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Drilling Fluids for Deepwater Fields: An Overview

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Abstract

The increasing oil demand around the world along with the depletion of onshore and shallow water oil reserves have forced the oil companies moving into the development of deepwater subsea hydrocarbon reservoirs. Drilling fluids play a key role in all drilling operations, but they get a greater relevance in deepwater environments where the technological challenges of drilling at these extreme conditions generate significant operational risks as well as very high costs during the development of this kind of fields. The operational issues and concerns related to the drilling fluid design and application for deepwater fields are generally well known: narrow pore/fracture pressure gradient margins, wellbore stability, clay swelling, gas hydrates formation, formation damage, salt formations, lost circulation, stuck pipe, cuttings transport and environmental and safety aspects. Therefore, the present chapter aims to give an overview on the main challenges and research related to drilling fluid design and application for deepwater fields through the revision of the state of the art of the current and innovative technological solutions reported in literature.

Keywords: drilling fluids, deepwater, clay swelling, gas hydrates, flat rheology, lost circulation, salt formations

1. Introduction

Exploration and production operations in deepwater and ultra-deepwater fields around the world have suffered important and critical changes over the last years. Deepwater is generally considered as any water depth greater than 1500 ft., whereas waters deeper than 7000 ft. move into the ultra-deepwater category [1]. New records for water depth and measured depth in deepwater are being set regularly. In general, developments of deepwater fields are carried out under conditions of high-costs, high-risks, and long-duration projects; thus, they are usually less sensitive to short-term fluctuations in oil prices than onshore developments [1–3].

Drilling is a primordial and critical stage in the success of exploration of deepwater fields. The overriding drilling objectives are to reach the target safely in the shortest possible time and at the lowest possible cost, with required additional sampling and evaluation constraints dictated by the particular application. Drilling itself is a much larger share of total well costs in offshore development than in onshore development. Key cost drivers for offshore drilling include water depth, well depth, reservoir pressure and temperature, field size, and distance from shore. Drilling fluids can represent from 15 to 18% of the total cost of well drilling but may cause 100% of drilling problems [4–10].

In this way, new deepwater discoveries around the world become challenging tasks of technical, operational, environmental, and economic issues, where many of those tasks are focused on the selection, development, and application of drilling and completion fluids technologies [1–5].

The operational issues and concerns related to the drilling fluid design and application for deepwater fields are generally well known: narrow pore/fracture pressure gradient margins, wellbore stability, clay swelling, gas hydrates formation, formation damage, salt formations, lost circulation, stuck pipe, cuttings transport, and environmental and safety aspects [1–11]. The design, selection, and application of the right fluid system or additives require balancing each of these issues with regard to their impact on the deepwater drilling operation.

There are several works reported in literature about topics reviewed in the present chapter; however, some of them just deal about challenges on deepwater drilling operations whereas others just deal about drilling fluids systems to control some of the operational problems found during deepwater drilling. Therefore, the present chapter aims to give a general overview on the main challenges and research related to drilling fluid design and application for deepwater fields through the revision of the state of the art of the current and innovative technological solutions reported in literature, where the drilling fluid systems and additives used to treat and control these problematic and challenging tasks are also carefully reviewed.

2. Challenges and new advances for deepwater drilling fluids

2.1. Wellbore stability and clay swelling

The geological aspects to consider during deepwater drilling are very different from those found on land and in shallow water. Generally, geological formations found in deepwater fields are relatively young and very reactive [11–15]. In this way, it is generally accepted that highly reactive shale formations are intrinsic to deepwater drilling, where their interaction with drilling fluids is the main factor in wellbore instability, which is considered one of the major causes of troubles, waste of time, and over costs during drilling [16–18]. In this way, problematic shales are responsible to origin more than 90% of wellbore instability problems [18]. Moreover, it has been reported that shales (principally clays) represent 75% of all formations drilled by the oil and gas industry [16].

Wellbore instability is mainly due to the clays dispersion into ultra-fine colloidal particles, which has a direct effect on the drilling fluid properties and performance [19]. Generally, wellbore stability is not a concern for most shale formations when drilling is carried out by

using oil-based and synthetic-based drilling fluids. However, the use of these drilling fluids is limited due to high costs and environmental restrictions particularly for deepwater operations [16, 19]. Thus, growing environmental concerns currently require the replacement of oil-based fluids by environmentally friendly water-based drilling fluids, which can interact with shales promoting undesirable clay-swelling phenomena [20].

Wellbore instability problems caused by clay swelling have been widely reported: sloughing shales, hole closure causing tight hole, cave-ins leading to fill on trips, and problems when running casing. In addition, other important problems have been identified such as cuttings accumulation leading to reduced hole-cleaning efficiency, buildup of thick cuttings beds, and reduced rates of penetration arising from balling of the drill bit with sticky clay [13, 15]. Moreover, wellbore instability can result in the loss of the drilling assembly, well side-tracks or in the worst case total abandonment of the well. Consequently, these problems can significantly reduce drilling rates as well as increase considerably the costs of exploration and production [15]. Therefore, minimizing and controlling shale-fluid interactions during deepwater drilling become one of the most important challenges for the design and selection of deepwater drilling fluids.

2.1.1. Clay mineralogy

Clay minerals account for about 50–60 wt.% of most shales; thus, physical properties and behavior of shale interacting with a drilling fluid rely on the type and amount of clay in the shale. Clays are naturally occurring minerals formed by the weathering and decomposition of igneous rocks. They are layered minerals, classified among the phyllosilicates, consisting of stacks of negatively charged two-dimensional aluminosilicate layers [15]. There is a great variety of different clay minerals, which differ in their composition, layer arrangement, and substitutions. However, for shale-stability purpose, the most relevant clay minerals are kaolinite, illite, smectite, and chlorite. Their main characteristics have been reported [11, 21] and are shown in **Table 1**.

Clay mineral	Chemical elements	Morphology	Surface area (m²/gm)	Typical range of CEC (meq/100 g)	Layer thickness (Å)
Kaolinite	$Al_4[Si_4O_{10}](OH)_8$	Stacked plate or sheets	20	3–10	7
Chlorite	$(Mg, Al, Fe)_{12}[(Si, Al)_8O_{20}](OH)_{16}$	Plates, honeycomb, cabbage-head rosette, or fan	100	10–40	14
Illite	$(K_{1-1'5}Al_4[Si_{7-6'5}Al_{1-1'5}O_{20}](OH)_4)$	Irregular with elongated spines or granules	100	20–40	10
Smectite	$(1/2Ca,Na)_{0.7}(Al, Mg, Fe)_4[(Si, Al)_8O_{20}] \cdot nH_2O$	Irregular, wavy, wrinkled sheets, webby, or honeycomb	700	80–150	12–14

Table 1. Characteristics of clay minerals involved in shale stability.

