Recent Advances in Coring Technology: New Techniques to Enhance Reservoir Evaluation and Improve Coring Economics

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This paper was prepared for presentation at the Society of Core Analysts Annual Meeting, held in Montpellier, France, September 8-10, 1996.

Abstract

Damage to core during acquisition and handling, as well as the high cost of some coring operations, have been major issues confronting the coring and core analysis industry. Core damage leads to analytical difficulties in the laboratory which can compromise the reliability of core analysis. It is necessary to conduct tests on undamaged core, because major reservoir evaluation issues and reserves estimates can be dependent on core-based data. The overall cost of coring is influenced more by rig time rather than direct charges for coring services. Two new tools, Gel Coring and Coring-While-Drilling (CWD), have been developed to provide geoscientists, reservoir engineers, and drilling engineers with options to improve reservoir evaluation and reduce coring costs.

Introduction

Downhole core preservation and encapsulation using high-viscosity gel is an alternative to operator-intensive wellsite core preservation. Standard downhole coring assemblies do not preserve in-situ reservoir properties because no provisions are made for core preservation prior to core surfacing. Low invasion coring systems help minimize drilling fluid invasion, but rock wettability and fluid saturations can still be altered by counter-current imbibition of mud filtrate and/or diffusion before core analysis begins. Core Gel is a viscous, high molecular weight, polypropylene glycol with zero spurt loss which is non-soluble in water and environmentally safe. Because the Gel comes in direct contact with the core during and immediately after it is cut, further exposure to core contaminants is minimized. The high viscosity Gel stabilizes poorly consolidated rocks with moderate compressive strengths and enhances core integrity. Core Gels can be customized to address most coring situations and rock types.

The Coring-While-Drilling (CWD) system is designed to provide operators with the flexibility of bottomhole coring or drilling with the same bit, without tripping-out of the borehole. In the drilling mode, the system is used in the same manner as a conventional bottomhole assembly (BHA). In the coring mode, a drill bit plug is replaced with an inner barrel and bearing assembly that transforms the drill bit into a core bit. After core recovery, the coring assembly is retrieved with a wireline and overshot assembly. Additional cores are cut or the retrievable drill plug is quickly reconfigured for drilling ahead. CWD uses high rate-of-penetration (ROP) anti-whirl polycrystalline diamond compact (PDC) bits and significantly reduces the time necessary to cut continuous full-diameter cores. The CWD system excels when core depths cannot be determined *a-priori* and where zones of interest are separated by thick non-reservoir sections.

Gel Coring

Drilling fluid filtrate invasion during coring can add uncertainty to the interpretation of core analysis results and may preclude fresh-state testing. In particular, in-situ rock wettability can be altered by drilling fluid components and affect critical petrophysical and reservoir engineering parameters-e.g., residual fluid saturations, Archie saturation exponent "n", and relative permeability. It is necessary to conduct tests on uninvaded core because major reservoir evaluation issues and reserves estimates can be dependent on core based data. Drilling fluid filtrate invasion occurs when the fluid phase of the drilling mud is forced into the formation by differential pressure. The amount of invasion is related to reservoir rock and fluid properties, drilling parameters (especially ROP), and the drilling fluid filtration characteristics.

The three principal areas where drilling fluid filtration occurs during coring are:

1. Ahead of the bit-- can be significant at low coring rates when the vertical flow (interstitial) velocity of the mud filtrate in the core exceeds bit velocity. Under severe conditions, drilling fluid filtrate will form a fluid bank ahead of the bit and a core can be totally invaded.

2. At the bit face and in the bit throat-- occurs in all coring operations regardless of coring assembly design or coring fluid properties. This type of invasion will be more severe at low coring rates or with high fluid loss drilling fluids. For muds with bridging solids or fluid loss additives, e.g. starch, this effect is reduced significantly.

3. In the inner core barrel-- static filtration as well as counter-current imbibition can redistribute reservoir fluids in the core and add to invasion problems. Low permeability streaks or breaks in cored sections generally minimizes the vertical migration of drilling fluid filtrate in the inner core barrel.

New low-invasion coring systems using PDC core heads have made a significant contribution toward reducing drilling fluid filtrate damage in cores.[1-4] Low invasion core heads have the following design characteristics:

- aggressive cutter design-- the number of cutters is reduced to increase the depth of the cut which increases coring rates and optimizes filtration parameters.
- parabolic bit profile-- reduces the dynamic filtration area for invasion.
- minimal number of gage cutters-- reduces the contact time of the gage cutters on the core.
- elimination of throat cutters-- to preserve the filter cake.
- extended pilot shoe-- close to the gage cutters to ensure the core enters the inner core barrel soon after cutting the core.
- face discharge ports-- directed away from the core center.

