hard rock formations.

When coring horizontally, variance in the scribe quality can sometimes be attributed to the stress field induced on a horizontal versus vertical core section.

## CORE HANDLING IN THE FIELD AND LABORATORY

Planning and cooperation among the horizontal core acquisition and orientation team are key elements in obtaining accurate data. Precoring meetings are highly recommended to insure all staff members are familiar with the objectives of the coring program. Field procedures must be designed to minimize the time necessary to mark, sample, and transport the core to the laboratory for processing. Preserving the physical condition of the core as closely to in-situ conditions as possible is a prerequisite to performing most petrophysical and reservoir engineering tests.

Once in the laboratory, the fiberglass inner barrel is laid-out horizontally and cut open to maintain the mechanical integrity of the core. The core is then fitted together and marked according to measured depth, and the true vertical depth (if any) should be calculated. The inscribed grooves formed by the knives should be inspected for continuity. The EMI data are used to determine the position of the principal scribe knife with respect to the highside of the core. A Master Orientation Line (MOL) is then drawn by the core analyst and surveyor at the highside down the length of the core (Figure 11). The amount of rotation of the principal scribe line is documented and compared to the rotation noted by the EMI (Figure 12). Survey data are accurate if the amount of rotation of the principal scribe knife reported by the EMI can be accounted for by the observed groove rotation, spin surfaces, *scribe skip,* fractures, and rubble zones. Quality control plots of EMI and observed principal scribe line rotation versus depth were constructed for several core sections.[15] On horizontal core orientation work where the LAS and strict operating procedures have been used, EMI and observed laboratory data essentially overlie each other. Figure 13 illustrates the observed groove line orientation plotted with survey data for a number of cases that are commonly found in horizontal core.

For structural analysis, the orientations of the fractures, stylolites, and bedding planes in the horizontal core are measured using an Electromagnetic Goniometer. This three-dimensional digitizer determines the coordinates of a point in space with an accuracy of ±0.3mm.[16] Points along the fracture plane are digitized with respect to the MOL. The coordinate data are converted by the goniometer software to dip azimuth and angle. Other parameters that are noted or measured for each fracture include: length, width, and depth of fracture, fracture condition (open, broken, mineralized), slickenside trend and plunge (if present), origin of fracture (natural or induced), and presence of oil staining (Table 3). The lithology of the formation should also be described in detail so that the intensity of fractures may be related to rock parameters such as mineralogy, bed thickness, permeability, porosity, etc.

Distinguishing natural tectonic or regional fractures from the coring-induced fractures is the most difficult task in analyzing the structural elements of horizontal core. One of the objectives of horizontal drilling is to traverse perpendicular to the fracture trends. Natural fractures in horizontal core are usually perpendicular to the Z core axis and appear as breaks in the core.

A number of criteria, which are summarized in Table 4[17], can be used to determine whether a fracture is natural or was induced during or after coring. Common characteristics of natural fractures include mineralization along the fracture plane, slickensides on the fracture face, parallel sets of fractures, and displacement of bedding across the fracture plane. In addition, natural fractures tend to be planar and have asymmetrical hackle marks and arrest lines (arc-shaped undulations) on the fracture face.[17]

Induced fractures which are perpendicular to the core axis in horizontal cores may have a conchoidal or irregular surface. They can also exhibit a slight to pronounced rotation around the core axis. Spiral hackle marks which diverge from the center of the core or from a point of weakness and meet the core boundary orthogonally, or at a high angle, may also be an indication of induced fractures. The hackle marks, as well as the arrest lines, may become more coarse at the core boundary. Many of the induced fractures perpendicular to the core axis in the horizontal cores analyzed also have a sinusoidal trace around the core which may be related to the in-situ horizontal stress field.

### Evaluation of Data

For convenience and efficiency, the fracture and bedding plane orientations are measured with the horizontal core in the vertical position relative to the MOL. Once the core is digitized, the data are rotated around the vertical Y-Axis, such that the MOL is in the direction of the borehole azimuth. The data are then tilted to the inclination angle and azimuth. This final data manipulation yields the in-situ orientations of the fractures and bedding planes and is performed by the goniometer software. The data may also be rotated and tilted by hand with stereographic projections (Figure 14).

The fracture data are presented in a rose diagram depicting the strike of the fracture planes, stereographic projection of the poles to fractures, and in a log-depth format (Figures 15, 16, and 17). These plots and figures define reservoir trends and sets of fractures present in the formation.[18]

This laboratory interpretation agrees with regional fracture data collected by geologists on outcrops from the reservoir rock under study.

## CONCLUSIONS

Several innovations have been described for the reliable acquisition and orientation of horizontal core for formation evaluation purposes. Experimentation with new hardware and procedures has lead to the following conclusions:

1) Comprehensive core analysis is essential to understanding the behavior of fractured reservoirs which are drilled horizontally.

2) Excellent horizontal core recoveries are obtainable with a newly designed coring assembly. Shorter core sections taken with fiberglass inner barrel construction and a modified core head have yielded quality core material suitable for laboratory fracture studies.

3) Stabilization of the outer and inner core barrels is critical when drilling horizontally. Inadequate outer barrel stabilization can lead to drilling complications and poor core recovery. Destabilization of the inner barrel can cause jamming and reduce coring efficiency.

4) Coring parameters and drilling procedures must be optimized to achieve high core recovery rates and minimize damage to the core.

5) Horizontal core orientation data have been found to be reliable from the Electronic Multishot Instrument. Problems reported by previous authors[13,14,15] have been overcome through survey instrument enhancements and improved operating procedures.

