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Environmental Impacts of Water-Based Fluids in Geothermal Drilling

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ABSTRACT

This paper examines the environmental impacts of selected water-based geothermal drilling fluids and their constituents based on research conducted within the ORCHYD (Novel Drilling Technology Combining Hydro-Jet and Percussion For ROP Improvement In Deep Geothermal Drilling) project of the Horizon 2020 program. ORCHYD aims to increase the rate of penetration (ROP) of hard rock drilling rates from the current range of 1 to 2 m/h to a range of 4 to 10 m/h by combining two previously separate, mature technologies: High-Pressure Water Jetting (HPWJ) and Percussive Drilling. Background information on onshore drilling is presented initially, with an emphasis on environmental practices, impacts, and mitigation measures. The industry has developed a wide range of materials and formulations for the facilitation and enhancement of the drilling process, including the prevention of fluid loss by creating an impermeable mudcake downhole. Drilling fluids are classified into water-based muds (WBMs), oil-based muds (OBMs), and synthetic-based muds (SBMs). Geothermal drilling uses mostly WBMs, typically consisting of clay particles suspended in water and other additives examined in this research. A full-loop fluid circulation system is crucial for a successful drilling campaign and generally consists of mud pits, mixing equipment, a pumping system, and solids control units: shale shaker to remove the rock cuttings; and centrifuges to remove finer sands. Solids control units are important to keep in check the residual sand content and to re-circulate the drilling mud. The main function of this engineered fluid is to maintain the downhole pressure; remove the drill cuttings and transport it to the surface; lubricate and cool the drilling bit; and transmit hydraulic power, among others. Environmental impacts of the drilling fluids may delay or even block geothermal operations. Their documentation is important for a better planning of drilling operations. The following common additives of WBMs were considered: bentonite; xanthan gum; graphene (oxide); barite; calcium and potassium chloride and sodium carbonate. Impacts on the soil profile; deeper formations; groundwater; surface waters; water acidification; eutrophication; greenhouse gas emissions; air pollution; odours; cytotoxicity; plant toxicity and human and animal toxicity were assessed. The research yielded no adverse environmental impacts by bentonite and xanthan gum; limited adverse environmental impacts by calcium/potassium chloride and sodium carbonate; and biological toxicity by barite impurities and graphene/graphene oxide. The work is rounded up with conclusions and recommendations. It is hoped that the findings of this research will prove useful to practitioners in the field as well as researchers that aim to develop environmentally friendly geothermal fluids. Forthcoming work within ORCHYD will address the issues of the socio-economic aspects and the public acceptance of geothermal energy.

1. INTRODUCTION

This work examines the environmental concerns of geothermal fluids that are being considered for use in, ORCHYD, a Horizon 2020 project, which aims to develop a novel drilling technology combining two mature, but previously separate technologies, High Pressure Water Jetting (HPWJ) and Percussive Drilling, for improved rate of penetration (ROP) in deep geothermal drilling. Lost circulation issues are critical to the project's success.

The paper is structured as follows. Section 2 reviews general information on the environmental effects of drilling discharges. Common materials used in drilling muds, such as water, bentonite, xanthan gum, graphene, graphene oxide, barite, calcium chloride, potassium chloride, and sodium carbonate are extensively discussed in Section 3. In Section 4, a brief comparison of drilling fluids takes place. The report is concluded with Section 5, which provides conclusions and recommendations.

2. ENVIRONMENTAL EFFECTS OF DRILLING DISCHARGES

Geothermal drilling is carried out under high-temperature conditions, into naturally fractured formations where large amounts of loss of circulation and degradation take place, causing a rise in drilling costs. The rise in drilling costs can be attributed either to a low ROP or issues such as lost circulation and wellbore stability. According to Saleh et al. (2020), lost circulation represents an average of 10% of total well costs in mature geothermal zones, while it frequently accounts for greater than 20% of expenses in exploratory wells and developing fields. Exploration of deep geothermal wells brings about the need for enhanced drilling fluids. Due to the high complexity of deep drilling operations, research focuses on fluids with high mechanical, chemical, and thermal stability.

