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AN INNOVATIVE APPROACH TO EXPLORATION AND EXPLOITATION DRILLING - THE SLIM HOLE HIGHSPEED DRILLING SYSTEM*

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ABSTRACT

Slim hole continuous core drilling and on-site near real time core analysis offers a new dimension for oil and gas exploration, especially in remote, difficult, and environmentally sensitive areas.

Technologies borrowed from the mining and oilfield drilling industries, coupled with newly developed technologies give genesis to a new drilling and evaluation system designed around continuous coring, slim holes, and inverse logging - the logging of the actual rock as it is retrieved.

It is possible this new system could cause a paradigm shift in the practice of exploration.

INTRODUCTION

Why drill a slim hole well? And what would be the definition of a slim hole.

There are two basic reasons to consider drilling a slim hole. The first is very simple and basic - better economics. The second answer is borrowed from the continuous core mining drilling industry. To achieve a high percentage core recovery and to be cost effective, it is necessary to drill a slim hole. Then what is a good definition of a slim hole? A slim

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hole well is a well where 90% or more of the length of the well is drilled with bits less than 7 in [1.78 (E-01) m] in diameter.

Slim hole technology is not new. Both the explorationist and the exploitationist recognized the possibility of using a small diameter wellbore to help reduce overall drilling costs. In the fifties, a major operator launched an initiative to drill slim hole exploitation wells in Utah, Louisiana, Mississippi, Arkansas, and Oklahoma, and stated in the conclusions that slim hole wells could be cost effective.[1] However, the interest in slim hole exploitation drilling waned in the sixties and did not re-emerge until the seventies. A slim hole drilling system was developed in Sweden to explore and exploit some of the small shallow reservoirs in that country.[2] Again, the author cited a 75% cost savings in this approach over conventional drilling practices. The success in Sweden encouraged more slim hole drilling in the United Kingdom and the Paris Basin in France.[3,4] Cost effectiveness was again cited. Another application for slim hole drilling was recognized by explorationists for drilling in remote areas such as Indonesia and Irian Jaya, Indonesia.[5,6] In both situations, the smallness of the overall drilling system and the reduction in wellbore size greatly impacted the logistical cost for drilling these wells.

The biggest use of slim hole technology is for continuous coring by the mining industry. The only sure way to evaluate if an ore body is large and has a sufficient mineral grade to justify the cost of sinking shaft(s) or embarking on a costly open cut is to obtain core to delineate the ore body. The leaders in continuous coring mining drilling are the South Africans who have developed deep gold deposit in South Africa, with some mines below 10,000 ft [3,048 m].

Continuous coring mining drilling is so big that it has a complete subindustry to support it which is totally unrelated to the oilfield drilling industry. There are special manufacturers of drilling machines, drill bits, tubulars, core barrels and other required tools. In fact, slim hole mining drilling has its own association called the International Drilling Federation (IDF) complete with a quarterly publication called Drill Bits.[7]

Currently, continuous coring mining drilling operations are booming in the United States (gold and coal), Canada (mainly nickel) and in Australia for a variety of minerals.

Over the years, there has been an ongoing interest in continuously coring oil and gas wells. During the late fifties and early sixties, a continuous coring system was developed and used to drill a number of shallow wells for oil and gas.[8] Unique to this continuous coring system was the design to reverse circulate the core from the well while drilling ahead. During the early seventies, a well was continuously cored to 11,600 ft [3536 m] using the slim hole coring system.[9] This record still stands as the deepest continuously cored well in an oil and gas sedimentary environment. This article claims a 50% cost improvement over a conventional well drilled to 6000 ft [1829 m] and indicates explorationists were aware of the advantages of continuous coring and the slim hole system, especially for drilling in remote areas. The concept of continuously coring as an alternative exploration strategy was championed in the early seventies in Australia where a series of oil and gas exploration wells were drilled in the Canning Basin.[10] During the middle eighties, two wells were continuously cored in the Permian age Delaware Basin in Texas and New Mexico.[11] Both wells recovered over 11,000 ft [3,353 m] of continuous core. Between 1987 and 1989, Amoco Production Company drilled over 40,000 ft [12,192 m] of continuous core in Oklahoma, Michigan, Kansas, Colorado, and Texas. Some of that drilling will be discussed in this paper.

With the apparent interest in slim hole and continuous core drilling over the past 40 years, why has not both approaches become more popular and gained acceptance in the oil and gas exploration and exploitation sectors? Is there a place (nitch) for slim hole and continuous core drilling for oil and gas exploration and exploitation? Can slim holes and continuous core drilling compete economically with conventional drilling? What are the advantages and disadvantages of slim hole and continuous core drilling? Can the continuous core philosophy change the way we do oil and gas exploration? What are the technical problems with slim hole and continuous core drilling? Can they be overcome? What about well control and safety?

It is the design of this paper to address these questions with the sole purpose of looking at the possibilities of slim hole and continuous core drilling in the oil and gas industry.

THE EVOLUTION OF THE CONTINUOUS CORING SLIM HOLE SYSTEM FOR OIL AND GAS EXLORATION AND EXPLOITATION DRILLING

The slim hole system has three basic variations:

(1) slim hole wells with little or no coring,
(2) slim hole wells where 90% or more is continuously cored, and
(3) slim holes that are a combination of coring and full bore drilling.

This paper concentrates on the slim hole continuous coring system. When first considering slim hole continuous coring, the obvious approach is to use a mining drilling contractor. The pursuit of this endeavor would clearly demonstrate the distinctions between the conventional drilling system and the mining drilling system as practiced today.

Figure 1 illustrates a typical mining drilling system (specific mining terminology is defined in Appendix 1). The machine is very small and lightweight compared to an oilfield drilling rig of similar depth capacity. Fluid circulation rates range from 5 to 70 gallons/minute [3.154 5 (E-04) m^3/s to 4.416 3 (E-03) m^3/s]. Rotation of the drill rod is by a top drive or a chucking device capable of speeds above 2,000 revolution per minute. The drill rod is externally flush and internally upset at the connection, which itself is a modified buttress thread type. Drill rod is rotated in a hole with commonly less than 1/2 in [1.27 (E-02) m] of annular clearance. Bits used are small diameter, 4-3/8 in [1.111 (E-01) m] or less, drag type core bits. Most of the mining bits that are used are impregnated with diamonds; however, there are a smaller percentage of surface set diamond bits that are also used. Well control equipment, if used at all, will usually consist of a ram or bag type of BOP, and an accumulator and controls. Understanding of well control practices and how to actually handle a kick if it occurs is questionable and poorly documented within the mining industry. Because the mining industry is interested in finding mineral deposits, continuous coring is most often practiced. The optimum way to do this is to use a wireline retrievable system. Core analysis is typically conducted offsite by mining engineers or core analysis service companies several days or even weeks later.