6) Error associated with the alignment of the principal scribe knife-survey instrument has been reduced significantly. The Laser Alignment System has proven to be accurate to ±1.0° (17.4 mrad) and its use is highly recommended for horizontal core orientation.

7) The development of a high frequency shock absorber, special running gear, blade centralizer, and improved orientation cross-over have made downhole horizontal core orientation possible.

8) *Scribe skip* is a type of groove discontinuity unique to horizontal coring. This phenomenon occurs when the coring bit loses contact with the formation while drilling laterally.

9) Planning and cooperation among the horizontal core acquisition and orientation teams are key elements in obtaining accurate orientation data.

10) Laboratory procedures have been described to handle horizontal core in the laboratory. Recently developed instrumentation, such as the Electromagnetic Goniometer have made the structural analysis of cores more accurate and efficient.

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## REFERENCES

1. Butler, R. M.: "The Potential for Horizontal Wells for Petroleum Production." JCPT 28 (3) (1989) 39-47.

2. Lamb, C. F. and Ferguson, D. G.: "The Role Of Core Analysis In Fractured Reservoir Evaluation." Petroleum Society Of CIM Preprint 88-39-86, Petroleum Society Of CIM Annual Meeting, Calgary (June 12-16, 1988) 10.

3. De Montigny, O. et. al.: Horizontal Well Operations - Conclusion, Horizontal-Well Drilling Data Enhance Reservoir Appraisal." OGJ (July 4, 1988) 40-48.

4. Giger, F. M. and Jourdan, A. P.: "The Four Horizontal Wells Producing Oil in Western Europe." Advances In Petroleum Recovery And Upgrading Technology Conference, Paper 3 - Session 1, Calgary (June 14-15, 1984) 1-12.

5. Bosio, J.: "A Fourth Well Successfully Completed By Elf Aquitaine: What Is The Next Step?" PI (Dec. 20, 1984) 4-6.

6. Filshtinsky, M., Aumann, J. T. and Quinn, J.: "New Tools Improve The Economics Of Coring." SPE preprint 12092, SPE Annual Conference, San Francisco (Oct. 5-8, 1983) 1-8.

7. Bosio, J. C. and Giannesini, J. F.: "Horizontal Drilling - A New Production Method." Twelfth World Petroleum Congress Topic 11, Twelfth World Petroleum Congress, Houston (1987) 1-13.

8. Diamant Boart Stratabit Internal Report, European Horizontal Coring Experience, January 1989.

9. Bourgoyne, A. T., Millheim, K. K., Chenevert, M. E. and Young, F.S.: Applied Drilling Engineering," SPE Textbook Series, Vol 2, Society of Petroleum Engineers, Richardson, Texas (1986) 351-473.

10. Thorogood, J. L. and Knott, D. R.: "Surveying Techniques With A Solid-State Magnetic Multishot Device." IADC/SPE Preprint 19030, IADC Drilling Conference, New Orleans (Feb. 28-March 3, 1989) 841-851.

11. Grindrod, S. J. and Wolff, C. J. M.: "Calculation of NMDC Length Required For Various Latitudes Developed From Field Measurements Of Drillstring Magnetization, IADC/SPE Preprint 11382, IADC Drilling Conference, New Orleans (Feb. 20-23, 1983) 217-225.

12. Brindley, C.P.: "Continuous Orientation Measurement Systems Minimize Drilling Risk During Coring Operations." IADC/SPE Preprint 17217, IADC Drilling Conference, Dallas (Feb. 28 - March 2, 1988) 341-346.

13. Bleakley, D. C., Van Alstine, D. R. and Packer, D. R.: "Core Orientation - 1, Controlling Errors Minimizes Risk And Cost In Core Orientation," OGJ (Dec. 2, 1985) 103-108.

14. Nelson, R. A., Lenox, L. C., and Ward, B. J.: "Oriented Core: Its Use, Error And Uncertainty," AAPG Bull. 71(4) (April 1987) 357-367.

15. Bleakley, D. C., Van Alstine, D. R. and Packer, D. R.: "Core Orientation - Conclusion, How To Evaluate Orientation Data, Quality Control," OGJ (Dec. 9, 1985) 46-52.

16. Norman, D. K. and Garrett, C. H.: "Advances In Fractured Reservoir Characterization." Petroleum Society Of CIM Preprint 88-39-111, Petroleum Society Of CIM Annual Meeting, Calgary (June 12-16, 1988) 22.

17. Kulander, B. R., Dean, S. L., and Barton, C.C.: "Fractographic Logging For Determination Of Pre-Core And Core-Induced Fractures-Nicholas Combs No. 7239 Well, Hazard, Kentucky," Energy Research And Development Admin., Morgantown, West Virginia, Eastern Gas Shales Project, MERC/CR 77(3) 1977, 44.

18. Davis, G. H.: "Structural Geology of Rocks and Regions, John Wiley and Sons," New York City (1984) 492.

## Table 1 - Outer Core Barrel Stabilization

| Type | Stabilizer Size (Inches Undergauge) | Inclination (Loss/30 Feet) |
|---|---|---|
| Slick | None | 0.3° |
| Dual<br>Concentric | 1/4<br>1/4 | 0.7° |
| Dual<br>Concentric | 1/8<br>1/2 | 0.1° |