Kaolinite is commonly considered as a highly stable mineral clay, non-swelling, presenting a relatively small surface area and a low adsorptive capacity (cation exchange capacity (CEC) = 3–10 meq/100 g) as shown in **Table 1**. Kaolinite clay can be easily dispersed in water-base drilling fluids [11, 18]. Chlorite mineral is generally considered as non-swelling clay. Chlorite minerals contain a layer of alumina sandwiched between two layers of silica and a layer of magnesium or iron oxide, and without interlayer water. Illite clay minerals are similar to chlorite in reactivity, presenting a low adsorptive and swelling/shrinking capacity and properties intermediate between kaolinite and smectites as shown in **Table 1**. It has been reported that some older shale rocks with a high degree of diagenesis contain only chlorite and illite as clay components. Most of these shales are relatively unreactive but some of them can hydrate and slough [11, 18]. **Table 1** shows also properties of smectite minerals which present higher adsorptive capacity (cation exchange capacity = 80–150 meq/100 g), indicating higher reactivity and swelling potential as it has been widely reported in literature [11–18, 20]. Smectite minerals include a variety of clays such as montmorillonite, hectorite, and beidellite. In addition, mixed-layer clay minerals, such as illite-smectite and chlorite-smectite, have also been found and reported [11, 21]. Several experimental techniques, such as X-ray diffraction (XRD), spectroscopy, and microscopy, are used in order to identify and characterize mineral clays. **Figure 1** shows scanning electron microscopic (SEM) photos of typical clay minerals described earlier.

Studies reported in literature about clay swelling and inhibition are most often focused upon smectite clays due to their well-known swelling potential and the frequency with which they are found during drilling operations [15]. However, it has been also reported [13] that kaolinite and illite shales can be highly unstable when drilled promoting bit-balling problems, suggesting that interlayer expansion cannot be considered as a universal causative mechanism of shale instability. Nevertheless, the tendency of sodium-saturated smectites to swell macroscopically has been generally identified as the principal source of shale instability that can potentially lead to collapse of the wellbore. Therefore, a deeper understanding about the mechanisms involved in the interactions between water-based drilling fluids and mineral clays is a key issue to get success during deepwater drilling.

2.1.2. Swelling mechanisms

Exposed to aqueous solution, clay minerals will adsorb water molecules and swell. The phenomenon is also known as clay hydration. The hydration of the clays is a function of the extent
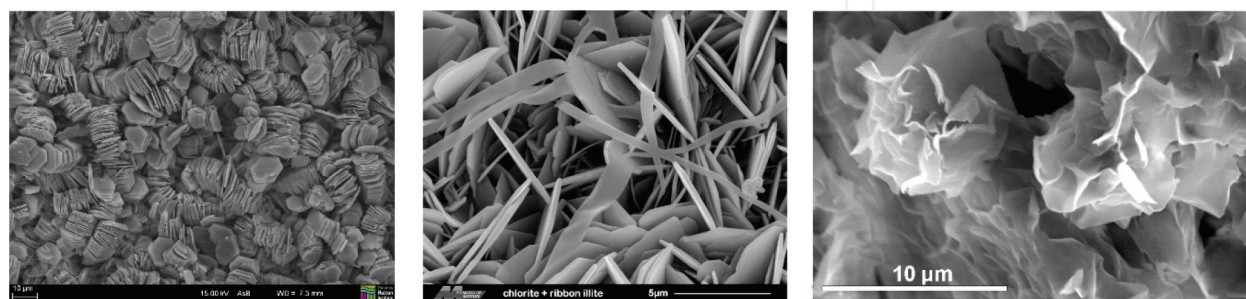

Figure 1. SEM photos of typical clay minerals involved in shale instability. From left to right: kaolinite, chlorite-illite, and smectite (montmorillonite). *Images reproduced from the "Images of Clay Archive" of the Mineralogical Society of Great Britain & Ireland and The Clay Minerals Society (www.minersoc.org/gallery.php?id=2).*

and location of layer charge, the interlayer cation species, the water activity, the temperature, the external pressure, and the salinity of the bulk solution [22]. Crystalline and osmotic swelling are the two main mechanisms reported in literature to explain clay hydration phenomena [13–15, 20–23]. Both mechanisms are described below.

Crystalline swelling. This mechanism, also called surface hydration, can occur in all types of clay minerals when they are exposed to concentrated brine or aqueous solutions with high content of divalent or multivalent cations. The mechanism is carried out through the stepwise formation of integer-layer or mixtures of integer-layer hydrates. The process is thermodynamically comparable to phase transitions. Several water-molecules layers may line up in order to build a quasi-crystalline structure between unit layers, resulting in an increased interlayer spacing [15, 18]. The principal action force of this mechanism is the adsorption energy of water on the surface of clays. The volume and thickness of water adsorbed on the clay surface will depend on the hydration energy of exchangeable cations and the charge density on the surface of clay. In addition, type, size and charge of exchangeable cations present in the interlayer have a significant impact on swelling process. It has been reported that the presence of Ca^{2+}, Mg^{2+}, and H^+ exchangeable cations in montmorillonite clay increases their interlayer attractive force, resulting in a thinner hydrated film and whit a directional and regular water molecules arrangement on the clay. On the other hand, for Na^+ exchangeable cations, the interlayer attractive force decreases, the hydrated film becomes thick, and the arrangement of water molecules on the clay is not directional and regular [13, 15, 23]. Therefore, sodium montmorillonite has a higher swelling capacity than calcium montmorillonite according to the mechanism described earlier. As reported in Ref. [15], molecular simulation studies have confirmed the stepwise mechanism of crystalline swelling described earlier observing that adsorbed water molecules form distinct layers in the interlayer region. Typical interlayer spacings recorded in the crystalline swelling mechanism lie in the range of 0.9–2 nm [15]. **Figure 2a** shows the crystalline swelling mechanism described earlier.
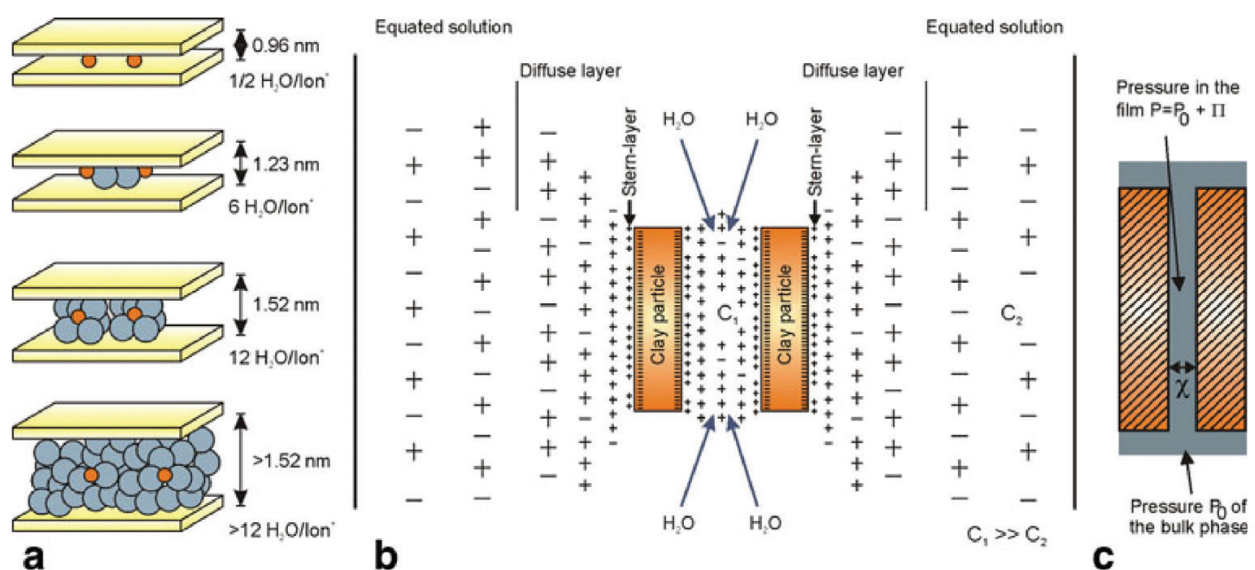

Figure 2. Swelling mechanisms [24]: (a) crystalline swelling and (b) osmotic swelling.