Mining Drilling Equipment

Mining rigs range in size from simple, one-man operated drilling machines weighing only several thousand pounds up to three-man drilling machines weighing close to 100,000 pounds [45 359 kg]. Most are capable of only drilling 6,000 ft [1829 m] or less, although a few can continuously core to 14,000 ft [4267 m]. Because most mining rigs are hydraulic, the chuck or top drive systems can rotate the drill rods at variable speeds up to 2,000 rpm, depending on available torque. These systems are also used to hydraulically raise and lower the rod. The chuck has a stroke ranging from 2 to 11 ft [.6096 to 3.353 m] at which time it must be hydraulically raised to re-grab (chuck) the rod. Drill rod sizes range from 1.75 in to 5 in [4.445 (E-02) m to 1.27 (E-1) m] OD. The externally flush rod provides a smooth surface which acts as a bearing shaft inside the small annular clearance wellbore. Drill rod lengths vary from 3.28 ft to 19.69 ft [.9997 m to 6 m]. A benefit of the mining system is each size rod can be used as casing, with the next smaller size of drill rod able to rotate inside the other pipe.

Circulation System

Circulation rates required for the slim hole system vary significantly from those of conventional oilfield practices. This is primarily because of the high annular velocities in the small annular space and the finer cuttings being lifted. Common flow rates when using an HQ rod range from 20 to 40 gpm [1.26 (E-03) to 2.52 (E-03) m^3/s], whereas when using the BQ rod the flow rates vary from 8 to 15 gpm [5.05 (E-04) to 9.46 (E-04) m^3/s].

The circulating system for the typical mining rig consists of an earthen reserve pit or possibly a steel mud tank(s). Solids control equipment is minimal, if even used.

Drilling Fluids

The mining industry has realized the need for a "no solids" circulating fluid since the inception of the wireline retrieval core system. Why is this? As the drill rods are rotated at high speeds, they act as a centrifuge which may cause plating of solids on the rods inside diameter. Not only would this eventually restrict flow down the rod with time, but, more important, it prevents wireline retrieval of the core, which could cause a rod trip. When possible, the mining industry uses water to core. If viscosity is required, usually to overcome rod vibration, a polymer is used. Large amounts of sedimentary formation with reactive clays are rarely drilled by the mining industry. Therefore, they have little expertise in designing the oilfield type mud systems to inhibit the various formations that have reactive clays.

Bits

Drag type core bits are almost exclusively used by mining drilling companies. These bits, properly designed, are ideal for drilling mineral type formations. Typical formations penetrated in minerals exploration are much harder, more competent, and uniform than those drilled by the oil industry. Therefore, direct application of mining bit practices to sedimentary formations will not necessarily yield economical results. The most predominant mining core bit is the impregnated diamond. This bit has very small diamonds (310-525 diamond particles per carat) continuously imbedded within a tungsten carbide matrix which wears as formation is drilled, exposing new cutting surfaces. The bit profile is flat. Surface set diamond core bits are also used, but to a lesser extent, when encountering softer formations. There is virtually no application of the PDC bit technology in the mining industry.

Drag bits, when rotated at the high speeds, can efficiently penetrate the rock with a low weight-on-bit (WOB). A typical WOB range is from 2,000 to 10,000 pounds [907.185 to 4535.924 kg]. Drag bits are susceptible to catastrophic failure if there is an abrupt formation change and the bit becomes "buried" and fluid starved. Therefore, a precise bit advance system is desired; however, this system does not exist on most mining rigs although the design of one is very adaptable to a drilling machine with hydraulic controls.

Well Control

As most formations penetrated by the mining industry do not contain hydrocarbons, well control practices are of no concern. Using this system for hydrocarbon exploration requires a thorough understanding of the physics associated with well control in the slim hole. When initially considering what would happen in a small annulus system and how to react if a fluid influx were to occur, it rightfully appears that slim hole mining type drilling is dangerous! However, after investigating the physics of the system, slim hole well control is very possible and even less dangerous than on conventional wells - if the proper practices are followed. A detailed discussion on slim hole well control physics and practices is contained in a paper by Bode et al.[12]

Core Retrieval

Core retrieval is accomplished by wireline. Figure 2 illustrates the components of the system. Most mining operations cut cores of 5, 10, or 20 ft [1.524, 3.048, or 6.096 m]. When coring is completed, a wireline overshot is lowered through the drill rods until it engages a spearpoint attached to the inner barrel containing the core. Upon reaching the surface, the inner barrel is laid down, another inner barrel picked up and dropped or lowered to bottom, and the core pumped out using a hydraulic pump. Various types of core barrel systems are available which consistently allow for 98-100% core recovery in all types of formations.

Core Analysis

Core analysis is typically performed by a mining engineer or core analysis service company. The responsibility of the mining drilling contractor normally ends with the boxing of the core at the site. Analysis of the core is similar to that in the oil and gas industry, with the primary objectives to determine the reservoir (mineral) properties; little consideration is given to true geological and geophysical evaluation, although the recent mining literature reflects more of an interest in evaluating the complete core.

EVALUATION OF MINING SLIM HOLE DRILLING PRACTICES

A mining drilling contractor was invited to continuously core a slim hole to a depth of 2,500 ft [762 m] at Amoco's Catoosa Field Drilling Research Facility. This area offers a suitable suite of lithologies with rock compressive strengths between 2,000 to 60,000 psi [13 789 514 to 413 685 420 Pa]. Lithologies range from shales to sands to carbonates with some shales being reactive to normal water-based drilling fluids. Formation pressure is subnormal so major concerns with well control are minimized.

The contractor was given a free hand to apply his mining technology to the sedimentary environment. A fresh water mud system was used with no solids control equipment. Hole washouts resulted. This caused the contractor to slow the rotation speeds, which reduced penetration rates. Later, the pipe became stuck. Bit selection was inadequate, and penetration rates were slow and bit life was poor. After 38 days and reaching a total depth of 1,950 ft [594 m], coring was suspended.

Logs from several oilfield logging companies were run to determine which ones could be run in a slim hole and what was the quality of the logs. Table 1 cites the results. Log quality was evaluated by comparison to logs obtained using conventional size tools from nearby wells. Mechanically, no problems were experienced while calibrating or running the tools. This test proved most typically required logs could be run in the slim hole environment.