## Table 2 - EMI Orientation Data

| Shot Number | Time | Measured Depth (Feet) | Inclination (Degrees) | Magnetic Field Strength (Gammas) | Final Gravitational-Magnetic Toolface (Degrees) | Core Groove Rotation (Degrees) |
|---|---|---|---|---|---|---|
| 408 | 15:34 | 7104.9 | 85.51 | 49136 | 54.0 | 55 |
| 409 | 15:36 | 7105.0 | 85.93 | 49153 | 55.9 | 56 |
| 410 | 15:38 | 7105.1 | 85.88 | 49187 | 64.8 | 60 |
| 411 | 15:40 | 7105.3 | 85.97 | 49042 | 120.2 | Scribe Skip |
| 412 | 15:42 | 7105.5 | 85.40 | 49032 | 142.3 | 147 |
| 413 | 15:44 | 7105.6 | 85.48 | 49917 | 147.0 | 149 |
| 414 | 15:46 | 7105.8 | 86.45 | 49137 | 149.5 | 151 |
| 415 | 15:48 | 7105.9 | 86.49 | 49123 | 150.2 | 151 |
| 416 | 15:50 | 7106.1 | 85.85 | 49030 | 151.4 | 152 |
| 417 | 15:52 | 7106.3 | 85.41 | 49099 | 152.3 | 153 |
| 418 | 15:54 | 7106.5 | 85.45 | 49116 | 153.0 | 154 |
| 419 | 15:56 | 7106.6 | 85.69 | 49000 | 153.4 | 155 |
| 420 | 15:58 | 7106.8 | 85.84 | 49068 | 154.1 | 155 |
| 421 | 16:00 | 7106.9 | 85.65 | 49011 | 154.6 | 156 |
| 422 | 16:02 | 7107.1 | 85.52 | 49035 | 154.9 | 157 |
| 423 | 16:04 | 7107.3 | 85.55 | 49144 | 155.8 | 157 |
| 424 | 16:06 | 7107.4 | 86.01 | 49071 | 156.9 | 158 |
| 425 | 16:08 | 7107.6 | 85.60 | 49012 | 157.5 | 159 |
| 426 | 16:10 | 7107.7 | 85.68 | 49065 | 159.9 | 160 |

## Table 3 - Laboratory Fracture Data

| Depth (Feet) | Dip Azimuth (Degrees) | True Angle (Degrees) | Measured Angle (Degrees) | Vertical Length (Inches) | Measured Width (mm) | Effective Width (mm) | Structure | Fluid | Fracture Condition | Mineral Type | Fill (Percent) | Lithology | Fracture Origin |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7104.5 | 10 | 77 | 47 | 0.870 | 0.090 | 0.090 | | | O | | 0 | LS | N |
| 7105.2 | 144 | 77 | 17 | 0.551 | 0.010 | 0.010 | | | C | | 0 | LS | I |
| 7105.5 | 143 | 82 | 12 | 0.618 | 0.010 | 0.010 | | Oil | B,M | Cal | | LS | N |
| 7105.5 | 143 | 82 | 12 | 0.300 | 0.180 | 0.010 | | Oil | B,M | Cal | | LS | N |
| 7105.6 | 143 | 82 | 12 | 0.400 | 0.200 | 0.010 | | Oil | B,M | Cal | | LS | N |
| 7105.8 | 143 | 83 | 11 | 0.748 | 0.010 | 0.010 | | Oil | B,M | Cal | 0 | LS | N |
| 7105.8 | 276 | 13 | 77 | 11.610 | 0.010 | 0.010 | BP | | B | | 0 | LS | I |

**Key To Fracture Abbreviations**

| ***Structure*** | ***Conditions*** | | ***Mineral Type*** | ***Lithology*** | ***Origin*** |
|---|---|---|---|---|---|
| BP - Bedding Plane | B - Broken | M - Mineralized | CAL - Calcite | Ls - Limestone | I - Induced |
| | C - Closed | O - Open | | | N - Natural |

## Table 4 - Criteria For Fracture Identification[17]

| **Natural Fractures** | **Induced Fractures** |
|---|---|
| Mineralization | Show slight rotation around core axis |
| Parallel Sets Of Fractures | Conchoidal or very irregular plane |
| Slickensides | Symmetrical hackle marks or arrest lines on vertical fractures |
| Asymmetrical Hackle Marks | Diverging hackle marks which meet core boundary |
| Asymmetrical Arrest Lines | Hackle marks become more coarse at core boundary |
| Relatively Planar | Spiral hackle marks around center of core |
| Extend Across Core | Arrest lines increase in relief at core bounday |
| Displacement Of Bedding By Fracture | Fracture edge along knife groove |
| | Sinusoidal trace around core (in horizontal cores) |