Lost circulation is a major problem in the oil and gas industry as well. The two industries share similar principles concerning drilling operations. However, there are two main differences between oil and gas on the one hand and geothermal on the other. The first difference pertains to the fact that lost circulation is more common in geothermal drilling operations, due to the fact that they are usually implemented through cavernous hard rocks in under pressured regimes of multiple zones of highly fractured and altered materials. The second difference is that cementing is completely different in geothermal projects than oil and gas, rising the likelihood of fluid losses during the process (Saleh et al., 2020). Qalandari and Qalandari (2018) noted that lost circulation occurs when the weight of the mud is greater than the fracture resistance of the formation, and this results in the volume of circulated fluids being smaller than that of its input.

ORCHYD is expected to concentrate on onshore geothermal drilling, with offshore lacking in maturity at this point in time (2021). Expected impacts to the different spheres of the environment are organized below. Impacts on the biosphere are analyzed only for onshore drilling operations. Impacts related to the use of geothermal drilling fluids and the lithosphere (or geosphere) concern (a) the soil profile (where drilling muds may be applied), (b) deeper formations that are drilled through (which may be affected by the intrusion of drilling mud), and (c) groundwater (which may be contaminated by chemicals in the drilling mud).

Due to their alkaline nature, the application of drilling muds onto the soil is less detrimental to acidic, highly organic, and sandy soils, and more detrimental to alkaline loam and soils with high clay content. UNEP (1985) reported no adverse environmental impacts resulting from drilling mud disposal on certain soil types. In fact, the water holding capacity of soils increased while the lowest drilling mud application rates were associated with increased vegetative production. Most drilling muds cause soil dispersion that results in surface crusting. Water leached into the soil (helped by heavy precipitation) may leach salts into deeper less productive soil layers (i.e., below the B horizon). Heavy metals are an important environmental concern. Nevertheless, UNEP (1985) reported that even at the highest level of drilling mud application, no heavy metal problems were detected, and there was no movement of heavy metals in the soil profile.

Regarding the hydrosphere, concerns are related to surface waters and particularly groundwater. In this respect, UNEP (1985) found that arid regions (with less than about 50 cm of annual precipitation) have a higher potential for adverse effects than regions with wetter climates.

Environmental concerns related to drilling fluids and the atmosphere would be linked to odors emanating from reserve pits as well as the application of muds onto the soil (i.e., landfarming). As far as traffic emissions related to the processing of drilling fluids, they should be largely independent from the type of drilling mud employed.

The literature reports that the used mud and solids from onshore drilling wells are usually discharged to earthen sumps (reserve pits) that are excavated adjacent to the well site (UNEP, 1985). Such reserve pits are normally used for storage and final disposal of water-based drilling fluids and drilled solids. Siting parameters that are considered (for locating reserve pits) include: hydrogeology, drilling mud composition, site accessibility, age of the site, soil types, land use, groundwater depth, well depth and chemical history, and climate (UNEP, 1985). The constituents of drilling mud may leak in sufficient quantities to pose an environmental hazard to human health or the environment, e.g., drilling mud and its components may affect the growth rates of plants (mainly due to the soluble salts they contain).

As mentioned before, the presence of heavy metals in some drilling fluids is an important environmental concern. These may include chromium (from additives intended to prevent corrosion) and barium (from barite and natural formations). Although drilling mud metals have only limited bioavailability because of the form they are in (insoluble salts, chemically bound to organic molecules of high molecular weight, or absorbed in clays), metal uptake in plants growing in soil that has been amended by mud is unlikely but not impossible (UNEP, 1985). Older oil drilling studies reported by UNEP (1985) found no significant heavy metal accumulations in plants, and no adverse impacts on livestock grazing.

Toxicity is another important environmental concern. Regarding toxic effects, some species are more sensitive than others, and juveniles are more sensitive than adults. Most drilling muds tested by UNEP (1985) had LC_{50s} (96-hour LC_{50}, which refers to the concentration required to kill 50% of the test organisms in 96 hours) that fell into the practically nontoxic range (10,000 to 100,000 ppm). Bentonite and barite are essentially nontoxic, while lignite and lignosulphonate are practically nontoxic (i.e., slightly toxic).

