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Abstract

Magnetic shielding of the Measurement While Drilling (MWD) directional tools and damages to mud pumps, downhole tools and casing/drill-pipe are some of the main problems caused by steel and magnetic contaminated drilling fluids. The magnetic shielding of the MWD directional tool have so far shown to be the biggest problem caused by magnetic particles in the drilling fluid. For directional drilling surveys, it has been found that magnetic particles in the drilling fluid may cause errors in the azimuth in the range of 1-2° [1]. This error may cause the directional driller (DD) to miss his pre-set target within the range of 1-200 meters while drilling long deviated wellbores. In order to have the magnetic shielding problem eliminated, it has been found to be the best practice, to completely remove all the magnetic contaminants from the drilling fluid by the use of ditch magnets. The presented work has been done in order to better understand the importance of the magnets and their ability to remove magnetic waste from the drilling fluid. Experiments, together with analysis of the different parameters that might affect the ditch magnet performance have been conducted.

In the presented report, a simple TRU-WATE™ Fluid Density Balance weight was used to measure the density differences upstream and downstream of the ditch magnets. This was done in order to see if there was any noticeable difference in density upstream and downstream of the magnets. It was assumed that any changes in density could represent the performance of the ditch magnet. It was found that uncertainties and unknown features related to the experiments made the test results unreliable and hard to interpret. No results indicated that it was possible to actually quantify the ditch magnet performance by use of the TRU-WATE™ Fluid Density Balance weight.

A Scanning Electron Microscope (SEM) was used to determine the size of the smallest particles extracted from the drilling fluid by the two different ditch magnet systems and the quantity of the smallest particles. It was found that the smallest particles extracted by M.A.P.S and EZ-Clean ditch magnets was 0.5 and 0.8 micrometers. The quantity of the smallest particles was not found.

Data from the same ditch magnet systems that was used for the experiments have been analyzed in order to see if there are any significant differences in the total amount of magnetic waste material collected from the two systems. All data are seized from the daily drilling reports (DDR) provided by Det Norske Oljeselskap ASA. From the results, the ditch magnet performance is evaluated. It has been shown how drilling length, inclination and casing size may affect the production of magnetic debris, and hence, show the dependence of the performance of the ditch magnets. Methods related to handling of the ditch magnet samples have also been found to affect the final ditch magnet weight results and from this, the overall ditch magnet performance.

The report presents, in addition to the experiments and analysis, the importance of the ditch magnets and an overview of the most common ditch magnet systems that are used in operation today. Different types of ditch magnets are discussed and information is given concerning each system.

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1 Introduction

Magnetic contamination of the drilling fluid caused by magnetic erosion waste particles from the well and drilling additives, are anticipated to contribute significantly to errors in directional surveying of wellbores [2]. This includes damage to mud pumps, damage to downhole tools and casing/drill-pipe wear. During drilling, large amounts of metallic particles and metallic wear products are mixed into the drilling fluid from sources as added weight material, drill solids and clays. In addition, metallic wear particles contaminate the drilling fluid due to wear of drill pipe, casing and downhole tools. A great quantity of these metallic particles tends to be magnetic. Magnetic contaminated drilling fluids are known to distort the geomagnetic field at the location of the Measuring While Drilling (MWD) directional tool magnetometer. This is the tool used to measure the direction of the well path [3]. This is, by far, the biggest problem caused by magnetic contaminated drilling fluids.

The problem became known to the oil industry around the year 2001. Laboratory experiments confirmed that the magnetic field of the Earth was attenuated when a three-axis probe was lowered into a field-used drilling fluid containing magnetic waste particles [4]. This theory was also confirmed by Tellefsen et al. (2012) [5] through their work. The problem is still present today. Methods to mitigate or eliminate the problem have not yet been developed. Ekseth [6] and Williamson [7] have developed some multistation measurement models to estimate the accuracy of the wellbore position, but the error caused by the magnetic contaminated drilling fluid is not implemented in their models. No theoretical model has yet been developed where the magnetic shielding caused by the drilling fluid, is implemented. The only known method today is to physically remove the magnetic waste material from the drilling fluid. For this purpose, downhole magnets attached to the drill string are used together with ditch magnets and solids removal with shale shakers that are installed in the drilling fluid return system.