Core recovery was 100% and of high quality. This confirmed the initial premise of the potential which exists to revolutionize exploration techniques through core analysis of a continuous section of rock. Development of an automated onsite core analysis facility was begun by our geological and geophysical researchers to take advantage of the core which would be generated by the future slim hole continuous coring system.

It was recognized that a major research and development program was needed to develop the mining drilling system into a system for oilfield application. An agreement was made with a mining contractor to assist in this effort.

EVOLUTION OF THE OILFIELD SLIM HOLE SYSTEM

A total system development approach was necessary to produce the desired slim hole system. Research into slim hole coring techniques, bit design, drilling fluid chemistry, fluid processing and solids control, well control, and exploration core analysis would be addressed. The program would include laboratory research, testing at the Catoosa field test facility, and further field testing to prove and completely develop the system.

Laboratory Research

Bit testing of various mining core bits was conducted on our laboratory drilling machine. Observations of the initial test results indicated there was poor hydraulic design, questionable concentration and placements of surface set diamonds, and minimal expertise in PDC designs. It was decided to borrow the expertise developed inhouse in full hole conventional drill bit designs and attempt to adapt it to slim hole core bit development. Results have been encouraging with performance improving as much as two-fold for both surface set diamond and PDC core bits.

A new water-based drilling fluid was developed for use with the slim hole system (Appendix 2). Modified shale rolling tests conducted on the most reactive shale at Catoosa show the cationic polymer brine fluid to be effective in preventing shale degradation. Oil-based drilling fluids were also researched to determine the one best suited for the slim hole system. A closed loop drilling fluid mixing and processing system was designed and fabricated. The system uses a centrifuge approach to solids control and features a 50 barrel [7.949 m^3] active and 200 barrel [31.8 m^3] reserve capacity. Fluid is mixed using a cylindrical mixer with a homogenizing pump for shearing polymer additions.

Development of a well control strategy was recognized as a key to slim hole drilling in sedimentary environments. Conventional well control models indicated a problem in controlling formation influxes in the slim hole. Literature searches revealed very little work had been done on pressure losses in a slim hole annuli. A program was developed to investigate slim hole well control physics, which included drilling a specially configured and instrumented well.

The control philosophy for operating a typical mining machine is a simple needle valve to bleed off pressure or control fluid flow on the hydraulic feed ram for the bit advancement. This method is very imprecise at maintaining the desired WOB. A control system using servo-valves and electronic servo-controllers was designed for the slim hole rig. Inputs to the controller include WOB, as measured through pressure transducers, penetration rate and rotary speed. The driller can control bit operating parameters either electronically through a control console or by computer via keyboard input.

Geological and geophysical research focused on the determination of physical measurements to be made on the core, how to compile and use the data, and how to process the core on a near real time basis. It was decided to develop an automated analytical core processing system which would include a mechanical apparatus to convey, clean, cut, label, and temporarily store the cores while maintaining their spatial relationship until analysis stations would be able to receive and analyze them. A microcomputer controlled drive mechanism would provide travel of the core from one geologic analysis station to the next. Additionally, disks would be cut from each 10 ft [3.048 m] of core for use in separate geophysical measurements. A modular onsite facility to house the evaluation equipment had to be designed and constructed.

Catoosa Testing

Bit testing at Catoosa provided information on bit life and penetration rates under actual coring conditions. Approximately 30 bits were tested, which included surface set diamond bits, PDC bits, Syndex, and impregnated core bits. Early results suggested the most applicable mining bit designs were the surface set types and design efforts were focused upon their improvement. Changes in bit profile, diamond concentration and placement, and coring parameters resulted in improved performance although not to the degree desired.

The drilling fluid mixing and processing system was successfully used to test the mixing of the various mud additives, and lost circulation materials. As previously mentioned, solids control is based upon centrifuging the entire circulating system. This equipment is supplemented by a high speed, fine screen shale shaker. Solids content was kept at a minimum as evidenced by the fluid testing and the lack of mud rings.

The water-based cationic brine fluid performed as laboratory tests had predicted. Washouts which had been evidenced on the well drilled by the mining contractor were eliminated, and the average hole size was within 1/2 in [1.27 (E-02) m] of bit gauge. Additionally, no stuck pipe problems occurred during the drilling of the five Catoosa wells.

Equipment was fabricated to cut and physically handle core in 40 ft [12.192 m] lengths rather than the 20 ft [6.096 m] length. Core recovery of 98% to 100% continued. This achievement resulted in fewer wireline trips, thereby increasing effective penetration rate.

Tests were conducted to investigate slim hole well control physics using a 2,500 ft [762 m] test well, as describe by Bode et al.[12] It was found that annular pressure loss in the slim hole was 90% of the total system pressure loss. Monitoring and quick detection of an influx in this system was very important. This could be accomplished by using quantitative flow meters placed on flow-in and flow-out points with the measurements depicted graphically on a computer monitor. Upon completion of the well testing phase, a detailed slim hole well control manual and school were developed.

Training all the personnel in the various aspects of slim hole coring procedures in sedimentary lithologies was a prime objective of the Catoosa work. Oilfield personnel realized it was not possible to directly apply one's previous knowledge to continuous coring operations. Mining personnel needed to be trained in the requirements to successfully operate in the oilfield environment. Training in rig operation, coring techniques, drilling fluid maintenance, and well control equipment and procedures are just some of what was learned during this period.

At the end of four months of development at Catoosa, there was confidence that the entire system could be used for exploration; however, to fully test its potential, wells had to be drilled outside the Catoosa field test facility. A joint test program was developed with exploration and production personnel within Amoco's various operating Regions.

Field Testing

The strategy of the field testing program was to drill a series of wells, beginning with one which would have minimal potential drilling problems and subnormal pore pressures. Each subsequent well would be in an area of greater difficulty. The first well was drilled in the Upper Peninsula of Michigan. The exploration objective was the Nonesuch shale of the Midcontinent Rift trend. Formations encountered were a variety of sands, siltstones, shales, conglomerates, and basalt. Pore pressure was subnormal with lost circulation in the upper part of the hole requiring an aerated fluid to be used. The well was originally planned for 4,000 ft [1219 m], but because of early diagnosis of the core it was analyzed that the well had to go below 7000 ft [2134 m] to achieve the exploration goals. The well reached a total depth of 7238 ft [2206 m].