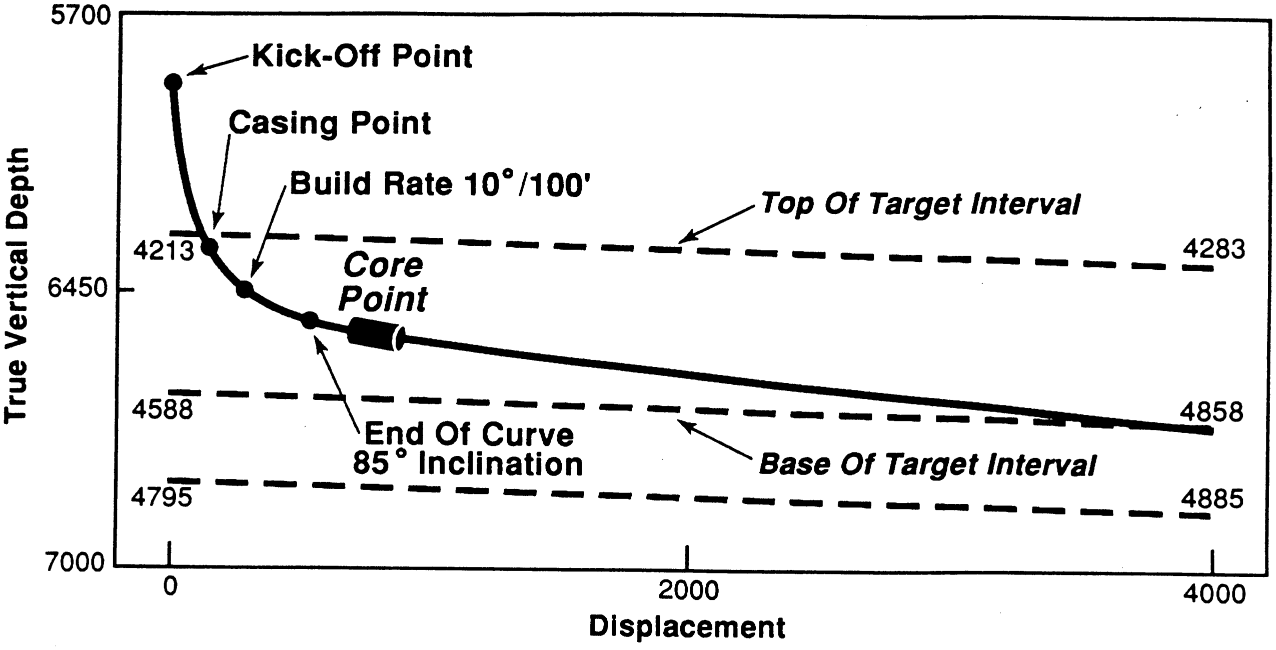


Figure 1 - General Horizontal Wellbore Path

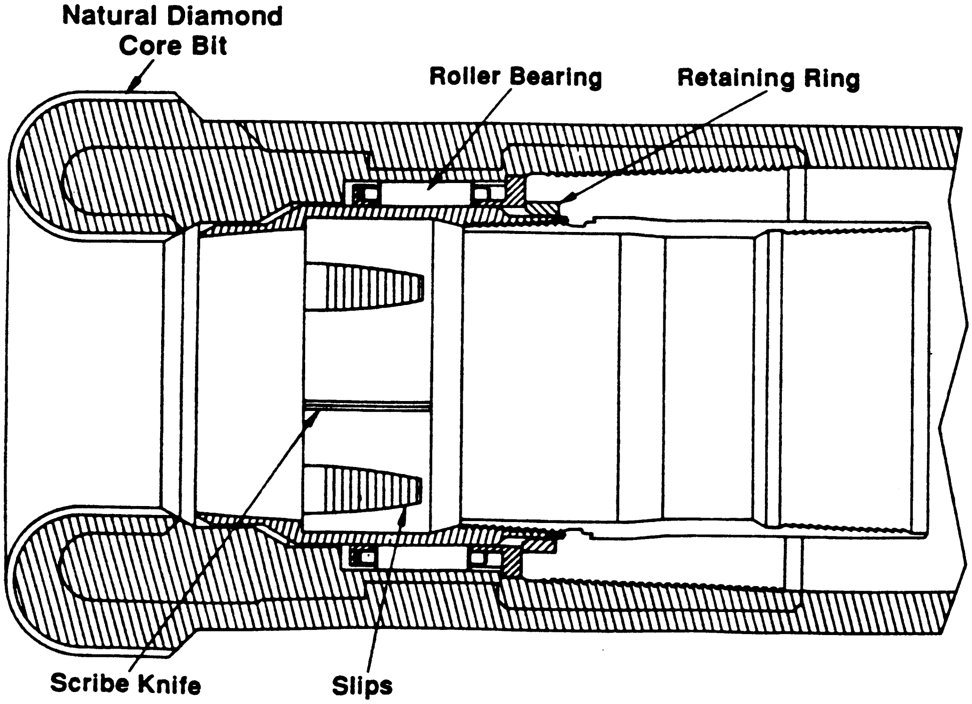


Figure 2 - Core Head Assembly

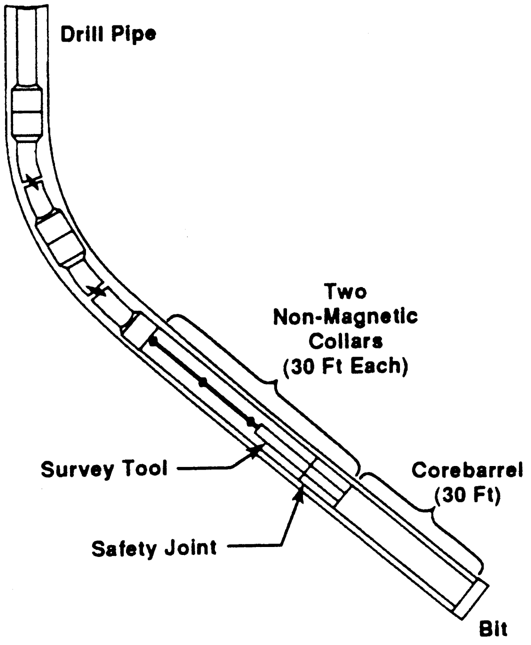


Figure 3 - Slick Coring Assembly

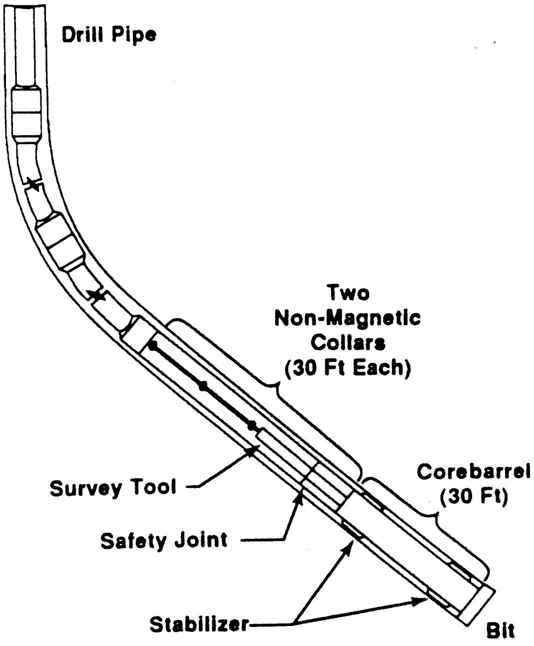


Figure 4 - Stabilized Coring Assembly