Osmotic swelling. This mechanism can occur only in clay minerals containing exchangeable cations in the interlayer region. A sketch of the mechanism is depicted in **Figure 2b**. As observed, when the concentration of cations in the interlayer is higher than that of the surrounding water, water molecules diffuses into the interlayer in order to dilute its ion concentration, restoring cation equilibrium [15, 23]. This phenomenon creates an osmotic repulsive pressure between the clay particles. The osmotic pressure is mainly related to the difference of the ion concentrations between the interlayer and surrounding water. In this way, the distance between clay particles increases greatly, and then the clay swelling is carried out [15, 23]. Compared with crystalline swelling, this type of swelling promotes larger volume increases with typical interlayer spacings of 2–13 nm [15]. In fact, osmotic equilibrium of the semipermeable membrane on clay particles is considered a key factor to influence the hydration film of clay swelling. Thus, it can be stated that osmotic hydration is the major factor of clay swelling. It has been identified that the tendency of sodium montmorillonite clay to swell through this osmotic mechanism is the main cause of wellbore instability that can potentially lead to collapse of the wellbore [13–15]. On the other hand, K^+-saturated smectite clay minerals do not swell through this mechanism and form crystalline hydrates even in aqueous suspension. Thus, the K^+ ion can be used to inhibit the swelling of sodium montmorillonite clay minerals [15].

2.1.3. Shales characterization

The main methods developed for shale characterization including shale-fluid interactions and clay-swelling inhibition deal with composition, reactivity (swelling), mechanical, and physicochemical properties of shales (or clay). Some of the most important experimental methods reported are described below.

X-ray diffraction (XRD). This is a basic tool in the mineralogical analysis of shales. This experimental technique has been widely used to determine clay mineral composition of shale samples, degree of crystallization and swelling profiles of clay minerals [25].

Small-angle X-ray scattering (SAXS). This technique is useful for the characterization of the microstructural and swelling properties of clay samples [15].

Small-angle neutron scattering (SANS). This is a useful and versatile technique for the study of in-homogeneities of both crystalline and amorphous structures on the sub-micron scale, with capabilities to measure samples with high degree of swelling (up to interlayer d-spacings of 2000 Å) [15].

X-ray fluorescence (XRF). It is an experimental method used to determine chemical composition (major and trace elements) of rocks, minerals, sediments, and fluids.

Computer tomography (CT). The technique is generally suitable for visualization from meter to millimeter scale. Shale applications include viewing full-diameter core sections to determine orientation relative to bedding, presence of fractures and nodules, density studies for highly interbedded interval, and quality assessment of prepared plug samples [26].

High-resolution micro-CT. This is a technique with similar principles and shale applications of the conventional CT, designed for smaller samples and employing a shorter distance between source and detector, which allows much higher resolution [26].

Scanning electron microscopy. This is an experimental method for high-resolution imaging of surfaces. It allows characterizing morphology, pore structure, and clay microstructure in shales samples. It can be also useful for studies of shale-fluid interactions [27].

Cation exchange capacity and methylene blue test (MBT). These are standard methods used to determine the reactivity (swelling capacity) of a clay or a shale sample. CEC is defined as the ability of clay minerals to absorb cations in such form that they can be easily exchanged for other cations present in an aqueous solution. Additional information about the reactivity of the shale can be obtained, if the exchangeable cations are identified and quantified [28].

Linear swelling tests (SLTs). This is a standard technique used widely to evaluate shale swelling by linear displacement [29]. Some experimental apparatus have the capability to evaluate swelling by this method at reservoir (high-pressure and high-temperature) and dynamic conditions.

Mercury injection porosimetry. This is a standard method for characterizing pore throat size distribution from micron to nanoscale. For shale samples, mercury is able to penetrate within and between the coarse rigid grains as well as the clay intergrain areas and secondary minerals [26].

Gravimetric swelling test (GST). This is an experimental method used to measure water and ion motion during shale/mud interaction in order to determine compatibility between shales and drilling fluids [29].

Capillary suction time (CST). This is an experimental test for determination of filtration properties and salt concentration optimization [16]. It is used primarily to determine filter-cake permeability, but data have been also used to study shales reactivity in filter cakes and the effect of brine composition on clays in a filter cake.

Thermal gravimetric analysis (TGA). This technique allows characterization of the different types of water (free, interlayer, bound, and crystalline) in a shale sample as well as to identify the type of clay content in shale samples [30].

Hot-rolling dispersion test. This technique is widely used in optimizing drilling fluid. This test provides an assessment of the inhibition of shale cuttings exposed to a drilling fluid evaluating in this way the risk of dispersion or swelling in the wellbore [16].

Pressure transmission test. This method can be used for confined or unconfined shale samples. The experimental apparatus allows evaluating shale-drilling fluid interaction and estimates shale permeability, coefficient of reflectivity (membrane efficiency) as well as ionic diffusion coefficient [31].

Rheological tests. This is an experimental method useful for the evaluation of rheological behavior of clays in aqueous suspensions to study clay-fluid interactions. It allows characterizing colloidal behavior of clay-fluid systems through rheological properties such as thixotropy, viscoelasticity, and yield stress [32].

Triaxial test. This technique is useful for pore pressure measurements and compressive stress/strain behavior in shale samples [15]. It also allows characterizing reactivity behavior of shales by measuring the swelling pressures and strains that result from exposure of shale cores to different test fluids. Preserved shale cores can be used [33].

Dielectric analysis. These experimental methods are useful to quantify swelling clay content and to determine specific surface areas in clays and shales samples. In addition, wettability and anisotropy properties of shales can be also determined by using dielectric techniques [26].

2.1.4. Additives in drilling fluids for shale stabilization

Over the past decades, the demands for effective shale stabilizers have never stopped. Especially, with the development of shale gas and deepwater fields all over the world, such demands have never become as urgent as today. Understanding of the behavior and responses of shale-reactive formations to drilling fluids with chemical additives has been an important challenge in the oil industry for many years because of the several and complex chemical and physical phenomena present in these types of formations. Different types of chemical additives for shale stabilization have been used in the oil industry and reported in literature [11, 14, 15, 17, 34–42]. The number of commercial shale stabilizers is impressive. Each of them has a particular mechanism by which they can inhibit the swelling, disintegration, and dispersion of clay minerals interacting with water. However, most of these mechanisms are based on the change of the ionic strength and the transport behavior of the fluids into the clays, where the cations and anions present in the additives determine their capability and efficiency for clay-swelling inhibition [18]. Some authors have reported three main mechanisms to reduce clay swelling: ion exchange, coating of the clay particles by stabilizers, and modification of surface affinity toward water [43]. In this way, clay-swelling inhibitors are classified as temporary and permanent shale inhibitors [42]. Temporary shale inhibitors prevent swelling and migration of clays but are easily removed by the formation-produced fluids following the treatment [41]. Simple inorganic salts are the most common temporary shale inhibitors. However, most recent advances in shale stabilization have been focused on the area of permanent clay stabilizer additives [41]. **Table 2** shows a summary of the main additives reported in literature for shale stabilization.