A second well (Morrow Sand play) was drilled in western Kansas. Lithology was somewhat softer than the first well with more reactive shales. Carbonates, anhydrites, chert, and 275 ft [84 m] of salt were cored. Again, pore pressure was subnormal with lost circulation occurring in several intervals. Total depth of the well was 5956 ft [1815 m].

Numerous shows were observed from the core that probably would not have been detected from cuttings and were not evident from the electric logs.

Two coal degasification wells were drilled in southern Colorado. The formations had low compressive strengths and the pore pressure was subnormal. This was the first time coal of significant amount had been cored using this system. Total depths of the wells were 2,047 ft [624 m] and 3,121 ft [951 m].

The final well was in west Texas in an area normally requiring the use of oil-based mud to drill the reactive shales. Formations had steep dips and contained significant sections of chert. Pressure was closer to normal than any of the previous wells. A total depth of 9,617 ft [2931 m] was reached.

A total of 73 core bits were run during the field test program. Table 2 shows the distribution and performance statistics of these bits. Surface set diamond bits were used more than any other drag bit type. These bits performed most consistently throughout the field program, although performance was not as anticipated. PDC and Geoset bits actually achieved lower costs per foot, although the applications of these bit types were limited and some of the performance was erratic. Impregnated bits performed the poorest; however, they were determined to be excellent for milling steel such as broken bits, stabilizes blades, etc.

Most of the coring was performed using rotation speeds ranging from 400-800 rpm. WOB ranged from 3,000 to 17,000 pounds [1361 to 7711 kg]. Overall field data showed a positive effect of increased RPM on penetration rate for all bit types. The most common failure for the diamond bits were ring-outs. Very few bits were pulled with wear flats on the diamonds. On bits with ring-outs, most of the remaining diamonds were in good condition. No consistent wear pattern was evidenced for the synthetic diamond bits. Failures resulted from cutters breaking away whole from the matrix, cutters chipping and breaking, and cutters wearing flat. Poor hydraulic design effected the performance of many of the bits run.

The performance of the cationic brine drilling fluid achieved the objectives for the drilling of all but the last well, with an average hole size for four wells of 1/2 inch [1.27 (E-02) m] larger than the bit gauge. There were no problems with stuck pipe or mud rings associated with the cationic drilling fluid system. On the west Texas well, the drilling fluid was tested to determine if it could replace the oil-based muds commonly used. The predominant problem was associated with water wetting of the microfracture planes of the steeply dipping beds. After drilling to approximately 3200 ft [975 m], the same amount of drill rod was set and a mineral oil system was used to drill the remainder of the well.

The drilling fluid mixing and processing system worked well. Modification of the mixing capability was required to provide better mixing of polymer products and LCM. Fluid volume of the surface system was found to be adequate for all depths of wells drilled. It was learned additional work was necessary to determine the proper centrifuge pond depth settings for the flow rates run to maximize centrifuge efficiency.

Field wells confirmed the data collected from tests on the well control test well at Catoosa. Rig personnel became versed in the nipple-up and testing of the BOP, and their responsibilities if a kick were to occur while drilling or tripping. Data collected in the field also provided signatures of the various wellbore phenomena that occur in a slim hole annulus. This information has helped in the development of an artificial intelligence (AI) well control system. No kicks were taken during this field test phase.

The field experience also provided a situation for improving operational practices. These included requirements for running and cementing casing and decreasing wireline core and drill rod tripping times. Actual coring practices in different formations, benefits and modifications to the automatic control system, and how to handle lost circulation were some of the other operations that were learned. Although we had anticipated stuck pipe problems, none associated with formation and drilling fluid interaction occurred. There were no downhole tubular failures during the field test program.

On our first well in Michigan, only the geophysical measurement module was ready for use. Approximately 700 samples of core were processed during this well. Geophysical measurements were: density, porosity, quantitative mineralogy, and seismic velocities. The geological modules were ready for service on the Kansas well project. Geological measurements were gamma scan, saturations, porosity, magnetic susceptibility, mineralogical composition, hydrocarbon determination, and a video recording of the entire core. Figure 3 depicts the core processing modules. Over 15,000 ft [4572 m] of core was successfully analyzed during the field test program. The core evaluation system has processed 550 ft [168 m] of core in a day and can be adjusted for slightly higher rates, if required.

Data collected by the core processing modules was used not only to quickly evaluate the exploration play, but also provided information that helped make onsite drilling decisions such as bit selection, drilling fluid properties, etc.

Upon completion of the field testing, it was evident the entire slim hole system worked. We successfully cored over 37,000 ft [11278 m] of formation (including Catoosa) with 98.3% recovery. The measured data was utilized to better analyze each exploration and exploitation plays. However, it was also learned that additional research would be needed to enhance and optimize the system. Present research efforts include the following:

(1) Continuation of core bit design
(2) Small diameter full bore drag bit designs
(3) Self-contained cementing capability development

(4) Open and cased hole formation testing
(5) Development of an exploration computer workstation
(6) The addition of a rock compressive strength tester
(7) Completion of the AI automated well control capability

THE MAJOR ISSUES FOR USING THE SLIM HOLE SYSTEM - INFORMATION AND ECONOMICS

The question was previously asked: with the apparent interest in slim hole and continuous core drilling over the past 40 years, why has not both approaches become more popular and gained acceptance by the oil and gas exploration and exploitation sectors? This is a very pertinent question which deserves answering. Unfortunately, only the key issues can be exposed and briefly discussed within the space limits of this paper.

The arguments against drilling a conventional slim hole well have been production limitations imposed by the small diameter pipe and the difficulty to work over such wells. Other arguments often cited are the lack of good penetration rates using small diameter tricone bits, the apparent deficiency of logging tools that would fit into the slim holes, cementing the small hole, the difficulty to test, and the overall limitation of not being able to run multiple casing strings.

Arguments against continuous coring basically encompass all the arguments about general slim hole drilling and include the additional complaint about the safety of drilling with a small annulus system. Also, there is a question of the real need for continuous core? What is it worth? And if today's current drilling environment is considered, which it must, can slim hole drilling complete with conventional drilling?

Assuming the technical arguments against continuous core drilling can be satisfied, does a continuously cored well have an advantage over a conventionally drilled well? This question digs deep into the current exploration paradigm of how a company currently explores for oil and/or gas. The article by Ashton[10] presents the current exploration paradigm practiced by most oil and gas exploration companies (Fig. 4). Ashton also cites a new paradigm (Fig. 5) that utilizes the concept of continuous coring.