3. WATER BASED MUDS AND ADDITIVES

The design and utilization of drilling fluids play a key role in the success of a geothermal project. Prixton and Hall (2002) suggest using a wide variety of drilling fluids, including water and bentonite/barite mud, which is along the lines of what ORCHYD intends to do. An inappropriate selection or design of drilling fluids would lead to more non-productive time.

Several factors need to be taken into consideration during the preparation of the proper drilling fluid for a geothermal well (Capuano, 2016). Lithology is one of the key aspects that need to be considered. Thickness, strength, permeability, and pore pressure of formations need to be analyzed. The existence of water sources for the preparation of the WBMs close to the site is important both for economic and technical reasons.

Another serious issue that renders conventional drilling difficult and costly is the high temperatures encountered in geothermal sites. These conditions favor the corrosion and oxidation of drill bits and drill stem (Goff et al., 1995). The thermal profile of geothermal reservoirs induces changes in rheology which affect the efficiency of the drilling fluid. According to Ali et al. (2020), among the issues that need to be dealt with, are high temperature gelation; high temperature fluid loss; rheological property control; material degradation; sagging of barite; and gas solubility.

Mud viscosity needs to be adjusted to a level where cuttings can be transported to the surface and loss of circulation is prevented. Capuano (2016) notes that the most preferred viscosifier during geothermal drilling operations is API grade bentonite (sodium montmorillonite. Proper lubrication and cooling of the drill bit are of high importance as well, which is achieved mainly using graphite.

The presence and coexistence of hydrogen sulfide (H_2S) and carbon dioxide (CO_2) need to be taken into consideration seriously, as their dissolution in water can alter the mud pH and cause profound implications. The alkalinity of the drilling fluids can control the contaminating effects of H_2S and CO_2, reduce corrosion rates and cause additives like lignite and polymers to react. Capuano (2016) recommends that the pH be kept near 10.5 by the addition of sodium hydroxide (NaOH) or potassium hydroxide (KOH) to the mud. Given the above, it is safe to point out that the pH level of the mud is crucial for the safety and economic viability of any geothermal project. Furthermore, the mud needs to be monitored at all stages and adjusted accordingly if needed. The mud density is particularly important as augmentation may be required, depending on the downhole pressure.

Traditional additives include bentonite, xanthan gum, starch, synthetic polymers, copolymers, and tetrapolymers. Nonconventional drilling fluids include carbon dioxide (CO_2) foam as circulation fluid, ionic liquids, and vegetable oils. Nanoparticles include nano zinc oxide, carbon nanotubes, silica nanoparticles, aluminium oxide nanoparticles, graphene, and hollow glass spheres. Green or eco-friendly additives include pistachio shells, sugar cane ash, tamarind gum, ground coca bean shells, rice fractions.

3.1 Water

Water (in the form of freshwater or geothermal brine) constitutes a cost-effective base fluid in a variety of muds (with density found to be equal to 998 kg/m³ in ORCHYD). Reduced cost is a major advantage of water as a drilling fluid since it is cheaper than any mud. In addition, water reduces the temperature further, prolonging the bit life; reducing the possibility of a differential sticking and a kick; and improving penetration rates. Disadvantages include large water volume requirements; increased risk of formation damage; reduced permeability; and long well recovery periods. A regular mud cleaning system must also be present to allow for the recycling and reuse of water through pumps. Despite the obvious environmental advantages of water, geothermal drilling cannot use just water because of the pressure regime. Something heavier is required, thus the use of bentonite, barite, and other substances used to lift the cuttings. An additional consideration in ORCHYD is that the drilling fluids used must be compatible with the mud hammer operation i.e., not be in capacity of plugging small flow channels.

Since geothermal drilling usually takes place in an under pressured regime, large water quantities may be lost in the formation, causing damage and inadequate cuttings removal after a certain depth. For this reason, various solids are inserted in the water to help achieve the desired values for certain properties like viscosity. A study by Bayer et al. (2013) claimed that holding ponds for transient discharges can be rather large, although their impact on the land footprint is deemed negligible.