2.2. Gas hydrates

Gas hydrate formation is another severe challenge to deepwater drilling fluid technology. Gas hydrate formation has been identified as a potential shallow hazard facing deepwater drilling since the mid-1980s [44, 45]. For deepwater drilling, conditions such as low temperatures and high pressures promote hydrate formation in the drilling fluid when gas is present, causing wellbore plugging, blockage in pipelines, or/and blowout preventers, thus leading to serious safety problems and increasing operation costs [46–48]. In addition, gas hydrates decomposition also causes serious problems such as wellbore instability, lost circulation, and blowout [45, 46]. In this way, for deepwater drilling operations, gas hydrate formation is not only an economic issue but also more importantly a safety issue [46]. Thus, the problem that needs to be solved is to avoid gas hydrates formation during well-controlled situations or

Group of shale stabilizers	Main characteristics	Shale stabilizer additives	References
Salts	Primary chemical of choice for clay stabilization. Capabilities to influence swelling and osmotic pressures, viscosities of filtrate and shale stability	Potassium chloride	[11, 14, 15]
		Sodium chloride	
		Concentrated brines ($CaCl_2$, $CaBr_2$, $ZnCl_2$, $MgCl_2$, $MgBr_2$, $ZnBr_2$)	
		Formate and acetate salts	
High-molecular-weight polymers	Shale stabilization through clay particle encapsulation, inhibiting swelling, and dispersion	Polyacrylamides	[11, 14, 15, 34]
		Polyvinylpyrrolidones	
		Acrylate copolymers	
Low-molecular-weight polymers	Clay swelling and dispersion inhibited through the intercalation of inhibitor species into the interlayer of clay minerals	Polyglycerols	[14, 15, 34, 35]
		Polyglycols	
		Polypropylene oxides	
Charged polymers	Swelling-inhibitive effect through their adsorption onto clay particle surfaces. Classified in cationic, anionic, and amphoteric. Synthetic or natural in origin	Polymeric quaternary amines	[15, 34–36]
		Celluloses	
		Starches	
		Charged polyacrylamides	
Non-polymeric amines	Clay swelling inhibition through the principle of substitution of cationic species for a sodium ion in the clay lattice	Mono-cationic amines	[36]
		Oligomeric cationic amines	
Carbonaceous additives	Very limited effect on shale stabilization and without effect on swelling pressure	Asphaltenes	[14]
		Gilsonites	
		Graphites	
Silicates	Inexpensive and usually recommended for all shale-stabilization uses, including formations in situ fractured	Sodium silicate	[14, 17]
		Potassium silicate	
Saccharides	Environmentally friendly low-molecular-weight viscosifiers and reducers of hydraulic flow of water in shales	Methylated saccharides	[14, 37]
Nanomaterials	Capabilities of shale permeability reduction during drilling which stops fluid invasion, inhibits swelling, and improves wellbore stability. Environmentally friendly	Nanoparticles	[38–41]

Table 2. Additives for shale stabilization.

to minimize the impact of hydrate formation, such as eliminate potential hydrate blockages [47]. Gas hydrates are crystalline inclusion compounds formed of hydrogen-bonded water molecules as hosts and gas molecules entrapped in the water cavities as guests [49, 50]. Gas hydrates can be only stable at high pressures and low temperatures (as observed in **Figure 3**), conditions found during deepwater drilling operations.

Most gas hydrates are formed from methane; however, gas molecules such as ethane, propane, and 1-butane, and inorganic gases such as nitrogen, hydrogen, and carbon dioxide are also able to be enclathrated into the water lattices. The three most common gas hydrate structures reported are cubic structure I (sI), cubic structure II (sII), and hexagonal structure H (sH) [49, 50]. Nucleation, growth, and agglomeration are the main stages of phase transitions associated with hydrate plug formation [49].

Gas hydrate problems found in deepwater operations become inaccessible or impractical for most conventional preventive methods. In fact and as reported some years ago, the annual costs to clean gas hydrate blockage might exceed $100 million at a rate near $1 million per mile of affected lines [45, 51]. In this way, injection of inhibitor chemicals is the main method generally used to avoid the formation of gas hydrates during deepwater drilling operations [45–50].

2.2.1. Hydrate inhibitors

According to the inhibition mechanism, hydrate inhibitors are classified as thermodynamic hydrate inhibitors (THIs) and low-dosage hydrate inhibitors (LDHIs) [45].

The main action mechanism of the thermodynamic hydrate inhibitors (THI) is to delay hydrogen bonding of water molecules forming hydrate structures, modifying in this way the
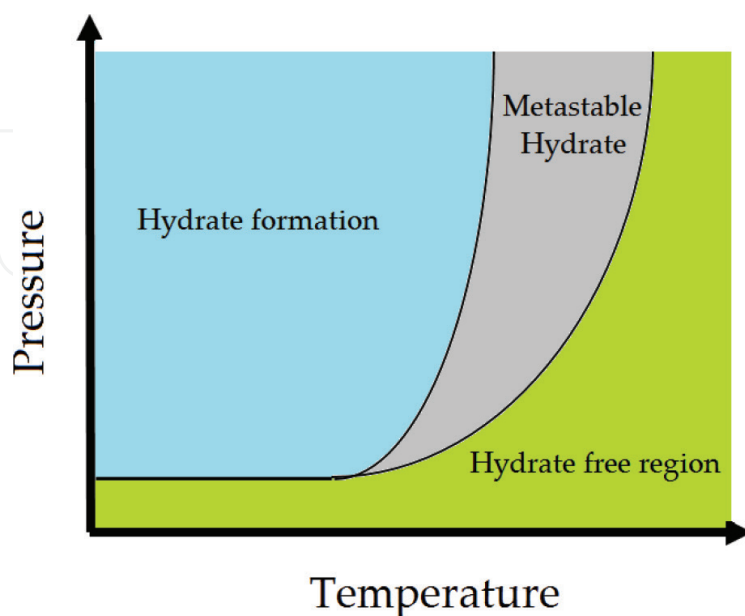

Figure 3. Typical phase diagram of hydrate stability zones.

hydrate–liquid–vapor equilibrium at a given pressure, temperature, gas composition, and water salinity [50]. However, thermodynamic hydrate inhibitors have a strong but limited capability to inhibit the formation of gas hydrates due to higher concentration of these inhibitors which may be required for deepwater drilling operations, which results in higher drilling fluid density, increasing operational costs as well as the logistical and environmental concerns [48–50].