Rather than spending a significant portion of an exploration budget on costly seismic programs, why not answer the key questions about any exploration area as quickly and economically as possible: Are there source rocks? Are there seals to trap the hydrocarbons? Are there potential reservoirs? Are hydrocarbons present? What is the potential for trapping the hydrocarbons? If any of the above questions fail, the area of interest might have a low probability of having hydrocarbon accumulations. Continuous core leaves little to the imagination. With nearly 100% of the rock to evaluate, the entire geology unfolds. The core also provides the necessary rock data to improve the quality of the seismic interpretation that is essential for the more subtle trap determination. Therefore, it is possible to reduce the <u>overall</u> exploration costs with an early continuously cored well which also affects the time to evaluate an exploration play.

The biggest contemporary question about slim hole drilling pertains to economics. Can a continuously cored well economically be competitive with conventionally drilled wells?

At the present time, most U.S. land drilling contractors are operating at a loss of $200 K to $500 K per rig per year.[13] The depressed oil and gas drilling market is contrasted by a boom mining market which is consuming most of the mining drilling machines. There is no reason for any mining drilling contractor to operate at the "fire sale" drilling rates currently bid by most U.S. and Canadian oil and gas drilling contractors. Even with the mining drilling contractors charging full competitive make-a-profit rates, the slim hole continuous coring system can compete or be on a break-even basis for a number of U.S. and Canadian applications. If logistical and environmental considerations are significant, such as for remote wells in Alaska and other frontier areas, the smaller more compact slim hole system is definitely less expensive. Internationally, the slim hole system appears more competitive, down to 12,000 ft [3658 m], than most conventional drilling operations, especially for the more remote drilling applications. Figure 6 gives a general cost comparison between slim hole continuous coring and conventional drilling in Alaska, Pakistan, and Kenya.

It is important to remember the slim hole costs include the drilling of continuous core over 90% of the entire depth of the well, as compared to no core in the conventional well. To use a conventional drilling system to continuously core would cost three to four times as much as slim hole continuously coring. This was confirmed by comparing conventional coring costs in areas where slim hole continuous core was taken.

If the technical complaints about slim hole drilling and continuous coring are satisfied, and the continuous coring strategy paradigm provides a better and more cost effective way to explore, then why not consider the slim hole systems as an alternative to previous drilling and exploration practices?

It is the authors' opinion the biggest barrier to the use of the slim hole and continuous core drilling is it is new and different - it causes change, and change takes time and accurate communication of the technology. The advantages of having a full section of core is in its infancy of understanding. Explorationists have seldom had the convenience of looking at all the geology as it really exists. With the near real time analytical capabilities to evaluate the core at the well site, the geologists, geophysicists, and engineers have data that was almost impossible to get previously. How to put the information to optimum use is going to take time and imagination to develop. It is one thing to have 10,000 ft [3048 m] of core; it is another to analyze it on a timely basis, and it is even more difficult to take and use the data to make a difference in an exploration program. Champions of new paradigms for exploration will create the market for continuous core drilling. Until this happens, only the economics will determine whether to use slim hole techniques vs. conventional drilling practices.

SUMMARY - WHAT IS THE CURRENT STATUS OF THE MINING TYPE CONTINUOUS CORE SYSTEM?

The biggest operational deterrent for the use of slim hole mining type drilling, where a small annulus occurs, is the critical issue of detecting a kick quickly and accurately, and taking the correct action to handle the influx. The notion that conventional well control practices will suffice are totally inaccurate. Bode et al.[12] presents what is necessary for slim hole, small annulus well control. To do less is inviting a potential well control problem. The major breakthrough in adapting the mining slim hole drilling technology to the oilfield is the understanding and practices of how to handle kicks in a slim hole small annulus system. This technology is proven and does exist.

Information in this paper should convince the reader a slim hole system can economically drill the various geologies in a sedimentary environment if a proper systems approach is used. Small drag bits for either coring or full bore drilling are required. To optimize their use, high rotational speeds are used (200 to 700 rpm). And to rotate the drill string at these speeds, a mining type drill string (flush joint) is needed, where the annular clearance is small. A precise weight-on-bit, usually less than 10,000 lbs [4536 kg] with a sensitivity ±500 lbs [227 kg], is also required to make these small drag bits drill optimally. This requires a hydraulic control of the bit advance and is best suited to the hydraulic rig designs used by the mining drilling industry. A near in-gage wellbore is necessary to support and stabilize the high speed pipe rotation. High speed rotation can cause a buildup of solids in the drill rod, and to prevent this, the drill fluid must be as solids free as possible. All this technology exists today.

The drilling of over 40,000 ft [12192 m] of continuous core in all types of sedimentary environments proves that the slim hole continuous core approach should consistently recover over 98% of the rock cored. With this type of recovery and the analytical core analysis described herein, the need for downhole electrical logs is minimized. It is possible to set slim hole packers, perforate and test. Furthermore, most cementing can be done with a simple batch mixer and pumped using the rig pumps, thus eliminating another third party cost. If the mining type hydraulic drilling machines are used for the slim hole wells, portability is almost guaranteed. Most mining drilling machines of a 10,000 ft [3048 m] depth rating weigh less than 100,000 lbs [45 359 kg] as compared to 400,000 to 800,000 lbs [181 437 to 362 874 kg] for a conventional rig to drill to the same depth.

The technology exists to process over 500 ft [152.4 m] of core a day, measuring geological and geophysical properties necessary to evaluate any exploration play. Over 15,000 ft [4572 m] of core has been analyzed using a real time onsite automated core analysis capability.

It is the authors' opinion the technical obstacles that kept slim hole mining type drilling, especially continuous core drilling, from penetrating the oil field have been overcome.

The big questions is "if I wanted to drill a mining type slim hole and obtain continuous core or embark upon a continuous core exploration program, how would I do it?"

If the wells are less than 6000 ft [1829 m] and the pore pressure is not a problem (less than normal gradient), there is a large number of mining drilling contractors with machines rated to 6000 ft [1829 m]. By adapting some of the technology presented in this paper and by Bode,[12] within 3 to 6 months most operators should be able to safely drill their own slim holes to 6000 ft [1829 m].

If the desire is to drill deeper than 8000 ft [2438 m], there is a problem. Less than a handful of mining type rigs (excluding the ones in South Africa) currently exist that have this capability. And only a few contractors have the drilling machine and solids control system to drill wells in a sedimentary environment. It is the authors' understanding that these contractors have little knowledge of the well control practices to tackle normal or overpressured environments. Once a decision is made to embark upon a continuous core program at depths greater than 8000 ft, it is the authors' opinion that it would take 1 to 1-1/2 years before an operator could be ready to drill safely in a hydrocarbon environment. This assumes none of the three or four deep mining rigs were available. If a rig is available, it would still take up to six to nine months to field a safe operation.