Figure 1 compares conventional and low-invasion core head designs. Tibbitts et al.[1] and Rathmell et al.[2] report filtrate invasion damage with low-invasion core heads under optimal conditions limited to the outer one-half of an inch and three-quarters of an inch in four inch diameter core, respectively.

Low-invasion coring is a three step process. If all of the prerequisites for obtaining low-invasion cores are not met, significant invasion and in some cases, total invasion may result. The prerequisites for obtaining low-invasion cores include the following:

1. low-invasion core heads and assemblies.

2. coring fluids with low fluid loss properties.

3. high coring rate-of-penetration (ROP) relative to coring fluid filtration rate.

Unfortunately, low-invasion cores cannot be obtained in **all** formations under **all** coring conditions. The objectives of low-invasion coring, on the face of it, appear quite simple-i.e., to acquire uninvaded cores for improved laboratory analysis and reservoir evaluation. In theory, geoscientists, teams of oil company engineers, and petrophysicists collaborate with service companies to design the optimum coring assembly, coring fluid, core tracer program, wellsite core handling and preservation procedures, and core analysis protocol to meet reservoir evaluation objectives. In practice, planning and execution of a low-invasion coring program rarely includes all of the steps necessary to minimize drilling fluid filtrate invasion.

A number of things can go wrong during the planning and core acquisition process:

- **communication breakdown--** petroleum technologists from the operating company should be involved with planning the coring job-e.g., drilling engineer, drilling fluid specialist, logistical specialist (critical when operating in remote locations), petrophysicists, geoscientists, and reservoir engineers. Many low-invasion coring programs are planned poorly and this can lead to problems in the laboratory analysis as well as in the data quality potential. In many cases, drilling staff see coring as a nuisance, and disinterest can lead to achieving no better than conventional core quality with a low-invasion core head. Rarely are pilot studies performed or calculations made for evaluation of coring fluid characteristics-e.g., bridging efficiency of solids and expected fluid losses, tracer-coring fluid compatibility, and interstitial filtrate velocity versus estimated ROP.

- **budget constraints--** the cost of low fluid loss coring fluids and tracers can be high. Bridging solids, such as sized calcium carbonate are expensive and large quantities may be required for certain rock types. Because low-invasion coring rates (ROP's) with PDC cutters may be greater than conventional drilling rates, coring fluid costs may be offset with reduced rig time.

In addition to operational difficulties inherent to low-invasion coring, this technology is not adaptable to all rock types or drilling situations:

- it may be impossible to achieve low-invasion in highly-permeable, loosely consolidated sandstones because of high fluid (spurt) losses-i.e., during the initial stages of filtration before pore openings are bridged and a filter cake is formed. Coring through soft rock *gumbos* with PDC cutters may be ineffective.

- insufficient coring rates in hard rock may cause significant invasion ahead of the bit. Generally, low-invasion coring ROP must be several 10's of feet per hour-e.g., 90 to > 120' per hour may be needed to reduce mud filtrate invasion. In very hard rocks, PDC cutters may be ineffective.

Downhole Core Preservation

Downhole core encapsulation and preservation can enhance low-invasion coring by limiting core-to-coring fluid and filtrate contact time.[5] Downhole core preservation may help compensate for many of the deficiencies common to low-invasion coring:

- when communication and planning fall short.
- poor coring fluid characteristics.
- drilling conditions are less than optimal-e.g., low ROP.
- uncontrollable issues related to formation properties.

New technology using high-viscosity gel for downhole core preservation is an alternative to uphole operator intensive wellsite methods.[6,7] Existing low-invasion anti-whirl coring assemblies have been retrofitted to accommodate use of a simple inner barrel floating piston (*rabbit*) for gel distribution and core encapsulation. The viscous core preservation gel is a high molecular weight polypropylene glycol which is non-soluble in water and environmentally safe. Because the gel comes in direct contact with the core immediately after it is cut, further exposure to drilling fluid is minimized.

The core is protected (preserved) in the area of cutter-to-rock contact where the gel replaces its volume of drilling fluid. To a limited degree, flushing and mud filtrate invasion in the formation ahead of the bit is reduced.