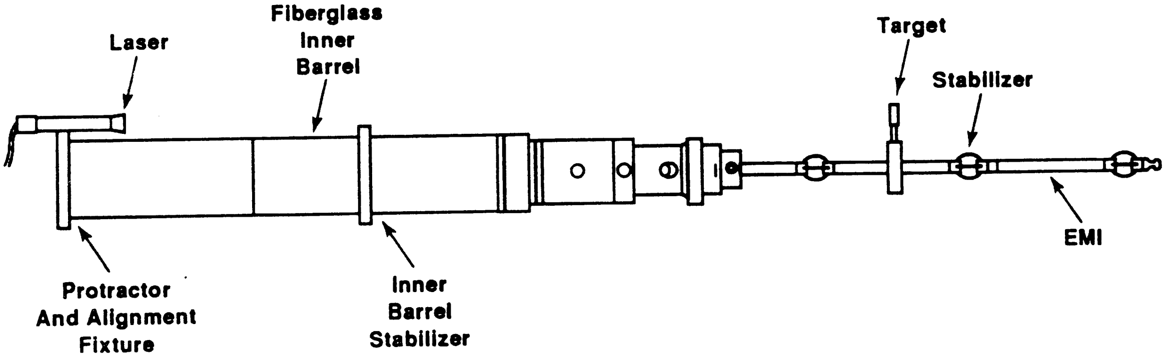


Figure 5 - Coring Assembly, And LAS

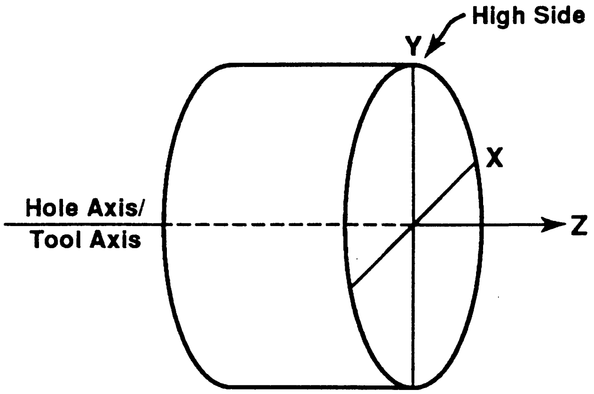


Figure 6 - Horizontal Tool And Core Axes

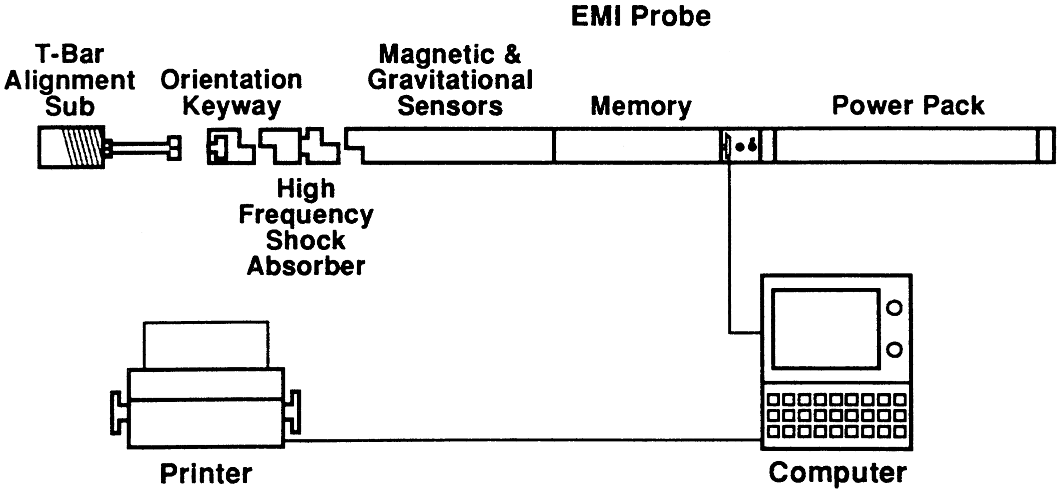


Figure 7 - EMI Enhancements

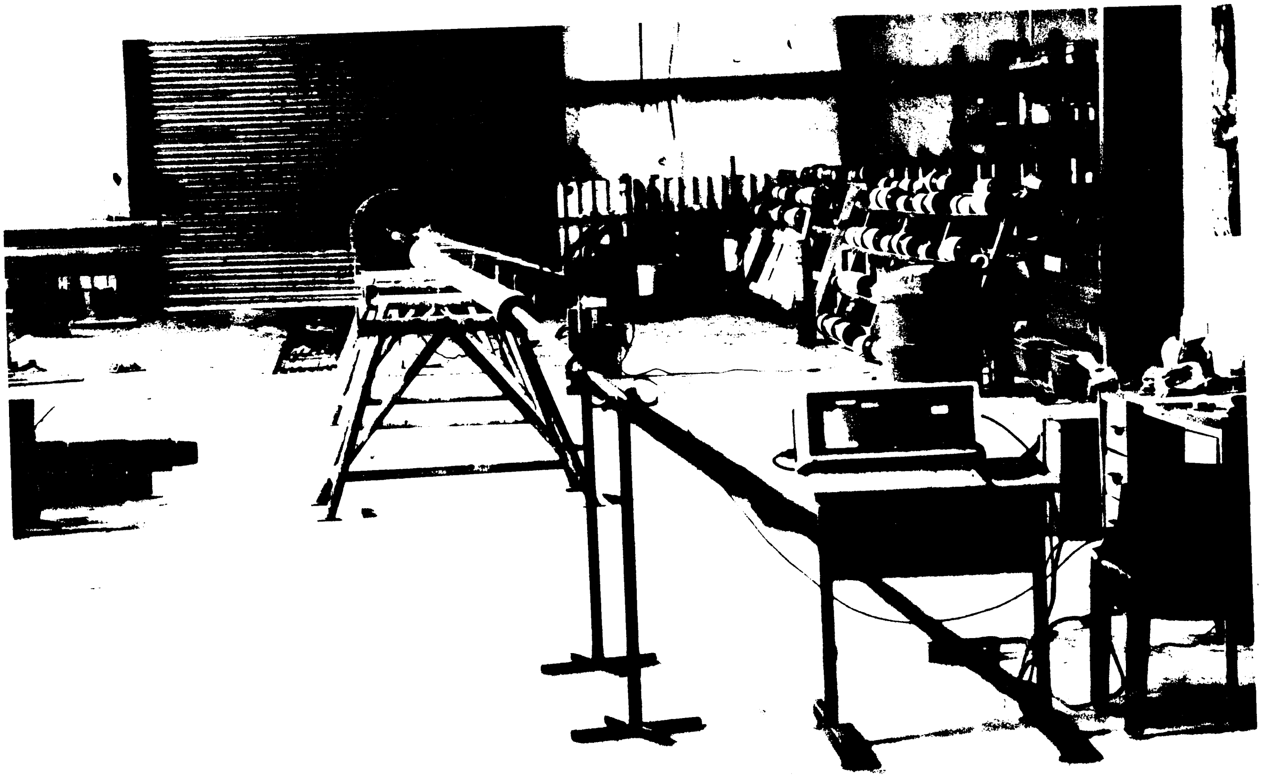


Figure 8 - Laser Alignment System (LAS) In Use