The only way to start your own slim hole program is to make an agreement with an existing mining drilling contractor to build a rig (three rig manufacturers offer designs) and support system, i.e., mud and solids control, well control, etc., or go to an oil field contractor to adapt one of its conventional machines to a slim hole continuous coring system. This last alternative will, in most cases, sacrifice the portability of the mining type system.

The desire to have real time core analysis capabilities similar to what is described herein will probably take one to two years to develop. At present, no service company offers this package of analysis for onsite, real time core analysis.

The slim hole system presented in this paper is an evolution of mining and oilfield drilling systems and evaluation tools into one that could cause a paradigm shift in the way companies do exploration and some exploitation. It will require champions to look at the new possibilities it brings and not be hamstrung by the comfortability of doing it like it has been done for the past 50 years. Managers, engineers, and explorationists should be aware of this technology and the possibilities the technology offers. It is hoped this paper and Bode et al.[12] accomplishes that objective.

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APPENDIX 1

MINING TERMINOLOGY

Drill Rod Nomenclature	Rod OD	Rod ID
AQ	1-3/4 in. (44.5 mm)	1-3/8 in.
BQ	2-3/16 in. (55.6 mm)	1-13/16 in.
NQ	2-3/4 in. (69.9 mm)	2-3/8 in.
HQ	3-1/2 in. (88.9 mm)	3-1/16 in.
PQ	4-1/2 in. (114.3 mm)	4-1/16 in.
CHD 76	2.754 in. (70.0 mm)	2-3/8 in.
CHD 101	3.701 in. (94.0 mm)	3-17/64 in.
CHD 134	5 in. (127 mm)	4-1/2 in.

Chuck - Mechanical device which grips the drill rod and is contained within the drive head which imparts rotation.

Drill rod - Terminology given to drill pipe. It is externally flush with an internal upset at the connection.

Mud ring - Build-up of solids on the inside diameter of the drill rod caused by centrifuging associated with high speed rotation.

Sandline - Wireline used in the retrieval of the inner core barrel.

Appendix 2

Formulation and Properties of CBF Drilling Fluid

	Viscosified CBF	Weighted CBF
Cationic Polymer, lbm/bbl	1.5	1.5
Pregelantized Starch, lbm/bbl	2	2
Hydroxyethyl Cellulose, lbm/bbl	1	1
KCl, lbm/bbl	38.1	22.1
$CaCl_2$, lbm/bbl	0	107
PV, cp	10	11
YV, lbf/100 sq ft	5	6
Gels (10 sec/10min), lbf/100 sq ft	1/1	1/1
API FL, ml	12	10
Density, lbm/gal	8.9	10.5