Once at the surface, exposure of the core to air is reduced significantly, thus eliminating the risk of reservoir fluid losses, core desiccation, and wettability alteration. Residual fluids remain intact and hydrocarbon expulsion or bleeding is reduced-i.e., the gel acts as a semi-permeable barrier, even with highly mobile fluids such as gas condensate. With or without gel, sample plugs for tracer studies or special core analysis should be cut at the wellsite to eliminate the possibility of fluid redistribution during core transportation. An additional benefit of downhole core encapsulation is obvious if one considers handling poorly cemented (unconsolidated) rock with moderate compressive strength. The high-viscosity gel stabilizes the core and enhances the rock's mechanical integrity. For rocks with little cementation, the polypropylene gel can be replaced with a self-hardening plastic, thus eliminating the need for time-consuming and expensive surface resination.

The Gel Coring System

Figure 2a shows the downhole core preservation assembly before coring begins. Before delivery at the wellsite, twenty-two (22) gallons of gel is preloaded into each 4 ¼ in. diameter by 30 ft disposable inner barrel. The gel is contained in the inner barrel before coring and is distributed around the core by a core-activated floating piston valve after core begins to enter the standard low-invasion core head (figure 2b). Excess gel is displaced from the inner barrel by the core through the extended pilot catcher shoe, out the throat of the bit, and past the cutters where it mixes with and is dispersed by the drilling fluid. At the cutter-to-rock interface, the gel displaces drilling fluid and protects the core from flushing and drilling fluid filtrate invasion. Static filtration invasion of the core by overbalanced drilling fluids in the inner barrel, an intrusive phenomenon common to conventional coring, is virtually eliminated.

A safety relief valve mounted at the top of the coring assembly prevents excessive pressure build-up in the inner barrel. Approximately two gallons of gel remains in the inner barrel annulus and forms a protective layer over each 30 ft section of core. Multiple 30 ft sections can be stacked for a single coring run, thus eliminating the need for added trips in and out of the borehole. Figure 2c shows a gel-encapsulated core before surfacing.

Chemical and Physical Properties of Core Gel

Standard core gels are used for most downhole core preservation programs. Polypropylene glycol (PG), the principal core gel component, is a harmless substance under normal handling conditions. The chemical is low in acute oral toxicity, non-irritating to the skin, and not readily absorbed through the skin. The viscous PG gel also contains additives to improve filtration properties and increase viscosity. Strict quality assurance measures are taken to ensure all gels meet spurt loss, viscosity, and heat capacity specifications. The spurt loss test is performed to measure gel penetration into a disc of porous media at elevated pressure and temperature. Zero spurt loss is one criterion for *off-the-shelf* gels. Viscosity and heat capacity tests are designed to ensure gels are effective at reservoir temperature and pressure. After a batch of blended gel has passed inspection, it is packaged in 55-gal. drums and readied for shipment.

Gels designed for specific applications can be formulated to meet special coring and core analysis objectives. Some of the reasons for designing custom gels may include the following:

- a core may be too unconsolidated or lack sufficient cementation to displace a highly viscous gel. Gels can be formulated with lower viscosities; however, they will become less effective as viscosity is reduced. Spurt loss will generally increase as viscosity decreases.

- mechanical properties-e.g., compressive strength, should be known *a priori* to assist in selecting gel type. Three (3) standard gels are available for various coring applications. An alternative to core gel is a *thinner* polyethylene plastic designed to operate at high temperature for in-situ core resination.
- bottomhole temperature and surface winter temperatures may affect gel performance, and this must be considered during the gel selection process. The ideal gel will have zero fluid loss at bottomhole temperature.
- some chemical components in core gel may affect certain geochemical analyses-e.g., total organic carbon (TOC) and source rock studies. If geochemical testing is planned, certain filtration components can be replaced with acceptable substitutes.
- a gel, coring fluid, and reservoir fluid compatibility study should be included in the planning stages of each gel coring job. Every gel coring job should be pre-screened for potential fluid incompatibilities. It is impractical, if not impossible, to design a gel immiscible to all hydrocarbons and all commercially-available drilling fluids. Standard core gel when immersed in kerosene for several days, has a solubility of about 1%, as confirmed by nuclear magnetic resonance (NMR). All tests performed thus far indicate no gel incompatibility with crude oils or drilling fluids.
- core gel is **NOT** designed for long-term core preservation. Exposure of core to PG gel for prolonged periods of time (several weeks to months) may affect intrinsic rock properties. Although Gel has limited solubility in oil, it can partially dissolve in a core's oil phase over time.

Laboratory tests on standard core gel at 200°F and 250 psig differential pressure on water-saturated gel-coated rocks with permeabilities as great as 10 Darcys, indicate no spurt loss and zero water loss. This means that gel effectively coats rock and gel invasion is generally negligible.