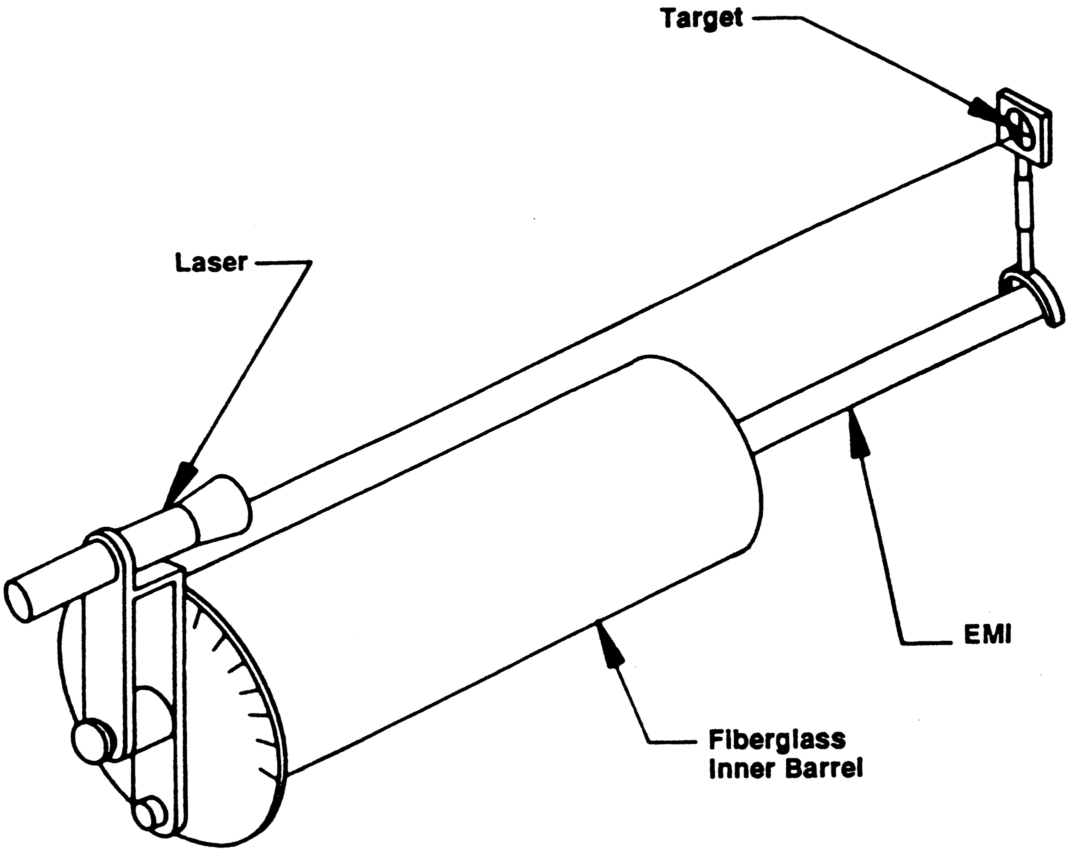


Figure 9 - Close Up Of LAS

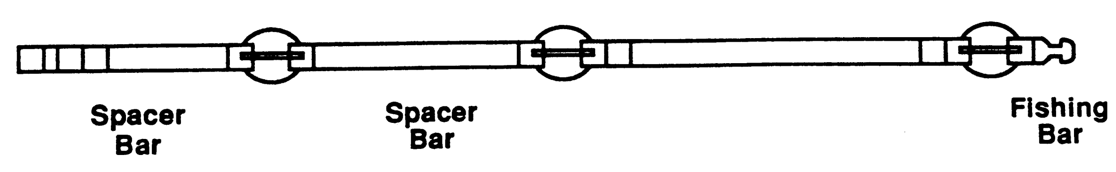


Figure 10 - EMI Survey Assembly

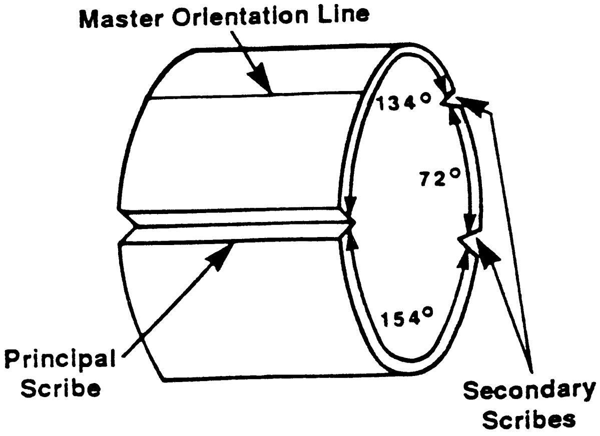
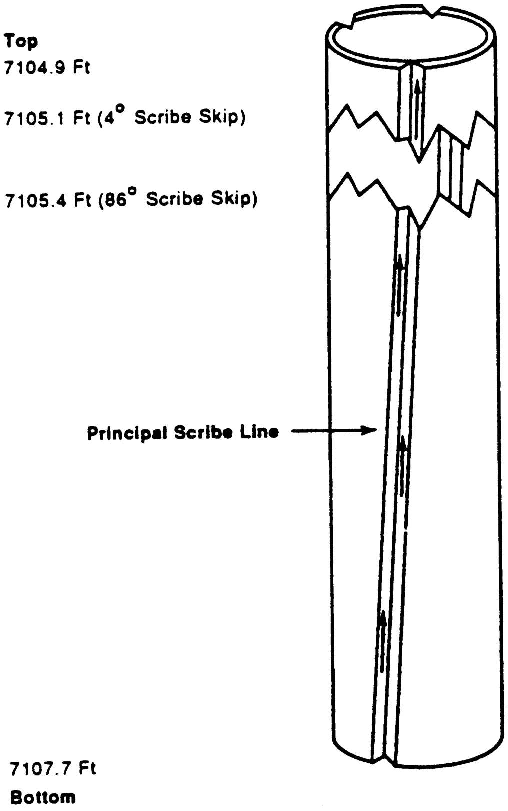
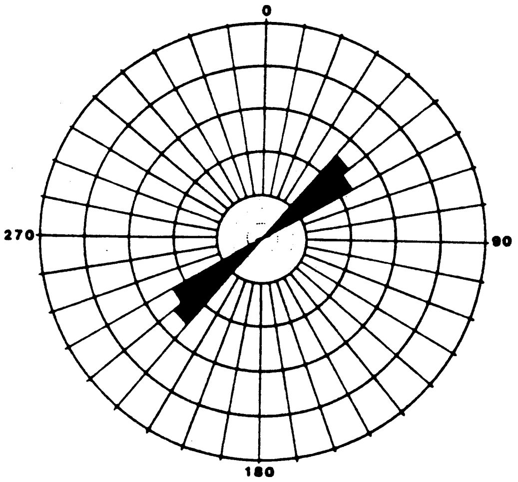


Figure 11 - Core Section With Orientation Grooves