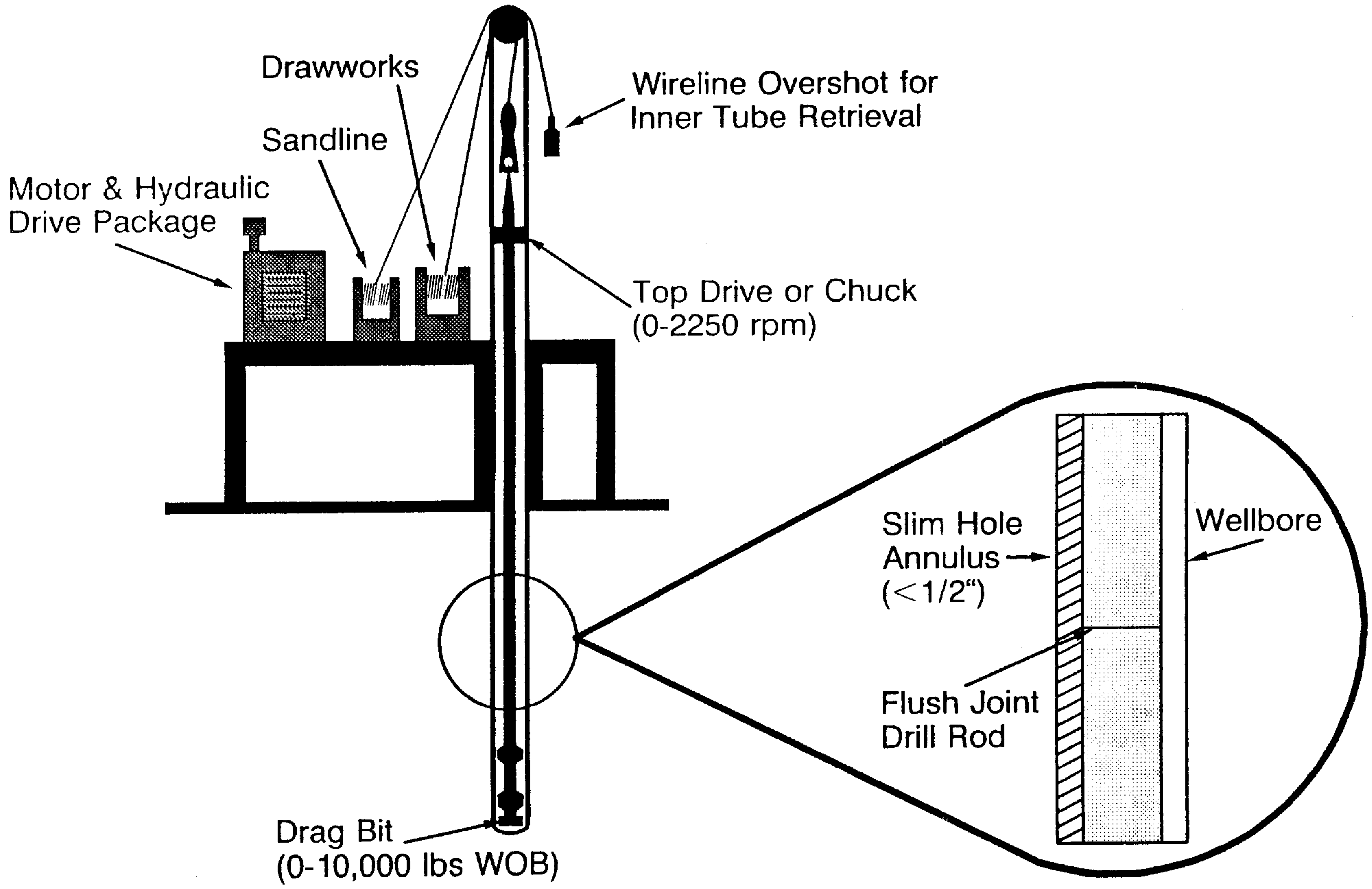


FIG. 1: *TYPICAL MINING CONTINUOUS CORE DRILLING SYSTEM*

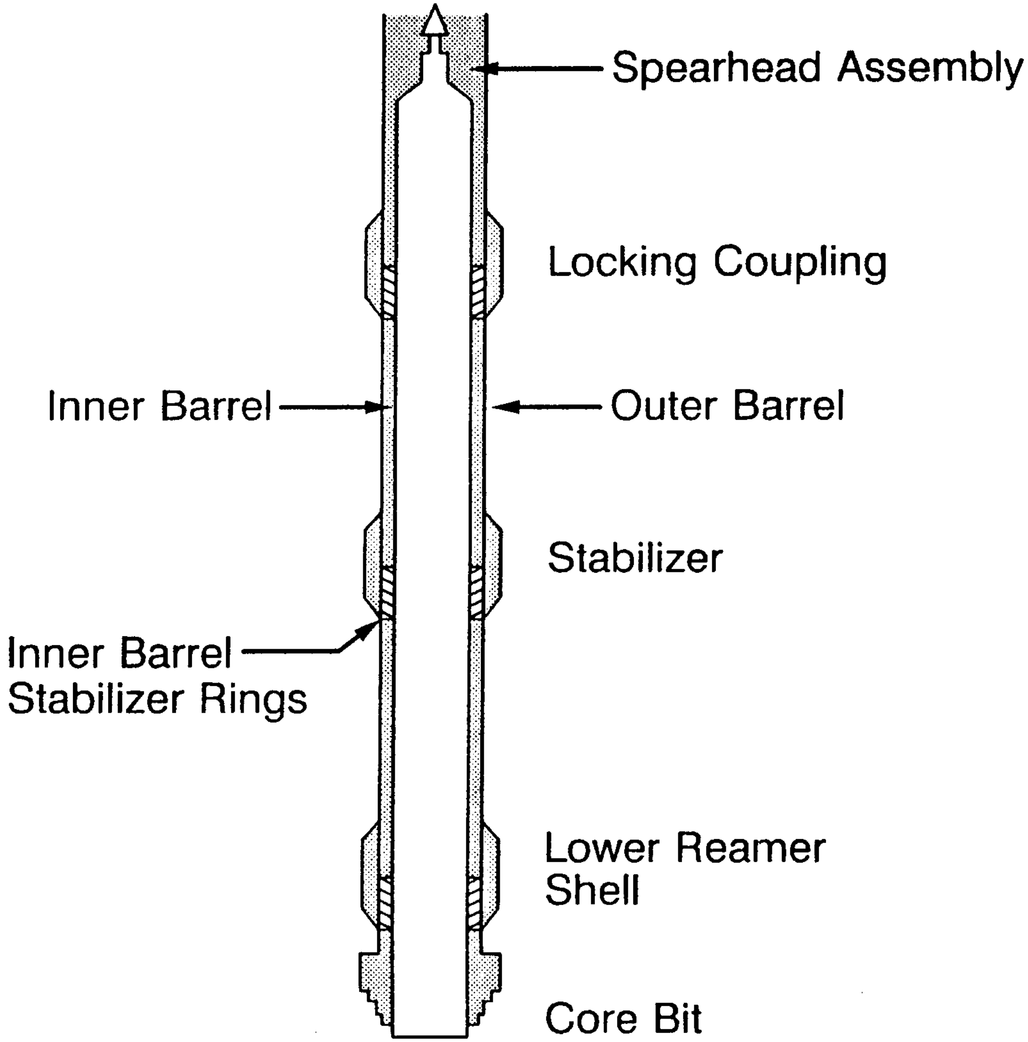
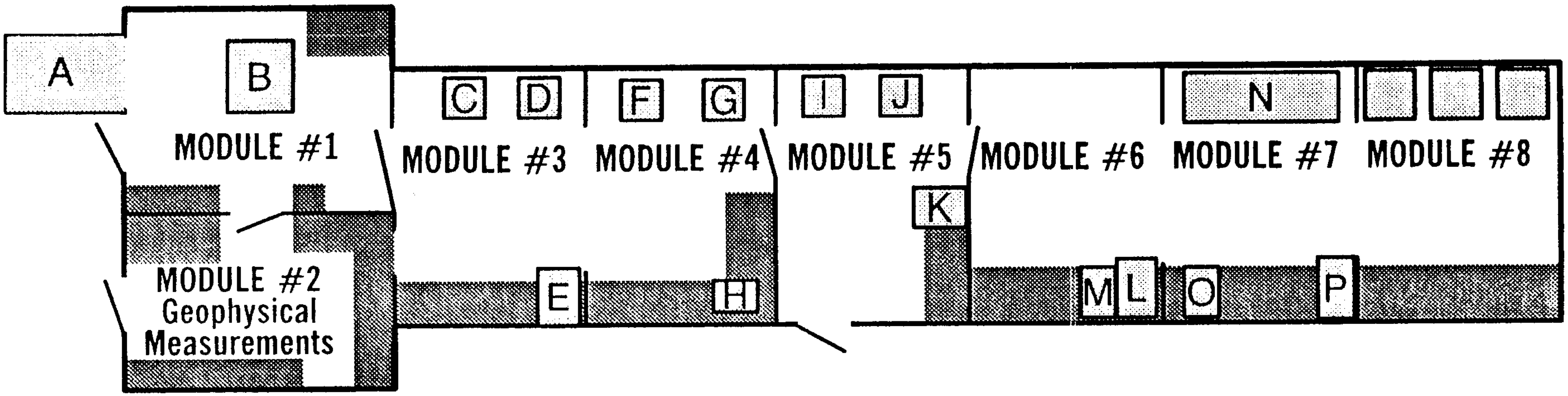


FIG. 2: WIRELINE CORING ASSEMBLY



A. Washing and drying.
B. Striping, labelling, cutting.
C. Gamma scan.
D. Magnetic susceptability.
E. Data storage and 'traffic cop' computer.
F. Qualitative mineralogy.
G. Ultra-violet fluorescence scan.

H. Computer for above.
I-J. Macro and micro view video cameras.
K. Video monitors.
L. Core description computer.
M. Video microscope.
N. Movable table.
O. Spare computer.
P. Gas chromatograph.