Low-dosage hydrate inhibitors are a more recent technology for preventing hydrate plugging [52]. LDHIs can be subdivided into two basic categories: kinetic hydrate inhibitors (KHIs or KIs) and antiagglomerants (AAs).

The main action mechanism of the KHIs is to delay mainly the nucleation but also the growth of the gas hydrates, extending the hydrate induction time, which is the most critical factor for field operations, to exceed the residence time of the reservoir fluid [47]. Thus, KHIs play a role mainly as gas hydrate *anti-nucleators* [52] where thermodynamic conditions of hydrate formation are usually not significantly affected, as KHIs do not modify the hydrate–liquid–vapor equilibrium [45].

Antiagglomerant inhibitors prevent gas hydrate crystals from increasing their size, which results in the formation of smaller particles dispersed during residence time in the subsea pipeline allowing the generation of transportable slurries [49]. A polar, hydrate-philic head and a hydrophobic, fatty chain form usually the structures of antiagglomerant inhibitors. In addition, due to their surfactant nature, they will accumulate at the water/oil interface, just where hydrates first begin to form [52]. The application of low-dosage hydrate inhibitors to prevent hydrate plugs in deepwater fields has been tested and reported as successful and is now a well-established technology [52]. In **Figure 4**, the main additives reported as hydrate inhibitors are shown [53–74].

2.3. Rheological behavior

Rheological properties of drilling fluids are key parameters in offshore operations, especially in the extreme and complex conditions found during deepwater drilling. The term "flat rheology" used to describe a drilling fluid is concept recently introduced to the oil industry and refers in general to "constant" or "continuous" rheological properties [46, 75–78] as shown in **Figure 5**.

The broad range of exposure temperatures typically found during deepwater drilling operations greatly influences rheological behavior of drilling fluids; particularly their viscosity and yield point properties can be affected. This can promote lost circulation and high equivalent circulating density (ECD) increasing difficulty of pressure control [46, 75, 76]. Thus, in order to avoid critical ECDs, drilling fluid rheology should be controlled. In general, a thinner fluid yield lowers ECDs. However, cuttings removal and barite suspension issues should also be considered for the rheological design of drilling fluids [77]. Therefore, one of the main challenges to design drilling fluids for deepwater operations is to effectively balance fluid rheology for equivalent circulating density, hole cleaning, and barite suspension simultaneously [77].
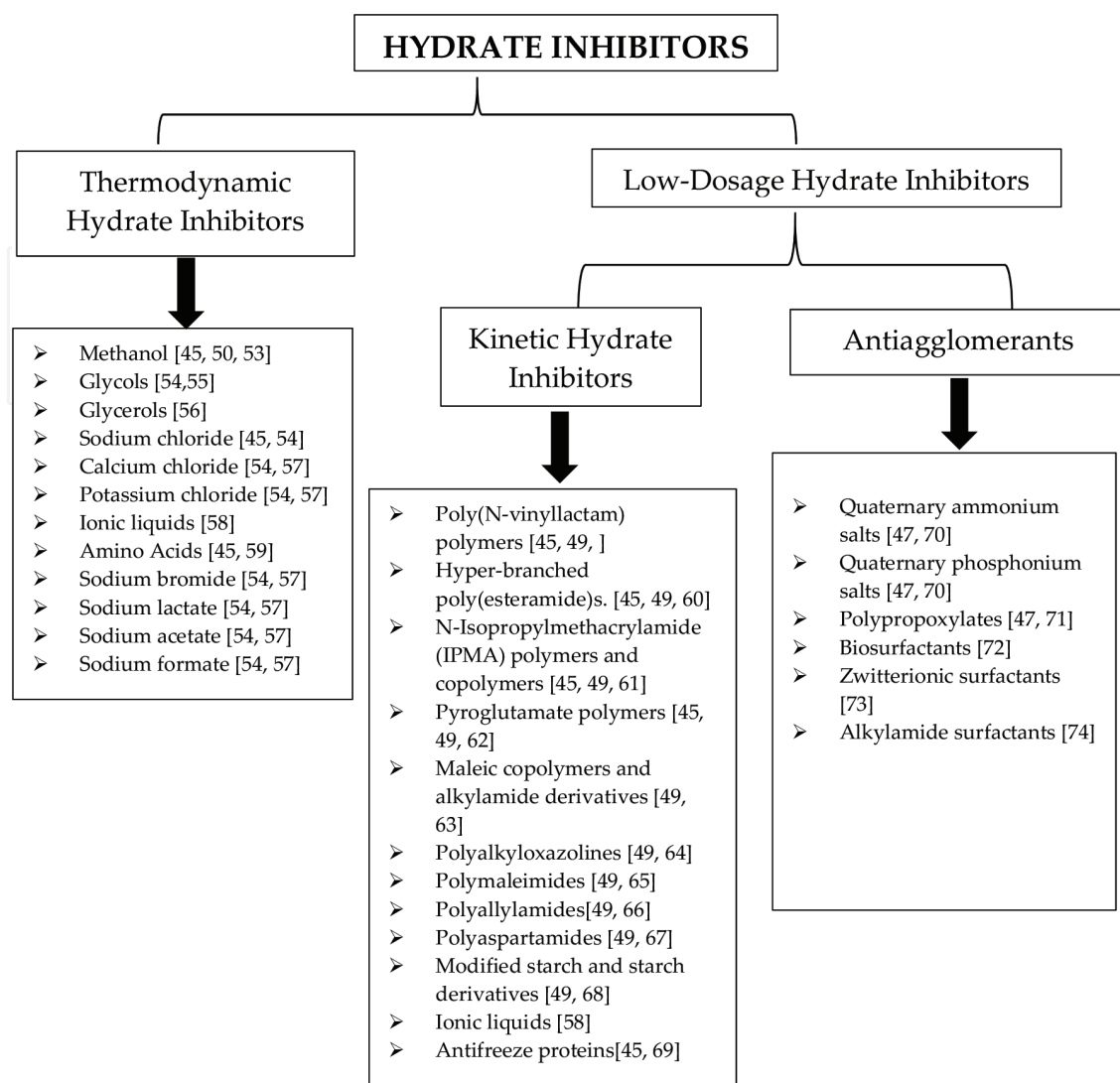
Figure 4. Additives for hydrate inhibition.