An investigation has been done to increase the understanding and importance of the ditch magnets and their performance based on data from two different drilling rigs operated by Det Norske Oljeselskap on the Norwegian Continental Shelf (NCS). Optimization of the ditch magnets are anticipated to reduce the problems related to magnetic shielding in the MWD tool significantly. The risk of having downtime during the drilling operations due to broken downhole tools, mud pump problems and other issues related to wear of equipment are also anticipated to be reduced.

Metallic particles in the drilling fluid also makes the drilling fluid prone to cause friction in the drilling fluid return system. If not removed, the particles will be re-circulated over and over again, causing wear on the system and problems with mud pumps, logging tools and the shale shaker screens. Small magnetic fines may clog downhole tools and cause failures to logging and steering assemblies. Mud pumps may experience more rapid wear and cause a higher need for maintenance. The shale shaker screens could get damaged by sharp metal particles and may cause a more frequently change of the screens.

2 Ditch magnets and magnetic fundamentals

2.1 Removal of metal particles from the drilling fluid

Damage to mud pumps, downhole tools and casing/drill-pipe are anticipated to be caused by magnetic waste particles from the well and by other downhole factors (vibration, temperature, pressure etc.). Magnetic particles in the drilling fluid may also contribute significantly to errors in directional surveying of wellbores [2]. Errors in the directional surveying of the wellbore position, caused by azimuth errors, may cause the directional driller (DD) to miss his pre-set target of a long deviated well section within the range of 1-200m. Small changes in azimuth ranging from 1-2° is typically caused by the magnetic contaminated drilling fluid, but errors five to ten times larger may occur under unfavorable conditions [2]. Missing the target with a distance of 1-200m may cause a significant cost increase to the operation as the original reservoir section in a worst case scenario needs to be cemented back and re-drilled. A significant time- and cost reduction of the operation may be achieved by having the magnetic waste particles removed from the drilling fluid in order to prevent magnetic shielding of the Measurement While Drilling (MWD) directional tool.

Poor removal of magnetic waste from the drilling fluid also results in exposure of the mud pumps to mechanical wear as erosional forces are caused by the magnetic contaminated drilling fluid. Service companies also experience tool failures due to plugging and damage done to the downhole tools by magnetic waste particles. It is anticipated that fine metallic particles, in combination with larger ones, clog the downhole tools and cause failures to the tools. This could have been prevented if the drilling fluid was cleaned properly. Figure 1 shows a picture of some metallic waste findings done by Schlumberger in one of their bottom hole assembly (BHA) tools.

Figure 1: Findings from downhole drilling tools done by Schlumberger. Picture taken offshore from Schlumberger archives.

Some of the “particles” in Figure 1 have a size of 6-7 centimeters. Metallic wear products of this size contained inside downhole drilling tools, are anticipated to cause a lot of problems and will delay any drilling operation if the tool stops working. Rotating parts, electric parts and logging devices may be affected by these metallic “junk” pieces and therefore they should be removed from the drilling fluid. One tool failure might delay a drilling operation for 1-2 days if a new tool is needed. From an operation perspective, the drill string needs to be pulled out of the hole and laid down onto the drill floor. The damaged/broken tool needs to be fixed or replaced and the drill-string then needs to be run back into the well. Tripping time varies for each well section, but tool failures tends to happen while drilling long deviated well sections (often the reservoir section) were the tools are exposed to harsh environments over a long period of time. It is anticipated that elimination of magnetic waste particles in the drilling fluid would increase the operational time of the downhole drilling tools, improve the quality of the logging data, reduce the drilling period and by this, reduce the total operation cost.

The above mentioned problems is anticipated to be solved in the best manner by having the magnetic waste particles completely removed from the drilling fluid. This is the best practice so far as no theoretical correction factors yet has been developed where the effect from the magnetic contaminated drilling fluid is implemented. Removal of the magnetic waste particles from the drilling fluid by use of the ditch magnets is also anticipated to be the most cost efficient approach in order to reduce the drilling time and total drilling costs.