FIG. 3: AUTOMATED CORE EVALUATION MODULES

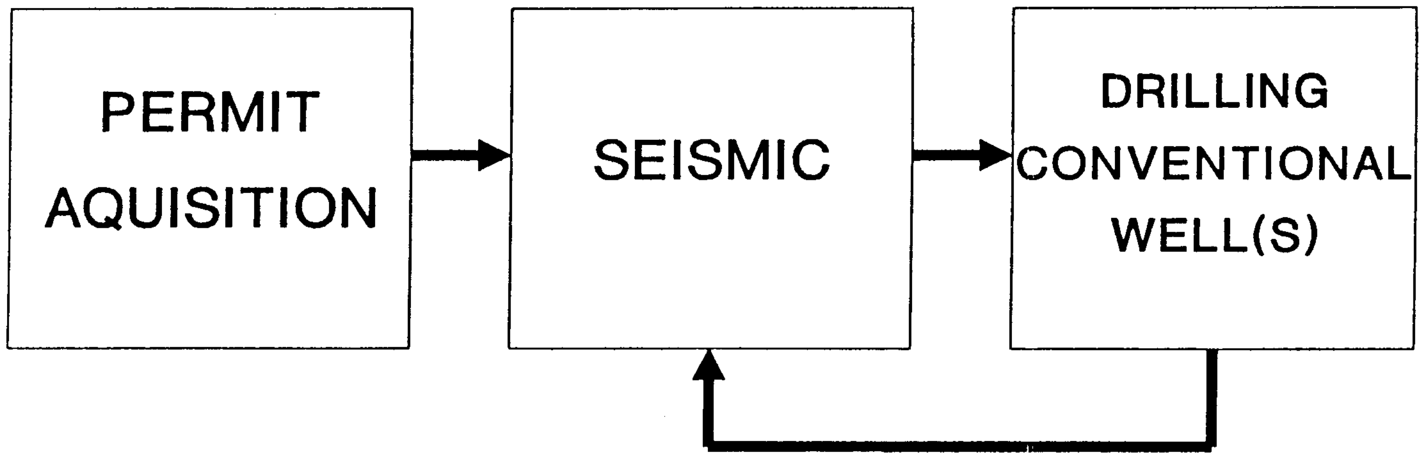


FIG. 4 EXPLORATION MODEL CURRENTLY PRACTICED BY MOST OIL AND GAS COMPANIES (after Ashton[10]).

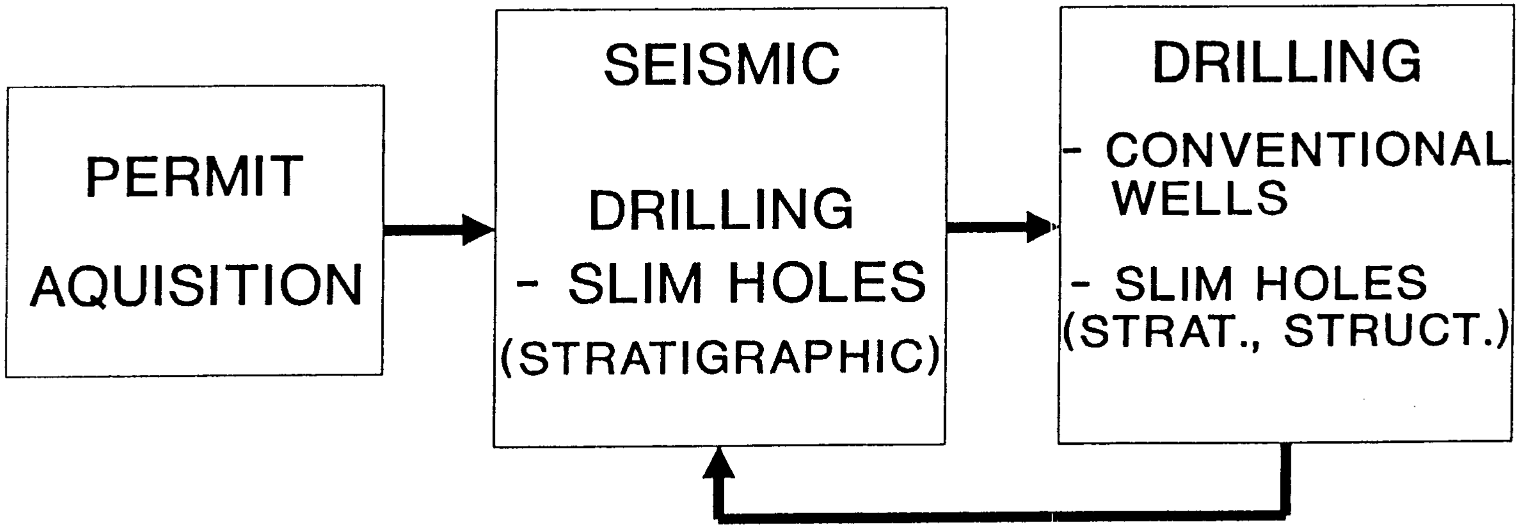


FIG. 5 EXPLORATION MODEL UTILIZING CONTINUOUS CORING CONCEPT (after Ashton[10]).

	Slim Hole ($/ft)	Conventional ($/ft)
Alaska	655	1224
Pakistan	132	193
Kenya	211	338[1]

[1] Actual cost.

FIG. 6: COST ESTIMATE COMPARISONS BETWEEN SLIM HOLE CONTINUOUS CORING AND CONVENTIONAL DRILLING

TABLE 1: *LOGGING TOOLS SUCCESSFULLY RUN IN SLIMHOLE WELL AT CATOOSA*

	COMPANY A	COMPANY B	COMPANY C
GAMMA RAY	*	*	*
SONIC	*		*
DUAL INDUCTION	*	*	*
SHORT NORMAL			*
SPHERICAL FOCUSES	*		
LATERO-LOG			*
SHORT GUARD		*	
SP		*	*
FORMATION DENSITY	*	*	*
COMPENSATED NEUTRON	*	*	
CALIPER	*	*	*

(BHTV WAS RUN BY AMOCO GEOPHYSICAL LOGGING SERVICES)

	Bit Type				
	Diamond	PDC	Geoset	Impregnated	Overall
Bits	40	7	19	7	73
Footage	17499	2830	7016	228	27573
Hours	1009	107	347	25	1488
Avg. ROP	17.3	26.4	20.2	9.1	18.5

TABLE 2: SUMMARY OF BIT PERFORMANCE DURING FIELD TESTING PROGRAM