Gel encapsulation of core is not known to affect surface gamma logging or non-destructive core imaging-e.g., X-ray tomography and NMR. Gel can be peeled, scraped, or wiped from the core surface. Extreme care must be taken to ensure the core remains intact during disposable inner barrel and gel removal. If core descriptions are planned, it is advisable to *slab-off* a small portion of the core prior to inspection. Gel on the outer surface and in the near-surface pore layers of the core generally presents no more problem to the core analyst than mudcake in conventional analysis. Special studies that rely on full-diameter samples may be affected-e.g., analastic strain recovery (ASR) or full-diameter directional permeabilities.

Gel Coring in Norway

Gel coring has been used extensively in Norway since early 1994. Over twenty-five (25) gel cores have been acquired in 6 to 12¼" boreholes with bottomhole temperatures as great as 275°F. Statoil, Norsk Hydro, Saga Petroleum, and Amoco have used gel coring for reservoir engineering and petrophysical objectives. In addition to the many analytical and preservation benefits of gel coring, core recoveries have improved dramatically at the Statoil operated Sleipner A and B platforms. After several successful full-recovery 90 ft gel coring runs, 180 and 240 ft cores were cut using a mud motor and conventional low invasion core heads. Coring on a mud motor has: improved core recoveries, reduced torque fluctuation, increased ROP, minimised drillstring vibration, and reduced complications when making drill pipe connections. Gel core barrels as long as 360 ft have now been run in Norway.

In better than half of all gel coring projects, gel has proven to improve core recoveries through lubrication of the inner core barrel; inner core barrel to rock friction must be minimised in loosely consolidated, friable sandstones to achieve high core recoveries. Core damage during transportation and handling has been reduced because gel acts as a *shock absorber* in the inner core barrel annulus.

Coring-While-Drilling

The Coring-While-Drilling (CWD) system is designed to provide operators with the flexibility of bottomhole coring or drilling with the same bit with minimal interruption to the drilling process.[8] The coring bit can receive a center drill plug in a specially designed end bearing allowing full-hole drilling without tripping the drillstring out of the hole. Coring inner tube assemblies can be interchanged between drilling and coring modes an unlimited number of times. Vintage continuous *wireline coring* (WC) systems popular in the 1950's to 1960's, used technology transferred from the mining industry. Early versions of WC systems suffered from low ROP mainly because they used natural diamond core bits. Many times WC cores were severely out-of-gauge, broken, and of limited value for quantitative core analysis. The CWD system with PDC core bits and anti-whirl features can provide ROP's comparable to their fullbore counterparts. Eliminating downhole vibration and adding high ROP PDC cutters has made continuous coring with conventional equipment an attractive option where coring may be uneconomic because of high rig costs. High quality CWD cores of up to 2" in diameter by 30 ft length cut with conventional rigs and tubulars offers an option previously unavailable to drilling engineers, geoscientists, and reservoir evaluation specialists.

Another unique feature of the CWD system is the overshot retrieval mechanism. The overshot is designed to pull the coring inner barrel assembly with a high-strength triple latch mechanism and will release the inner barrel without the need for additional hardware.

CWD Drilling Benefits Include:

- reduction in the number of trips when long core sections are required .
- shorter trip times for deep coring targets.
- fewer trips with multiple zones of interest (especially when separated by long drilled sections).
- reduction in safety risk in abnormally pressured formations-- lubricator heads can be utilized and assemblies can be retrieved while pumping mud at normal flow rates.
- practical in rugose boreholes where sidewall coring is ineffective.
- no need to change the bottomhole assembly (BHA) to drill the rat hole.

CWD Geology and Reservoir Evaluation Benefits Include:

- practical in situations where conventional coring is cost prohibitive or a risk to the drilling operation-i.e., where cores would otherwise not be cut.
- unlike sidewall coring, CWD provides high quality, undamaged, continuous core sections for sedimentological assessment and they are suitable for fluid flow studies-e.g., restored-state relative permeability.
- cost effective in areas with poor stratigraphic control and where core points are difficult to determine.
- useful in reservoirs where cores must be surfaced quickly for hydrocarbon volumetric determinations-e.g., coalbed methane.
- cost effective in fractured formations where inner core barrel jamming is unavoidable.