3.2 Bentonite and xanthan gum

Bentonite (density found to be equal to 2300 kg/m³ in ORCHYD) and organic polymers such as xanthan gum (density found to be equal to 1500 kg/m³ in ORCHYD) are introduced as additives to WBMs mainly for viscosity control. Bentonite is a colloidal aluminum clay mainly composed of montmorillonite (Lewis, 1993). Bentonite is also used in wastewater treatment for the removal of various contaminants. Mahmoud et al. (2021) highlight the importance of bentonite in geothermal drilling operations because of its flexibility. Sodium, calcium, and potassium bentonites are the most common forms of bentonites used. It is regarded as one of the best fluid barriers due to its low permeability, which prevents fluids from easily passing through. In many circumstances, bentonite is combined with other minerals to make a grout mix to increase thermal conductivity. Cement, water, sand, and graphite are the most frequent bentonite additives.

Xanthan gum is a good viscosity control polymer. As Echt and Plank (2019) pointed out, xanthan gum is commonly used as a geothermal drilling additive due to its excellent cleaning capability and carrying capacity of drill solids. Furthermore, it is preferred as a viscosifier in geothermal drilling operations in Europe. When xanthan gum is present in adequate concentration, the viscosifying mechanism is based on the creation of a vast network due to the tangling of the individual hydrocolloid chains. Because these chains are only loosely linked to one another, they flow freely when stressed. The loss of viscosity following high-temperature aging is caused by the radical breakdown of the polymer. A study by Paydar and Ahmadi (2017) claimed that plastic viscosity is proportional to polymer concentration. The increase is minimal until 1.5 grams of xanthan gum concentration is reached. However, there is a significant rise of plastic viscosity following that.

The combination of bentonite and polymers like xanthan gum in WBMs is often advantageous. Filtration properties of bentonite doubled by low viscosity of xanthan gum makes this kind of mud suitable for deep geothermal drilling conditions. It is important that it can reduce the risk of friction-related complications while lifting cuttings adequately. Its properties can also reduce the problem of lost circulation. It can sufficiently stabilize the borehole and minimize water loss, which is very important when clay-rich formations are drilled. Lastly, due to the mud's lower slip velocities compared to water, the risk of a stuck drill string can be reduced significantly. However, there are certain disadvantages related to the disposal of drilling mud; clogging of the borehole; formation damage; reduction of ROP; and differential sticking (if the choice of drilling mud is not optimum).

From an environmental standpoint, xanthan gum can potentially adsorb small quantities of carbon dioxide (Park et al., 2007). According to the OSPAR commission's (for protecting and conserving the North-East Atlantic) list of substances or preparations used and discharged offshore which are considered to pose little or no risk to the environment (PLONOR) (CEFAS, 2019), both bentonite and xanthan gum are considered as substances which pose little to no risk to the environment in terms of bioaccumulation potential, acute toxicity, and the possibility of endocrine effects.

3.3 Graphene and graphene oxide

Graphene ($C_{140}H_{42}O_{20}$) is a nanomaterial that was isolated in 2004 by Konstantin Novoselov and Andre Geim, who received a Nobel Prize in Physics six years later (density equal to 2267 kg/m^3). Graphene has been widely researched and used in multiple applications, including drilling and completion fluids, due to its thermal, electrical, chemical, and mechanical properties.

The oxidized form of graphene is Graphene Oxide (GO). It is a single-atomic-layered material formed by the oxidation of cheap and readily available graphite. Because it dissolves in water and other solvents, graphene oxide is simple to process. Graphene oxide is not conductive due to the oxygen in its lattice, but it can be reduced to graphene via chemical methods. One of the primary advantages of graphene oxide is that it is water dispersible. This enables the use of solution-based processes.