Flat-rheology properties for drilling fluids can be obtained through the usage of mixtures or packages of several specific additives such as emulsifiers, rheology modifiers, and viscosifiers. Typical components for a flat-rheology synthetic-based mud (SBM) have been reported [77, 78]. The main components are usually the following:

• Organophilic clay

• Emulsifier

• Wetting agent

• Fluid loss control

• Polymeric rheology modifier

• Viscosifier

The emulsifier additive helps to minimize the impact of drill solids on the rheological properties of the synthetic fluid. Wetting agents or chemical thinners can be used to reduce yield point
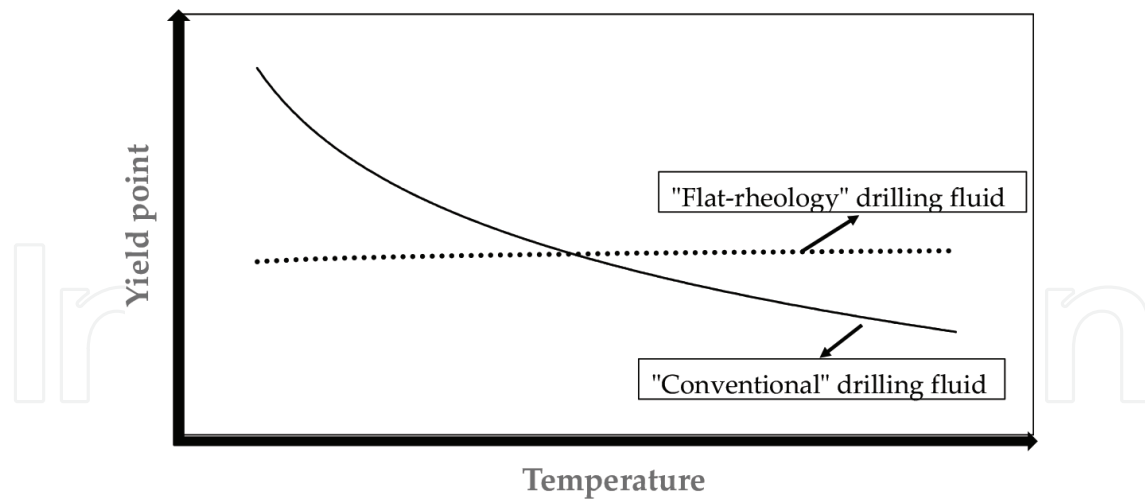
Figure 5. Representative rheological behavior of "flat-rheology" and "conventional" drilling fluids.

in invert-emulsion fluids as well as to reduce the solids tolerance of the fluid. Organophilic clays used at a minimal concentration provide an optimal rheology modification. The polymeric rheology modifier also reduces viscous properties at low temperatures while increasing them at high temperatures. Finally, the viscosifier provides the desired enhancement in overall viscosity and suspension capacity [77, 78].

High performance has been reported using "flat rheology" approach for drilling fluids, which can be achieved by using accurate combinations of emulsifier, wetting agent, rheology modifiers, and supplementary viscosifiers. However, the ability to control a flat-rheology profile can be also influenced by other parameters and phenomena, which cannot always be controlled such as temperature-pressure variations, interactions of rheological modifiers with drill solids, shear-rate variations in the annulus, salinity effects, and changes in the concentration of rheological modifiers during circulation of drilling mud [77, 78].

Another key rheological parameter for deepwater drilling fluids is the "gel strength." It is defined as the shear stress of the drilling fluid measured at a very low value of shear rate after it has been set for 10 min [79] and it is considered as a measure of the degree of thixotropy present in the drilling fluid. Gel strength determines the ability of the drilling fluid to suspend drilled cuttings and other solid additives along the length of the drill pipe/borehole annulus when the circulation of the drilling fluid is stopped during tripping or in any other operation [79]. However, for deepwater fields, drilling fluid can suffer shear degradation processes due to increased depths and high pipe shear, then its rheological properties, including the gel strength, can be severely affected; therefore, its capabilities to suspend and transport drill cuttings are reduced considerably [79, 80].

2.4. Lost circulation

Lost circulation is one of the most troublesome problems for deepwater drilling operations. Lost circulation (or lost returns) is an undesired event where a smaller amount of drilling fluid is returned from the wellbore than is pumped into it, thus drilling mud is lost into the formation [81, 82]. Lost circulation is a major cause of nonproductive time (NPT) in drilling, which can

significantly raise operational costs. It has been reported that more than 12% of NPTs are due to problems of lost circulation in drilling areas of the Gulf of Mexico (GoM) [81]. Worldwide, the impact of lost circulation on well construction has been estimated to be around two to four billion dollars annually in nonproductive times, drilling fluid loss, and materials used to stem the losses [83]. **Figure 6** shows candidate formations for lost circulation events [84].

Lost circulation is carried out through one of two basic mechanisms: invasion and fracturing. Invasion refers to fluid loss to formations that are cavernous, vugular, fractured, or unconsolidated, whereas fracturing mechanism refers to the fluid loss due to hydraulic fracturing from excessive induced pressures [11]. However, most fluid losses are due to hydraulic-driven fractures covering from the wellbore to the far-field region [81]. Thus, lost circulation will be carried out mainly through fracturing mechanism, where the mud pressure in the wellbore promotes or creates new fractures or opens preexisting fractures on the wellbore wall [81]. In this way, formations with a narrow mud weight window, the safe drilling margin between pore pressure (or collapse pressure) and fracture pressure, have a greater propensity to suffer lost circulation problems.

For deepwater formations, water depth can cause a lower fracture pressure resulting in a narrow mud weight window, making it very challenging to maintain the needed wellbore pressure, and increasing considerably the propensity of lost circulation [81, 85]. Therefore, minimizing and controlling lost circulation is another important challenge to deepwater drilling fluid technology.
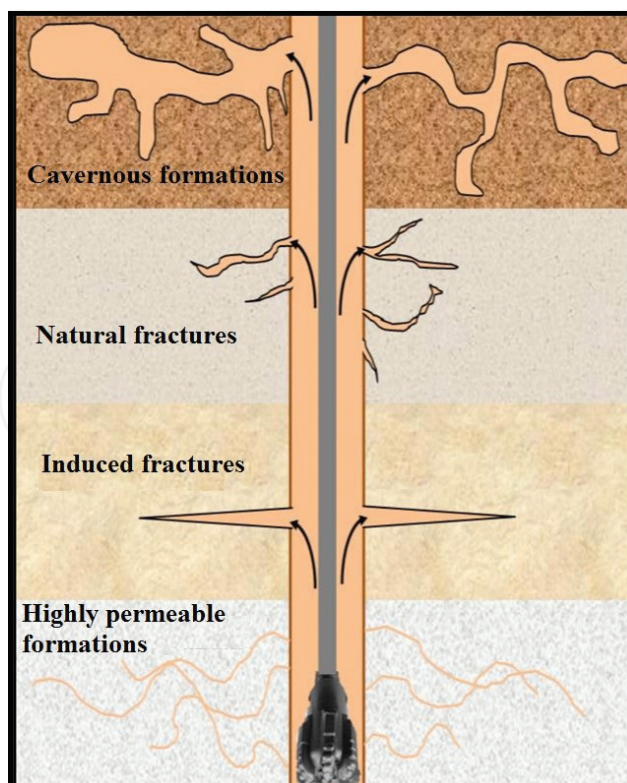

Figure 6. Schematic classification of lost circulation [84].

Some authors have identified some main concerns associated with lost circulation in deepwater environments. These issues are the following: drilling salt formations, identifying loss zones, controlling seepage losses, running casing and cementing, excessive rates of penetration, wellbore breathing, drilling fluid rheology, inadequate shoe tests, synthetic-based fluid compressibility, and well control [84].

In order to solve and control lost circulation problems, the following treatments are usually employed: lost circulation materials (LCMs), settable materials, and blends of the two [82].