The Coring While Drilling (CWD) System

The CWD outer core barrel assembly consists of a top sub, a top sub stabilizer containing the latch assembly, the outer tube, and a bottom (near bit) stabilizer containing the drilling drive latch assembly (figure 3a). Outer barrel stabilization is accomplished with standard integral blades. The inner core barrel (coring mode) assembly consists of an upper- and lower-shoe, steel inner tube barrels, tri-latch assembly, adjusting rod and upper bearing assembly, and ball seat (figure 3b). The inner drill rod (drilling mode) assembly consists of the extension drill plug, drive latch assembly, drill rods, tri-latch assembly, and automatic spacing mechanism (figure 3c). The CWD system can be operated in 7 7/8 to 8 3/4" diameter boreholes with conventional drillstrings with a minimum bore of 2 13/16". The core barrel is 6 1/4" in diameter by 15 to 30' in length and accepts cores up to 2" in diameter. A standard 5/16 to 5/8" wireline (slickline, braided line, or sandline) is required for retrieving the inner coring assembly (180 lbs) and inner drilling assembly (425 lbs). The recommended trip speed for the wireline is 200 to 400 ft/min. The core barrel assembly can be dropped inside the drill string or pumped downhole provided it is full of drilling mud with sufficient rheological characteristics. The drill plug and drill rods are wirelined downhole to prevent damage to the PDC cutters.

Figure 4a shows the CWD low friction, low-invasion, anti-whirl bit with the drill plug inserted. This bit incorporates PDC cutters for aggressive ROP and a combination of small fluid passages and fixed ports for each bit blade to aid cleaning. Insertion of the drill plug does not affect bit stability and while in the drilling mode, the CWD bit performs as well as standard PDC drill bits. Figure 4b shows the 2 in. drill plug fitted with six (6) ½ in. PDC cutters (CWD drilling mode). The drill plug is attached to the same wireline retrievable head that is used for coring, but two (2) drive latches are added for rotation of the drillstring.

Figure 5a and 5b are schematics of the CWD bit head in the coring mode and drilling mode, respectively. The internal geometry of the bit includes a bearing assembly that provides a landing shoulder for the inner core barrel or drill plug as well as internal centralization and stabilization. Since the inner barrel is in the bit, this allows for a larger diameter inner barrel and thus a larger diameter core as compared to other systems. A standard spring type core catcher is fitted into the lower shoe of the inner core barrel. An increase in mud pump pressure at the surface verifies when the inner barrel has seated properly. Mud pressure acts against the cross-sectional area of the inner barrel and provides added system stabilization and hold down. Maximum recommended drilling fluid flowrates for the CWD system are 300 gallons per minute (GPM) in the coring mode and 400 GPM in the drilling mode. Also shown in figure 5b is the drive latch extension (drill rod) attached to the drill plug. The primary function of the drive latch, located in the near-bit stabilizer is to transfer torque from the drill string to the core plug.

The overshot (retrieval mechanism) uses a knuckle joint coupling to eliminate wireline cable torsion, centralizing rubber fingers, and a safety release device to eliminate the need for tripping should the inner barrel become stuck. The core can then be handled and preserved with conventional wellsite core handling procedures. Because CWD cores are of high quality, both basic and special core analysis follows standard analytical protocol. Where long horizontal core sections are required, composite samples can be configured.[9]

Conclusions

Gel Coring assemblies combined with low-invasion core heads can provide additional protection against drilling fluid filtrate invasion in cores. When coring fluids have insufficient fluid loss characteristics, gel can help alleviate this deficiency. If low-invasion cannot be achieved because of coring conditions-e.g., low ROP, gel will help minimize drilling filtrate invasion in the core barrel. Gel can provide an added measure of protection of core damage in highly permeable rocks. In loosely consolidated rock, with moderate compressive strength, gel can add mechanical integrity to the core, thus eliminating potential damage during surface handling. Gel coring can enhance special core analysis studies and improve reservoir simulation through acquisition of better data from fresh-state core-e.g., improved residual oil saturation.

Coring-While-Drilling can be used in drilling and geological scenarios where cores would otherwise not be cut because of budget constraints or technical difficulties. CWD is a cost effective means to obtain critical reservoir information for geological assessment and reservoir evaluation.

Acknowledgements

The authors wish to thank the management of Baker Hughes Inteq for permission to publish this paper. We thank several operating companies for the opportunity to perform Gel Coring and Coring While Drilling services.