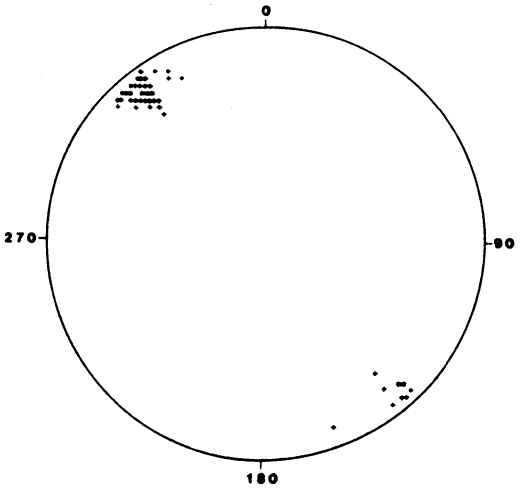
| Observed Groove Rotation | Groove Depth (Feet) | Orientation Azimuth (Degrees) |
|---|---|---|
| 1° | 7104.9 | 55 |
| 1° | 7105.1 | 60 |
| | 7105.3 | 61 |
| | 7105.4 | 147 |
| | 7105.6 | 149 |
| | 7106.1 | 152 |
| 11° | 7106.5 | 154 |
| | 7106.9 | 156 |
| | 7107.3 | 157 |
| | 7107.7 | 160 |