Qalandari and Qalandari (2018) noted that the hexagonal arrangement of carbon atoms in graphene sheet has resulted in an extremely flexible material that has proven efficient in sealing fractures that can arise during drilling operations. Wellbore strengthening is the process of closing fractures in the wellbore. Its addition in the mudcake improves stability and reduces formation damage due to minimization of fluid loss. Cheraghian (2021) notes that, due to the graphene dispersion problem in aquatic conditions, graphene has poor performance in water-based drilling fluids, whereas graphene oxide has adequate aqueous stability.

A variety of studies (Kosynkin et al. 2011, Husin et al. 2018, Ikram et al. 2020) support the efficiency of GO as an effective fluid-loss-control additive in WBMs. However, Ikram et al. (2020) pointed out that GO nanocomposites are produced in small amounts and at a high economic expense. Another study by Kusrini et al. (2018) suggested that graphene is more suited for high formation pressure wells, while GO is better suited for low-pressure wells.

According to Fu et al. (2020), graphene shows good biocompatibility, but at the same time, it has high biological toxicity. Due to the likelihood of graphene nanoparticles releasing to the environment and impacting the biosphere, its toxicity must be considered carefully. Schinwald et al. (2012) pointed out that graphene particles are easily inhalable and can cause severe toxic effects in the lungs, such as pulmonary fibrosis and cysts. A study by Jamrozik (2017) suggested that graphene can have toxic impact on human and mouse epidermis.

Fu et al. (2020) claimed that graphene materials have also been demonstrated to be hazardous to animals. The majority of the research is done on mammals such as rats and mice. The toxicity of graphene materials to animals is highly related to their active position, action mode, and action concentration, as well as their size and surface functional group types. Graphene's toxicity to mammals is reflected as low acute toxicity. GO is more hazardous to mammalian lungs than graphene; nevertheless, surface modification can mitigate the toxic effects of GO.

The toxicity of graphene to terrestrial plants and algae seems to be high, according to a study by Begum et al. (2011). Concerning algae, studies by Nogueira et al. (2015) and Ouyang et al. (2015) have suggested that damage is caused due to the increase in the presence of reactive oxygen, which is enhanced by the graphene accumulation (which renders oxygen radicals, Jarosz et al., 2016), affecting seriously the growth of algae species. Hu et al. (2010) addressed the antibacterial activity of graphene-based nanomaterials and found that it can affect the growth of E. Coli.

Concerning toxicity, it is important to examine cytotoxicity, plant and animal toxicity, and the antibacterial properties of graphene and graphene oxide. Cytotoxicity, in particular, is a highly important factor for the evaluation of the safety of any pollutant. As Fu et al. (2020) point out, graphene nanomaterials are cytotoxic, and their toxicity is directly related to their physical and chemical properties, as well as the types of cells. It also has a considerable concentration dependence.

Wang et al. (2010) argued that the toxicity of GO aqueous solution is very low at concentrations below 20 μg/mL, but significant at concentrations above 50 μg/mL. Due to GO's high surface activity, which yields a high number of Reactive Oxygen Radicals (ROS), DNA fragmentation, cell membrane damage and mitochondrial dysfunction may be caused (Jarosz et al., 2016). Qu et al. (2013) found that GO's interaction with the toll-like receptor 4 (TLR4) may trigger an inflammatory response which leads to programmed cell death. The same study further claimed that GO could directly damage the cytoskeleton and affect the morphology and normal function of cells.

On the other hand, graphene is an efficient adsorbent that can help remove heavy metals from the aquatic solution (Zhang et al., 2019). Graphene may also help make carbon capture cheaper and more efficient (Huang et al., 2021).

Overall, graphene and graphene oxide are good lost circulation materials: they are quite effective in plugging formation holes. As a result, they are difficult to do without, so they would have to be used selectively to mitigate any negative impacts.

3.4 Barite

An important component of WBM is the weighting agent, which increases the mud density. This is important for blowout control during drilling operations. The most widely used weighting agent is barium sulfate ($BaSO_4$), most commonly referred as barite (density equal to 4480 kg/m^3). Barite is a high specific gravity mineral related to barium sulfate, barytes, and heavy spar (Lewis, 1993).