Settable materials are usually pumped in a liquid state and solidify downhole, sealing the thief zone. Examples of these kinds of materials are bentonite-oil-mud systems, cement, gunk, and cross-linked systems. Thus, these materials usually need some extra preparation time and some setting time downhole before they can reduce and stop lost circulation [82].

Lost circulation materials (LCMs) have been widely used to avoid or stop losses. These materials are pumped downhole in order to bridge and seal fractures and voids, thereby stopping losses [82]. LCMs can be classified according to their physical and chemical properties as well as their action mechanism [84]. Physical properties are mainly size and appearance, whereas chemical properties include solubility in acids, swellability, and reactivity with other chemicals [84]. Their performance, however, commonly declines with the circulation time, which is related to the decrease in the average size of the solid components of these materials. This phenomenon is known as "shear degradation" [86].

Figure 7 shows a summary of the treatments employed for lost circulation. Finally, in order to adequately choose and design the optimal treatment to solve and control lost circulation,
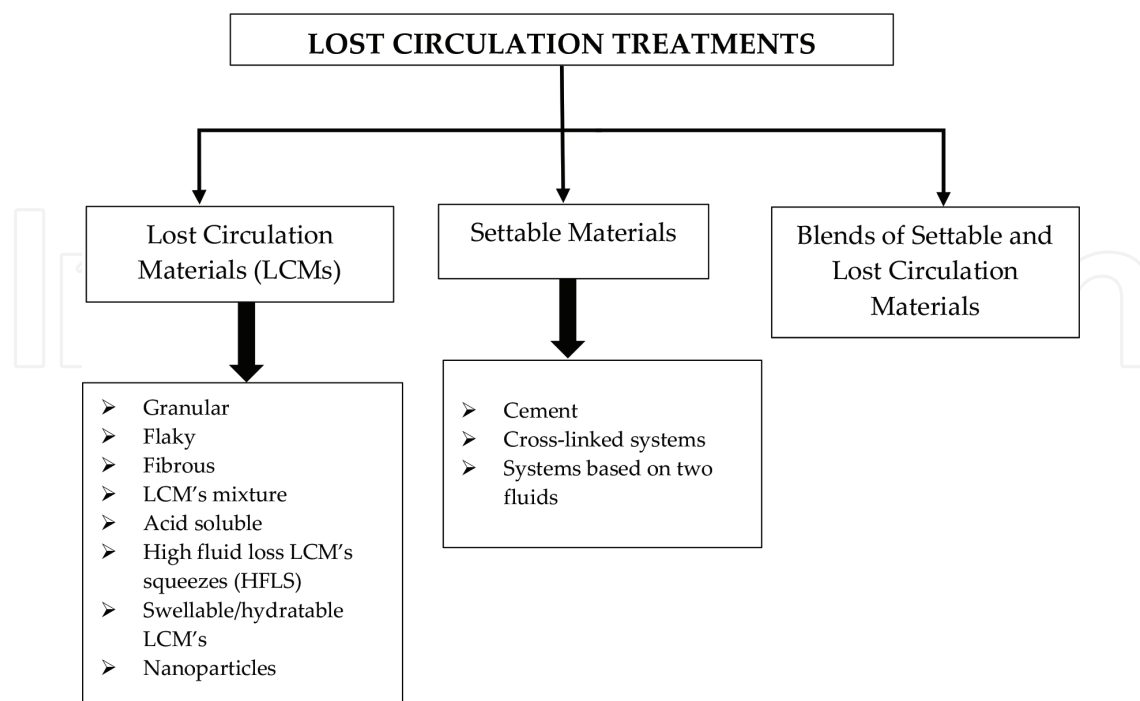

Figure 7. Classification of lost circulation treatments.

available data should be processed, analyzed, and used. Required information include the amount of loss, the kind of loss mechanism, quantitative data about fractures and pores such as fracture apertures, spacing, and pore throat size; geological setting (pay zone, shale, unconsolidated sand, gravel, etc.) and for deepwater formations, the mud weight window is a critical parameter that should be determined [81–85].

2.5. Salt formations

In many deepwater plays around the world, salt formations overlie prolific reservoirs containing a significant amount of hydrocarbons [87]. Successful drilling of the salt layers is not easy, and it is considered a challenge in deepwater drilling operations due to the complex salt behavior. The Gulf of Mexico (GoM) is the most active deepwater region in the world where salt is a dominant structural element that increases drilling risks and affects long-term well integrity [88].

Salt formations are considered efficient traps of hydrocarbons as observed in **Figure 8**. These traps were developed due to local faulting and bending processes in formations nearby the salt layers and upward migration of salt layers displacing other sediments [87, 88]. The chemistry of salts found in these formations can vary significantly. However, typical salts reported [11, 88] are the following: halite ($NaCl$), Sylvite (KCl), Bischofite ($MgCl_2 \cdot 6H_2O$), Carnalite ($KMgCl_3 \cdot 6H_2O$), Polyhalite ($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$), and Tachydrite ($CaCl_2 \cdot MgCl_2 \cdot 12H_2O$).

In addition, salt formations can contain other evaporate minerals such as gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), kieserite ($MgSO_4 \cdot H_2O$), limestone ($CaCO_3$), or dolomite ($CaMg(CO_3)_2$) associated with their structure [11, 88]. Salt presents exceptional and problematic characteristics. One of the most critical is its capability to deform or creep. Thus, it can exhibit plastic flow at certain temperature and pressure through other geological rock beds under stress, which results in the reduction of wellbore size, wellbore closure, drill string sticking as well as in casing collapse [11, 87]. The creep rate of salt will depend on
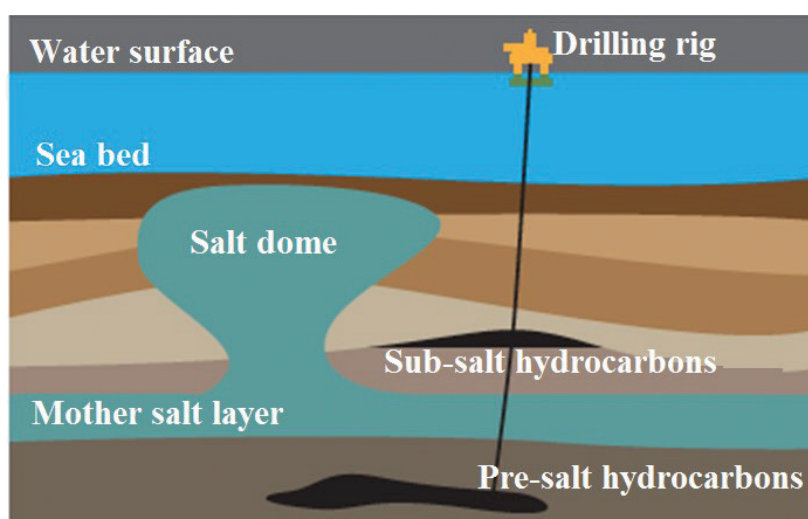

Figure 8. Typical geological salt dome formation [90].

several factors such as depth, overburden pressures, temperature, minerology and presence of impurities, moisture content, local, and regional geomechanical stresses [87]. In addition, salt dissolution during drilling can promote hole enlargement due to the increase of rates of penetration [11, 89]. Other salt-drilling hazards are sutures and inclusions, rubble zones, and tar, as reported [87].