2.2 Basic concepts of magnetic fields

This section summarizes the work done by Amundsen et al. (2005) [1]. A shorter version of the paper is presented by Amundsen et al. (2006) [8]. The magnetic field of the Earth is present at all times and during drilling it is used to navigate the drill-bit towards the pre-set target using the Measuring While Drilling (MWD) directional tool as steering assembly. The strength and direction of the magnetic field, which is measured by any type of magnetic sensor, is determined by the magnetic field vector **B** (also called the magnetic induction, or the magnetic flux density). The resulting magnetic force on a particle moving with a velocity **v** and with a charge **q** is:

$$\mathbf{F}_{m} = q\mathbf{v} \times \mathbf{B}. \quad \textbf{(1)}$$

From Equation (1), the force required to extract a magnetic particle from the drilling fluid can be calculated. Due to several parameters affecting the calculation (viscosity, rheology, size of the particle, value of charge, velocity, etc.), accurate calculations in non-Newtonian fluids are difficult and no equations has been derived at the time being (2016). In most cases, it is more convenient to measure **B** by the magnetic torque, **T,** on a magnetic dipole of magnetic moment **m** (e.g. using a compass needle or a current loop):

$$\mathbf{T} = \mathbf{m} \times \mathbf{B}. \quad \textbf{(2)}$$

Non-existence of free magnetic charges (magnetic monopoles) implies that **B** must satisfy:

$$\nabla \cdot \mathbf{B} = \mathbf{0}. \quad \textbf{(3)}$$

In a system, the magnetic field is caused by local current distributions, in addition to possible superimposed external magnetic fields (caused by currents external to the system under discussion). The effect of a current density, **j**, on the magnetic field is conventionally expressed through an auxiliary field, **H**, traditionally – and unfortunately – called the magnetic field intensity (or magnetic strength). **H** and **j** are then related through Ampère’s law:

$$\nabla \times \mathbf{H} = \mathbf{j} \tag{4}$$

In the absence of any magnetic materials in the system, we simply have $\mathbf{B} = \mu_0\mathbf{H}$, where $\mu_0 = 4\pi\cdot10^{-7}$ H/m is a conventional constant called the magnetic permeability of vacuum. Equation (1), (2), (3) and (4) given above remain valid in the presence of magnetic materials, except that the relation between **B** and **H** is not necessarily simple.

The magnetic properties of matter are caused by the molecules in the magnetic material which possess a magnetic dipole moment. A number, **N**, of such molecular dipoles $\langle \mathbf{m}_i \rangle$ (i = 1…N) contained in a macroscopically small volume, **V**, will act together as single dipole of strength, $\sum_i \mathbf{m}_i$. The average combined dipole moment is the magnetization, **M:**

$$\boldsymbol{M} = \frac{1}{V}\sum \boldsymbol{m}_i = \frac{N}{V}\langle \boldsymbol{m} \rangle = n\,\langle \boldsymbol{m} \rangle \tag{5}$$

where **n** is the number density of the dipoles and ⟨…⟩ denotes the space average (assumed equal to the time average in the case of fluctuations).

If there is present a magnetizable medium, the relation between **B** and **H** is modified to:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}). \tag{6}$$

In Equation (6), **H** has the same value, given by Ampère’s law, as it would have if no microscopic dipoles were present. The same current distribution, **j**, is then assumed. Thus **H** can be interpreted as the external magnetic forcing of the material, causing a magnetic field **B**. Equivalently, it can be interpreted as the magnetic moment per unit volume of the external macroscopic electric currents.

In general, no simple relation between **M** and **H** exists, and hence not between **B** and **j**. Indeed, for permanent magnets **M** one can have a random direction with magnitude up to a certain maximum, even if an external field is absent. However, in most materials the molecular magnetic dipoles are randomly oriented with a vanishing average, so **M** = 0 if **H** = 0, and they respond only weakly and practically linearly to an external field. If the magnetic medium is also isotropic (no direction is preferred), it leads to the following relations:

$$\mathbf{M} = \mu\mathbf{H} \Leftrightarrow \mathbf{B} = \mu_0(1 + \chi)\mathbf{H} = \mu\mathbf{H}. \quad \textbf{(7)}$$

where χ represents the magnetic susceptibility. χ is a dimensionless number with thermo-dynamical material properties. The useful combination

$$\boldsymbol{\mu} = \boldsymbol{\mu_0}(\mathbf{1} + \boldsymbol{\chi}) \quad \textbf{(8)}$$

is called the magnetic permeability.