Barite is "by far the largest ingredient of drilling fluids" and has a specific gravity of 4.2 to 4.5 (Noorollahi & Sahzabi, 2005). It is widespread in the industry due to its low cost, inertness, high specific gravity, and low abrasive tendencies. Mohamed et al. (2020) have argued that a disadvantage of its use is attributed to barite's tendency to sag. Viscosifiers and other gellants are required to maintain it suspended. Furthermore, drilled solids that blend into a drilling fluid quickly assume the particle size of API prescribed barite, resulting in decreased solids separation efficiency at shakers and centrifuges.

Another drawback of barite is its impurity content. As Ibrahim et al. (2016) noted, commercial barite typically contains impurities and exhibits a lower specific gravity attributed to other minerals such as quartz, chert, calcite, anhydrite, celestite, and different silicates. Furthermore, it typically contains numerous iron minerals, some of which may raise the product's average specific gravity. Barite is a mineral extracted by mining and can also contain heavy metals (Norwegian Oil & Gas, 2017).

Barite has low water solubility and does not interact with other mud components. Although it is not considered a toxic component of WBMs, a major concern is its mercury content. According to Neff (2008), metals in drilling fluids are traced primarily as impurities in barite. The toxicity of some heavy metals, including cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), lead (Pb), and zinc (Zn) is of great environmental concern. Often their concentration can be over ten times higher than their naturally occurring concentration in formation sediments. High concentrations of aluminum (Al), iron (Fe), and silicon (Si) are also observed in barites, although those are not considered as toxic. Excess barium (found in barite) may act as proxy for eutrophication (Gooday et al., 2009).

There exist literature studies that have proposed alternatives to the use of barite. Abdou et al. (2018) found that mud samples treated with a barite/ilmenite mixture exhibited suitable filtration loss and mud cake characteristics. Alternative weighting materials which can provide superior properties, such as barite, should be available in sufficient reserves to meet field requirements and be competitively priced. A weighting substance that can be found locally to replace barite would be a good breakthrough in the drilling sector. Another study by Mohamed et al. (2020) claimed the effectiveness of perlite as an enhancing material for drilling fluids performance at high temperatures.

3.5 Calcium chloride

Calcium chloride (density equal to 2150 kg/m^3) is a high-volume chemical that comes in various forms ($CaCl_2$, $CaCl_2 \cdot H_2O$, $CaCl_2 \cdot 2H_2O$, and $CaCl_2 \cdot 6H_2O$) all of which are soluble in water and alcohol (Lewis, 1993). Calcium chloride is often used in the drilling industry for the creation of brine and completion fuels. Lime mud, gyp mud (a calcium-based water mud containing gypsum), and calcium chloride mud are water-based drilling fluids that utilize dissolved Ca^{+2} as a component. Calcium chloride is a suitable salt for solid-free brines (used as drilling fluids). Solid-free brines improve the ROP, the stabilization of sensitive formations, and the density and abrasion or friction (Gowida et al., 2019).

The water phase salinity of mud needs to be controlled during drilling operations. As Redburn and Heath (2017) explained, water activity measures inhibition to prevent freshwater migration into the formation, which is a crucial property of water-based drilling fluids. The activity level of mud needs to be equal or lower to that of the formation's water. Chloride concentration is inversely proportional to the activity level of mud. Therefore, adding calcium chloride will prevent mud losses into the formation and clay swelling issues. Dankwa et al. (2018) wrote that the increase of concentration of calcium chloride decreases the plastic viscosity and yield point of WBM.

Calcium chloride is also used in the drilling mud for cooling and lubrication of the drill bit, as well as removal of cuttings from the borehole. With its wide range of densities, availability, low cost, and capacity to lower fluid water activity, calcium chloride is regarded as one of the most cost-effective brine systems, according to Gowida et al. (2019).

Calcium chloride has zero toxicity in normal amounts, is not biodegradable but does not bioaccumulate. However, it causes an exothermic reaction when it dissolves in water and has desiccating properties. Calcium chloride interacts with solution acidity and thus affects the extraction of heavy metals such as cadmium (Kuo et al., 2006).