Figure 12 - Groove Rotation Report



**0 to 100 PERCENT**
**63 NATURAL FRACTURES**

Figure 15 - Rose Diagram



**63 FRACTURES**

**◆ SINGULAR-DATA POINT**
**• MULTIPLE-DATA POINT**

Figure 16 - Stereographic Projection

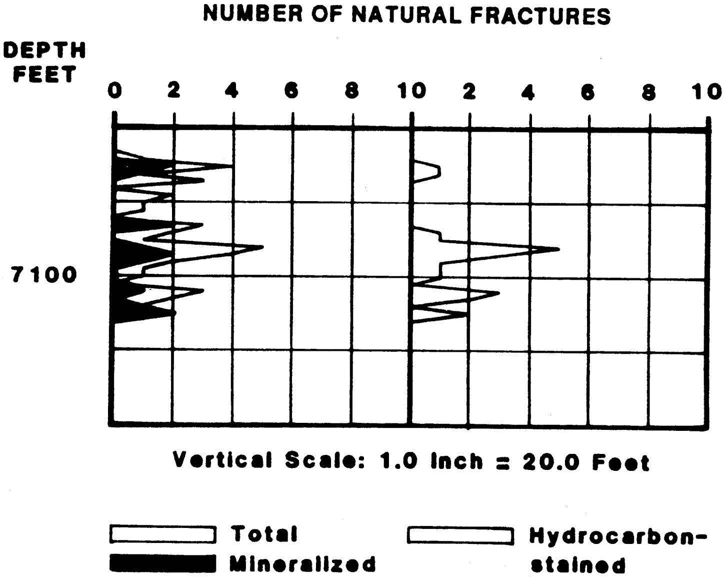


Figure 17 - Core Fracture Log

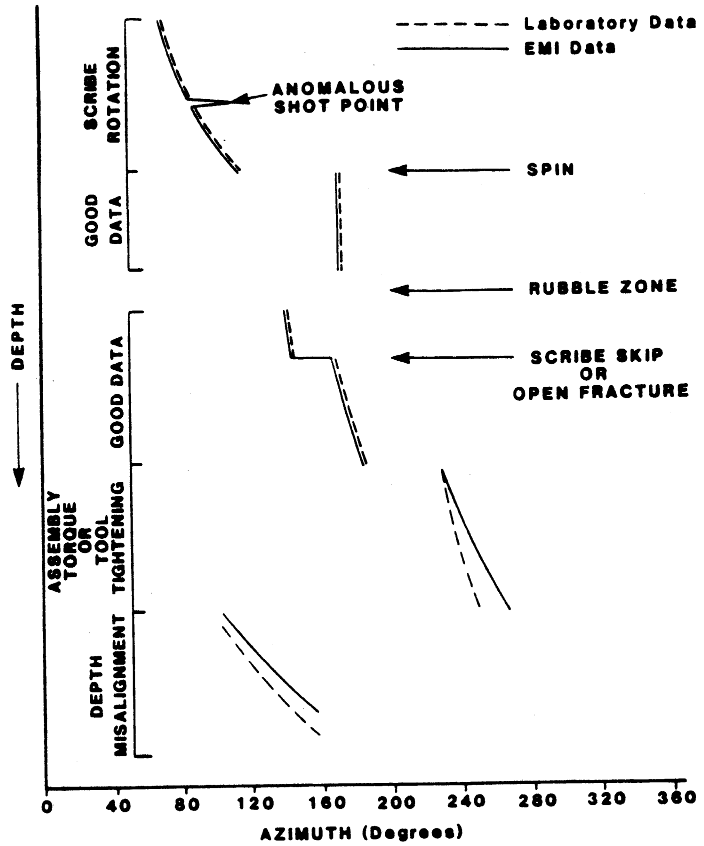


Figure 13 - Comparison Of EMI And Observed Principal Scribe Line Rotation

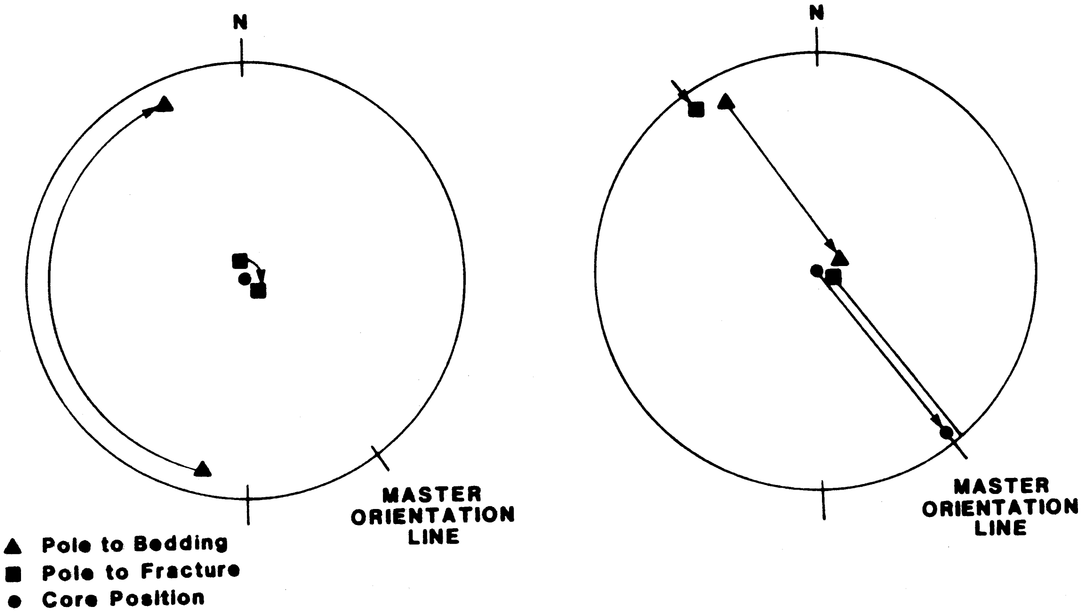


Figure 14 - Stereographic Rotation Of Data