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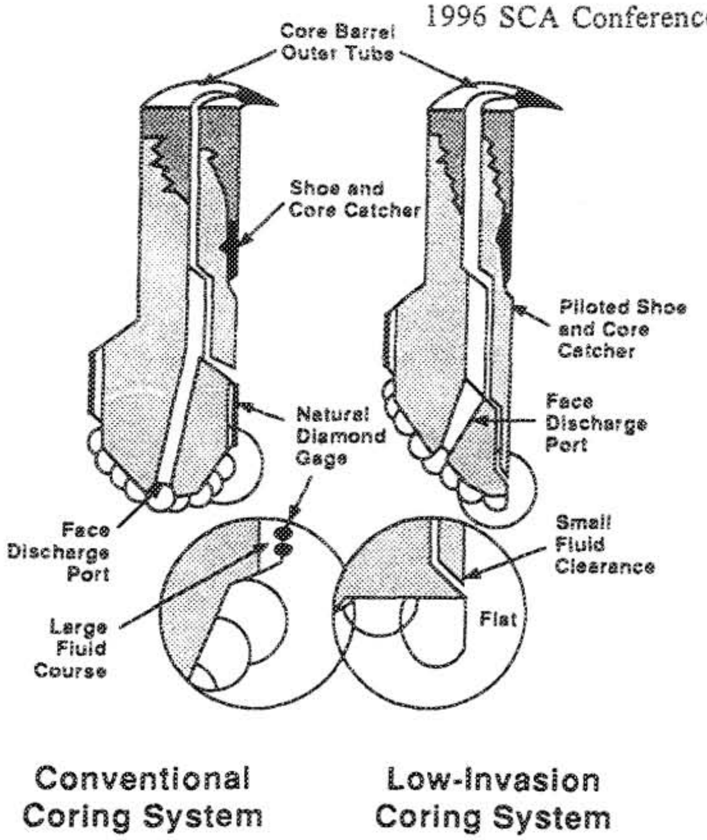


Figure 1. Comparison of conventional and low-invasion core head designs (from Tibbitts, 1990).