3.6 Potassium chloride

Potassium chloride (KCl, density equal to 1980 kg/m^3) is a salt occurring naturally as sylvite, is soluble in water and slightly soluble in alcohol (Lewis, 1993). Potassium chloride is used widely in the drilling industry due to its shale stabilizing properties (mainly hydro sensitive clays). It is a cost-effective material and efficient swelling inhibitor of WBMs. It provides ions which promote the stabilization of such reactive clays which subsequently minimizes swelling phenomena. For the prevention of clay swelling and hydration, relatively high KCl concentrations ranging from 2% to 37% are demanded, according to Patel (2009).

From an environmental standpoint, regulations in many countries prohibit or set severe constraints on the release of chloride residues in croplands. High contents of KCl in the drilling mud could be toxic to the marine environment, drilling environment, and disposal area (Murtaza et al., 2020). Elevated concentration of ions can affect plants and bacteria (Burden et al., 2013). This happens as a result of the alteration of the osmotic balance of the cells of plants and bacteria, which causes a lack of nutrients. A plant growing in soil containing a high salt content will have yellow or brown leaves and stunted growth.

Nitrogen, phosphorus, and potassium ions in high concentrations and quantities may immediately negatively affect the soil or water upon release. However, the natural environment will break them down over a relatively short amount of time. The use of potassium sorbate as an alternative to potassium chloride has been suggested in the literature. In particular, a study by Naemavi et al. (2019) claimed that potassium sorbate is a biodegradable substance that degrades more than 60% of its sorbic acid in 28 days, and the residual potassium ion can be used to support plant development. It is less harmful to the soil than potassium chloride. The substitution of potassium sorbate for potassium chloride in drilling fluid protects the environment against chloride ion contamination. On the other hand, like calcium chloride, potassium chloride interacts with solution acidity and thus affect the extraction of heavy metals such as cadmium (Ma et al., 2019).

In a study by Jiang et al. (2019), a gelatin composite with potassium chloride was developed as an environmentally friendly shale hydration inhibitor (contained in WBMs), which decreased swelling. However, as pointed by Murtaza et al. (2020), potassium chloride adversely affects the properties of drilling mud, which leads to high fluid loss, flocculation of bentonite, and coagulation of the cuttings around the bit in some cases.

3.7 Sodium carbonate

Sodium carbonate (Na_2CO_3 density equal to 2200 kg/m^3) is commonly known in the drilling industry as soda ash. Sodium carbonate may contain impurities (up to 1%) including sodium chloride (NaCl), sodium sulfate (Na_2SO_4), calcium carbonate ($CaCO_3$), magnesium carbonate ($CaCO_3$), and sodium bicarbonate ($NaHCO_3$) (Lewis, 1993).

Sodium carbonate may seal ponds as sodium ions bind to clay particles that swell and seal leaks (Lewis, 1993). According to Schlumberger (2021a), it is used during drilling operations to treat calcium ion contamination of freshwater or seawater muds. Clay flocculation, polymer precipitation, and pH reduction are caused by the presence of calcium ions from drilling gypsum, anhydrite, and calcium sulfate. In case of cement contamination, sodium bicarbonate ($NaHCO_3$) is preferred.

Sodium carbonate is introduced in WBMs to reduce the amount of soluble calcium, increase pH and flocculate spud muds. The latter is desirable for removing large gravel cuttings encountered at shallow depths. As Mahmud et al. (2020) mention, potassium, sodium, magnesium, and calcium chlorides are examples of salt pollutants that may contaminate drilling mud. Because of calcium and magnesium ions in saltwater, it is another major source of salt contamination in drilling mud. Calcium and magnesium ions are insoluble in WBM and caustic soda additives, as well as any other additive, and must be combined with the mud to precipitate the calcium and magnesium ions. A study by Anthony et al. (2020) suggests that the concentration of sodium carbonate is proportional to the alkalinity (pH) of a mud sample. In this research it is further noted that the highest bentonite and sodium carbonate concentration, the most improved are the flow and rheological properties of the WBM.