Lost circulation problems are often found in salt formations [82, 91]. The thief zone at the base of the salt promotes drastic lost circulation and well control problems, often resulting in loss of the interval or the entire well [90]. Controlling losses in this kind of formations is extremely problematic. Thus, treatments to control lost circulation problems in salt formations during drilling can last for weeks, affecting considerably operation costs, particularly for deepwater drilling operations [82, 91].

Drilling fluids play a key role to carry out a successful drilling operation in salt formations found in deepwater fields. Key properties of muds need to be controlled when drilling salt formations are mainly density, salinity, and rheology [87]. About density property, the key role of mud weight in drilling salt formations is to minimize the creep rate. It has been reported that increasing mud weight can efficiently control salt creep and thus prevent wellbore size reduction, wellbore closure, and drill string sticking [92]. Salinity of drilling fluid is important in order to minimize salt dissolution, which is necessary to maintain the drilling mud salinity at or near saturation with respect to the drilled salt formation [87]. In addition, salt dissolution can be influenced by the flow regime [87, 89]. Rheological properties of muds can be modified during drilling of salt formations as the drill cuttings interact with the drilling fluid, affecting the drilling performance. However, rates of salt dissolution can decrease as the viscosity increases [87]. **Table 3** shows the main types of fluids commonly used to drill salt formations including deepwater plays as reported [87].

Type of drilling fluid	Advantages	Disadvantages
Riserless water-base fluids	• They can be designed and formulated for different salinity levels ranging from freshwater to supersaturation • Cost typically lower than other fluid types	• Limitations to get optimal performance. • Additional equipment can be required to maintain acceptable rheological properties.
High-performance water-base fluid	• Good hydrate-inhibition properties. • Similar performance to synthetic-base fluids when designed properly	• Environmentally less recyclable from one well to another and may require biocides depending on the formulation
Synthetic-base fluids	• High stability in terms of contamination tolerance • Superior performance in terms of rates of penetration (ROP) • Higher capacity for hydrate inhibition	• Very expensive

Table 3. Drilling fluids for salt formations.

2.6. Environmental and safety aspects

Safety and environmental concerns have long been a priority for deepwater operations. Waste-drilling mud is produced inevitably and has a negative impact on marine ecological environment during offshore oil exploration and development, resulting in a serious damage to the marine environment and harming the people's health [93–95]. Thus, preventing pollution and minimizing environmental impact in a cost-effective way are the challenging tasks confronting the industry of drilling fluids nowadays [11].

The Macondo incident in the Gulf of Mexico in 2010 has been widely studied, which led to the deaths of 11 workers on the transocean's deepwater horizon drilling rig as well as the release of an estimated 4.9 million barrels of oil [96]. Thus, drilling fluid companies must now comply with new offshore safety and environmental regulations [93]. The best available techniques and best environmental practices based on the waste management hierarchy of avoidance, reduction, reuse, recycling, recovery, and residue disposal can be also applied to the management of waste-drilling mud produced during deepwater operations [11, 93]. Usually for waste disposal during offshore operations, there are three basic options: discharge, haul to shore, or grind and inject [11].

The basic items, present in waste-drilling mud, having potential to cause environmental damage are heavy metals, salts compounds, organic wastes, acid or bases, and suspended solids. Toxicity tests are used to determine the combined effects of pollution on test organisms [11]. In addition, hazardous effects of additives such as defoamers, descalers, thinners, viscosifiers, lubricants, stabilizers, surfactants, and corrosion inhibitors on marine and human life have been reported. Such effects range from minor physiological changes to reduced fertility and higher mortality rates [97]. In this way, the oil and gas industry anticipates that the zero discharge of oil-contaminated drilling wastes will soon be the global standard.

Therefore, another of the great challenging tasks in deepwater operations is the development of novel environmentally friendly drilling fluids with better or similar performance, efficiency, and cost than oil-based drilling fluids. Several researchers and companies have reported new formulations of drilling fluid with minimal but not zero environmental impact [97]. **Table 4** shows some examples of this kind of drilling fluids.

Environmentally friendly drilling fluid system	Main characteristics	References
Silicate-based drilling fluids	• Good environmental compatibility • High performance for drilling reactive shales • Potential to damage the formation	[98]
High-density HPHT water-based fluid system	• Excellent fluid-loss control and capabilities to generate thermally stable rheology. • Chrome-free fluid	[99]

Environmentally friendly drilling fluid system	Main characteristics	References
Low-salinity glycol water-based drilling fluid	• For reactive shale formations • Performance limited to the presence of electrolytes	[100]
Zirconium citrate-based drilling fluid	• Environmentally friendly • Good rheological stability at high temperature • Performance affected by solids absorption	[101]
Water-based drilling fluids with eco-friendly polymers	• Eco-friendly polymers derived from tamarind gum and tragacanth gum • Cheaper than conventional polymers • Favorable rheological properties and low potential of formation damage	[102]
Formulations of water-soluble polymer amphoteric cellulose ether	• Low cost • Environmentally friendly • Potential to damage the formation	[103]
Starch additives for water-based muds	• Environment friendly fluid loss additives • Low manufacturing cost	[104]
Oil-based drilling fluid based on vegetable oils	• Derived from palm oil and groundnut oil • Highly biodegradable and good eco-toxicological properties	[105]
Polymeric potassium-silicate drilling fluid	• Excellent borehole-stability properties • Environmentally friendly	[106]
Formulations of hyperbranched polyglycerols	• Clay-inhibitive properties • Potential to be used as an environmental friendly inhibitor additive in WBFs	[107]
Offshore-drilling fluid system	• Good rheological properties, temperature tolerance, and collapse prevention performance • Low chromaticity, nontoxicity, and little effect on marine environment	[95]
High-performance water-based drilling fluid	• High performance on shale stabilization • High rate of penetration • Eco-friendly fluid	[108]
Nanoparticle-based drilling fluids	• For reactive shale formations • Stability in rheological properties • Environmentally friendly	[109]

Table 4. Some examples of environmentally friendly drilling fluids.

3. Conclusions

Large volumes of the world's future oil reserves are located in deep and ultra-deep water fields. Advances in exploration and production of these fields over the last years indicate that as soon as one deepwater record is broken, another surpasses it. Technological challenges of drilling at these extreme conditions generate significant operational risks as well as very high costs. Exploration of new technology frontiers of deep and ultra-deep water drilling will increase inevitably the demand and thus the devolvement of innovative technological solutions related to the design and application of drilling fluids for this kind of challenging and complex formations.

In this chapter, an overview about the main challenges facing the deepwater drilling fluids industry around the world was presented. The main concerns about deepwater drilling fluids reviewed were the following: wellbore stability and clay swelling, gas hydrates, rheological behavior, lost circulation, salt formations, environmental, and safety aspects. The design, selection, and application of the right fluid system or additives will require balancing each of these issues with regard to their impact on the deepwater drilling operation.

Therefore, the future of deepwater technologies must be focused toward the design and development of innovative materials with high performance, low cost, and with sustainability characteristics such as environmentally friendly and zero impact on the environment.

Acknowledgements

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