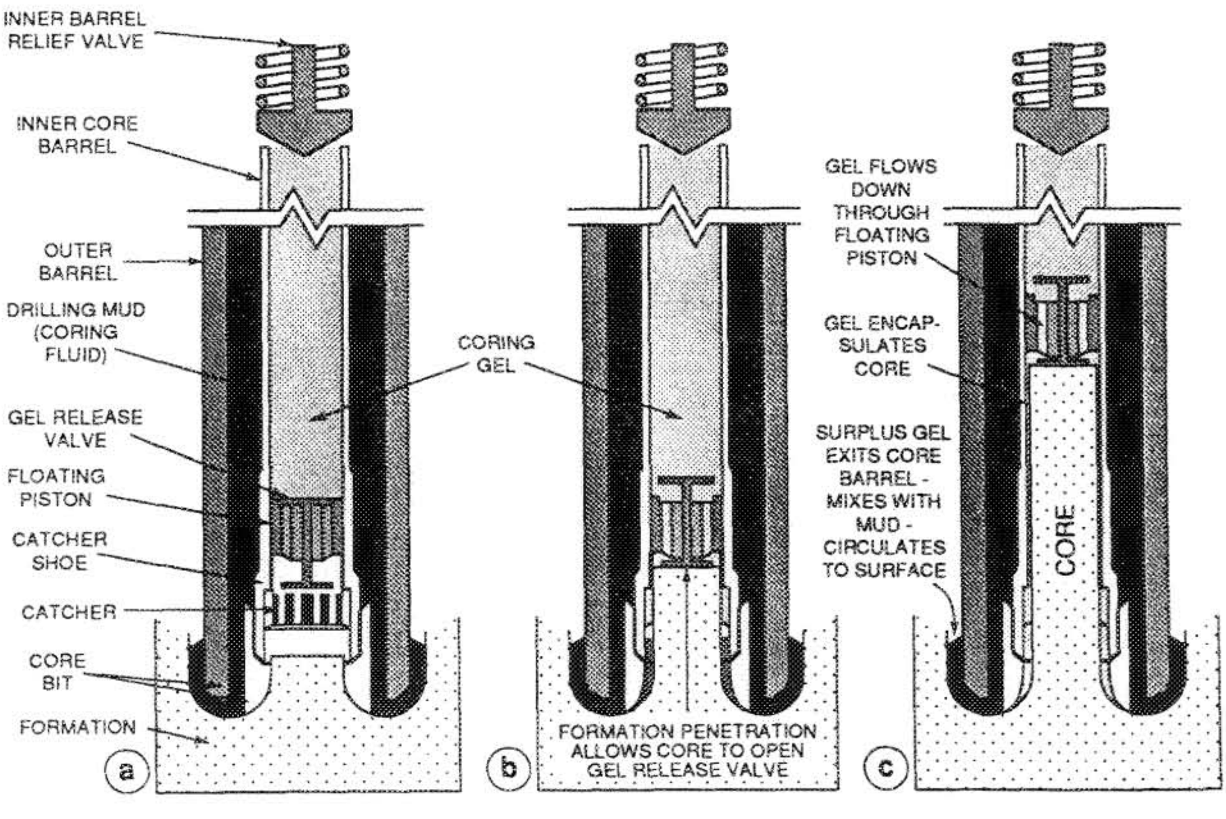
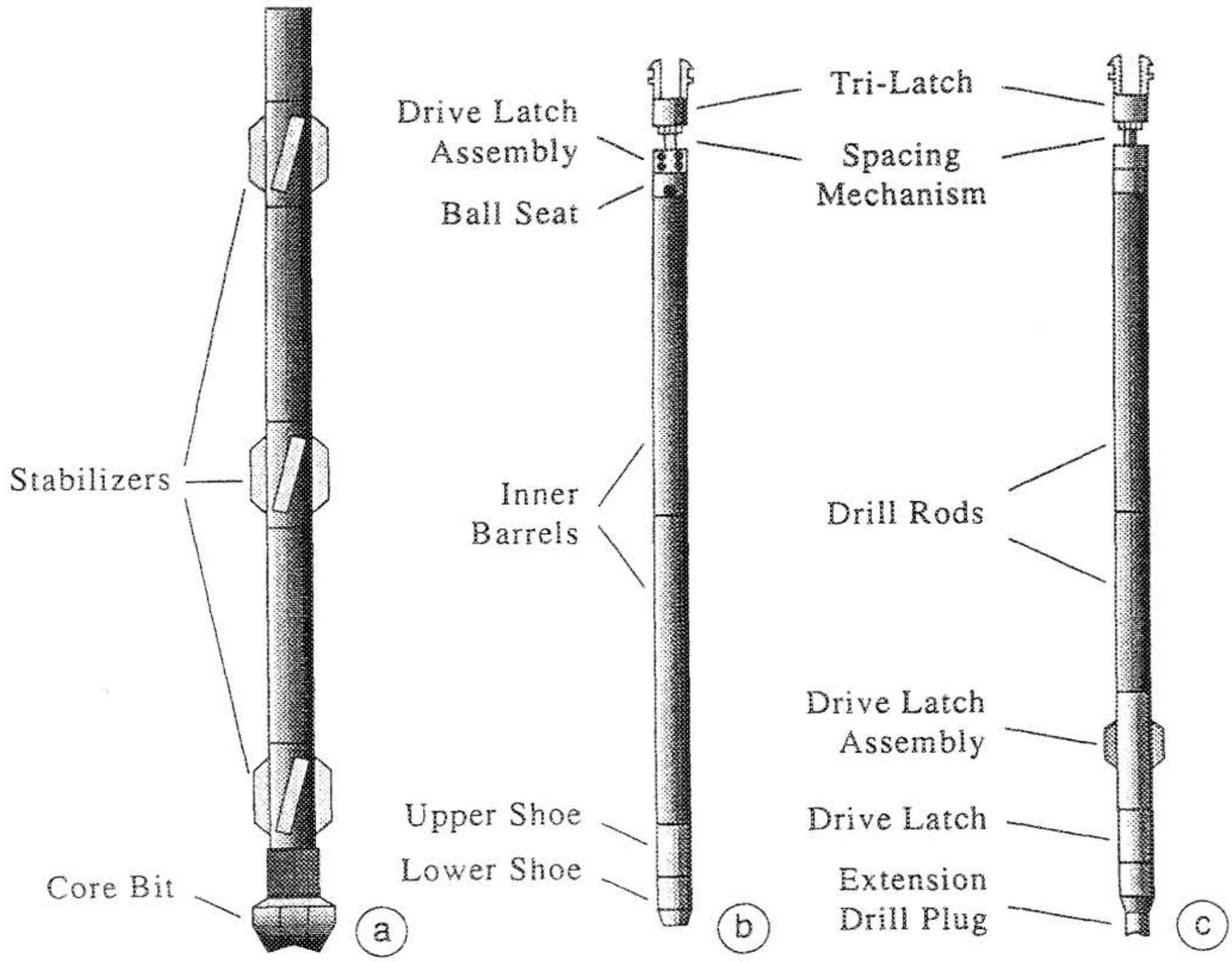
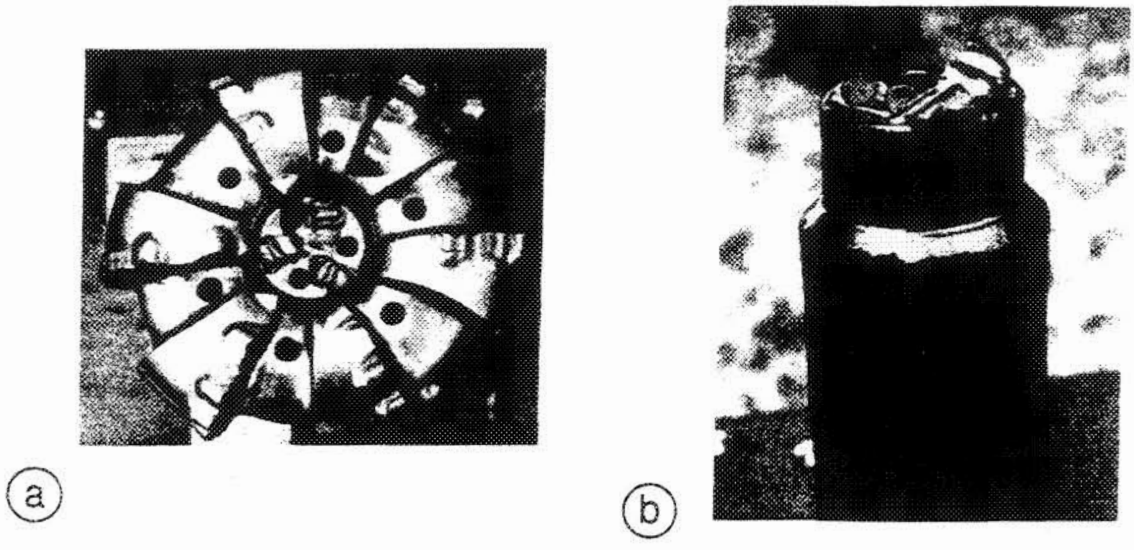