Sodium carbonate is a naturally occurring material and is commonly found in soil and aqueous environments, according to EPA (2006). The EPA (2006) further suggests that low-level release of sodium carbonate doesn’t have adverse impacts on wildlife or water resources. Concerning health impacts, Schlumberger (2021b) notes that soda ash is an alkaline substance that can irritate the eyes, skin, and respiratory tract. Soda ash should be slowly introduced to the mud system, either by mixing through the hopper or by using a chemical barrel. It is further mentioned that sodium carbonate should not be mixed with other chemicals like caustic soda or lime.

4. COMPARING DRILLING FLUIDS

Considering the lithosphere, bentonite and xanthan gum should have no adverse impacts on the soil profile – in fact, they should increase the water holding capacity and help adsorb heavy metals. Barite may contain heavy metals as impurities, and these could contaminate groundwater, although they may not be readily available for plant uptake. Calcium and potassium chloride may leach into deeper soil formations and interfere with soil acidity. Graphene (oxide) may also increase water holding capacity and help with the removal of heavy metals. So, as far as the lithosphere is concerned, bentonite, xanthan gum, and graphene (oxide) would be better choices from an environmental standpoint.

Similar considerations are valid for the hydrosphere, with bentonite, xanthan gum, and graphene (oxide) being good environmental choices that can help adsorb heavy metals. Bentonite and graphene (oxide) may help prevent or reduce eutrophication. In the case of surface waters, though (more so than in the soil solution), calcium and potassium chloride may affect the speciation and precipitation of heavy metals, so they may potentially play a favorable environmental role by helping with their removal. Barium present in barite may aid eutrophication, which would result in less dissolved oxygen. If calcium chloride reduces the pH of a surface water body, barite may be dissolved easier (along with its impurities), so complex interactions among the drilling muds may be expected here.

Turning to the atmosphere, regarding greenhouse gas emissions (and air pollution), there appear to exist minimal differences among the drilling muds examined. However, their role in processes unrelated to geothermal drilling may make a difference. Barite may be the only drilling mud that can potentially have an unpleasant odor (when crushed). Bentonite and graphene (oxide) possess good anti-odor capabilities.

Finally, turning to the biosphere, graphene (oxide) appears to be the only drilling mud with some cytotoxicity, high plant toxicity, and several potential toxic effects on humans. Calcium and potassium chloride may affect the growth of plants negatively. Barite may have some toxicity potential due to its impurities (especially mercury). Xanthan gum and bentonite are the drilling muds with little bioaccumulation potential, and the least toxicity potential.

5. CONCLUSIONS AND RECOMMENDATIONS

The goal of this study was to make preliminary recommendations by reviewing the research literature on the environmental impacts of geothermal drilling muds that are (likely to be) used for the novel drilling technology that will be developed by ORCHYD, combining Hydro-Jet and Percussion for improved ROP in deep geothermal drilling. The environmental effects of discharges emanating from onshore geothermal drilling were described, with references to reserve pits, landfarming, (plant uptake of) heavy metals, and toxicity.

The study then focused on water-based muds and additives, encompassing water; bentonite and xanthan gum; graphene (oxide); calcium and potassium chloride; sodium carbonate; and barite. These are commonly used in geothermal drilling operations, and their impact has been documented in various studies. Their environmental impacts were grouped into the soil profile; deeper formations; groundwater; surface waters; water acidification; eutrophication; greenhouse gas emissions; air pollution; odors; cytotoxicity; plant toxicity; and human and animal toxicity.

All in all, a preliminary grouped ranking of the examined drilling muds in increasing environmental concern would be as follows:

1. Bentonite and xanthan gum: no adverse environmental impacts.
2. Calcium/potassium chloride and sodium carbonate: limited adverse environmental impacts.
3. Barite and graphene/graphene oxide: heavy metals (in impurities) and biological toxicity.

According to internal ORCHYD communication, water with xanthan gum (4%) and calcium chloride were used in previous field tests. This composition may not be ideal for percussive deep geothermal drilling at depths over 2 km. With graphene (oxide), it is understood that it is a promising material for use in geothermal drilling due to its unique properties. In fact, its negative environmental impacts are limited to its biological toxicity, so it could be used with measures taken to protect living organisms.

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