Figure 2. The downhole core preservation (gel coring) assembly: (a) inner barrel piston closed before core encapsulation with gel, (b) gel release valve opens on contact with core, and (c) gel encapsulation and core preservation.



3. The Coring-While-Drilling system: (a) outer barrel, stabilizers, and core head, (b) inner core barrel (tubes), shoes, and triple latch overshot, (c) drill plug, drive latch assembly, drill rods, and triple latch overshot.



4. Coring-While-Drilling: (a) drilling mode (bit face view with drill plug inserted) and (b) drill plug.

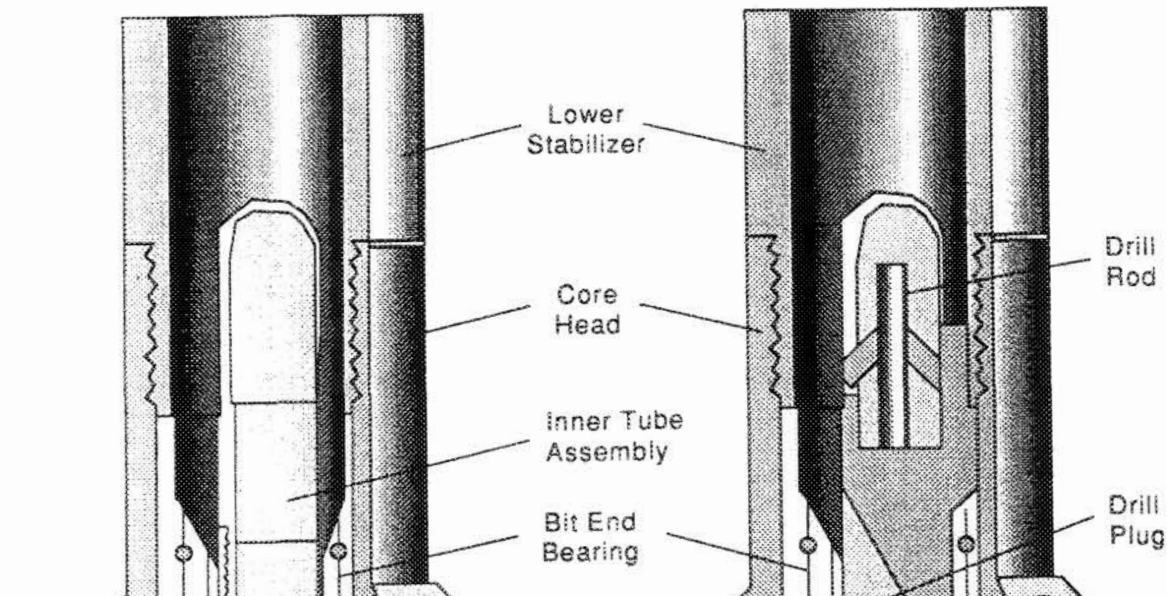


Figure 5. Coring-While-Drilling core head axial view: (a) coring mode and (b) drilling mode.