If the magnetic susceptibility, $\chi > 1$, the material is paramagnetic. If $\chi < 1$, the material is diamagnetic. If the absolute value, $|\chi| << 1$, it can be treated as a possibly temperature dependent material constant in most of the cases, but if $\chi >> 1$, in which case the material is called ferromagnetic, χ itself depends on **H** in a rather non-trivial way (hysteresis). Since the magnetic susceptibility is a material property, so is μ, and in inhomogeneous systems, μ is generally position dependent → $\mu = \mu(\mathbf{r})$.

In physical data tabulations one often does not tabulate χ directly, as most experimental setups instead measure the mass susceptibility:

$$\boldsymbol{\chi}^{\boldsymbol{m}} = \frac{\boldsymbol{\chi}}{\boldsymbol{\rho}}, \quad \textbf{(9)}$$

where $\boldsymbol{\rho}$ is the mass density of the substance. In addition, the molar susceptibility:

$$\boldsymbol{\chi}^{\boldsymbol{A}} = \frac{\boldsymbol{\chi A}}{\boldsymbol{\rho}}, \quad \textbf{(10)}$$

is often tabulated. In Equation (10), **A**, represents the molecular mass (molecular weight) of the substance. If two volumes, $\mathbf{V_1}$ and $\mathbf{V_2}$, of two different materials with different susceptibilities, χ_1 and χ_2, are mixed, the relation, $\mathbf{M} = \frac{1}{\mathrm{V}}\sum \mathbf{m}_{\mathrm{i}} = \frac{\mathrm{N}}{\mathrm{V}} \langle\mathbf{m}\rangle = \mathrm{n}\,\langle\mathbf{m}\rangle$, leads to Wiedemann's law for the susceptibility of a mixture (It is assumed that the two materials do not interact chemically or magnetically with each other):

$$\boldsymbol{\chi} = \frac{\boldsymbol{\chi_1 V_1} + \boldsymbol{\chi_2 V_2}}{\boldsymbol{V_1} + \boldsymbol{V_2}}\ ; \quad \textbf{(11)}$$

with an obvious generalization to more complex mixtures. For the mass susceptibility, χ^m, one correspondingly has:

$$\chi^m = \frac{\chi_1^m M_1 + \chi_2^m M_2}{M_1 + M_2}. \tag{12}$$

Because the average magnetic dipole moment $\langle \mathbf{m} \rangle$ often is very sensitive to the molecular surroundings, the use of Wiedemann's law is not always very accurate in practice [1].

2.3 Shielding effect from magnetic contaminated drilling fluid on MWD tool

Since the year of 2001, magnetic shielding of the measuring while drilling (MWD) directional tool caused by magnetic contaminated drilling fluid, has been known to the oil industry [4]. Magnetic contaminated drilling fluids tend to degrade the accuracy of the borehole position and interfere with the magnetic azimuth by creating a "shield" around the MWD tool magnetometer. This effect may be observed when the intensity of the Earth's magnetic field is recorded with a tool surrounded by the fluid. Some experiments [2, 5] were conducted using a magnetometer called Barrington Mag-01H to measure this shielding effect. The phenomenon of shielding appears briefly as a damping of the measured cross-axial components of the Earth`s magnetic field intensity in the tool, and it often dominates over most other relevant error sources [9]. Azimuth errors contribute to complicate the drilling operation and may prevent the directional driller (DD) from hitting the planned target. Normally the azimuth errors reach from 1-2°, but in some cases, the azimuth error may be five to ten times larger if drilling occurs in predominantly east-west direction and/or close to the North- or South Pole [1, 4, 5, 9].

To determine the magnetic shielding effect from the drilling fluid, the magnetic susceptibility, χ, of the drilling fluids is measured. Magnetic susceptibility, χ, is a basic material property used to measure the ability of a substance to get magnetized when placed in an external magnetic field [10]. The magnetic susceptibility is also described in chapter 2.2. In drilling operations, the magnetic contaminated drilling fluid acts as the substance and the external magnetic field would be the magnetic field from the Earth. Often, drilling fluids used in drilling operations has a small positive (paramagnetic) susceptibility value. Steel particles from the well, weight materials and the base fluid that is used to make the drilling fluid are the main sources to establish this positive value. Figure 2 shows a magnetic susceptible drilling fluid.

However, there is no intentionally added magnetic particles in this fluid. In the figure, a magnet is partially immersed into the drilling fluid and “pulls” the fluid towards one of the poles. One pole is visible while the other is submerged into the drilling fluid.

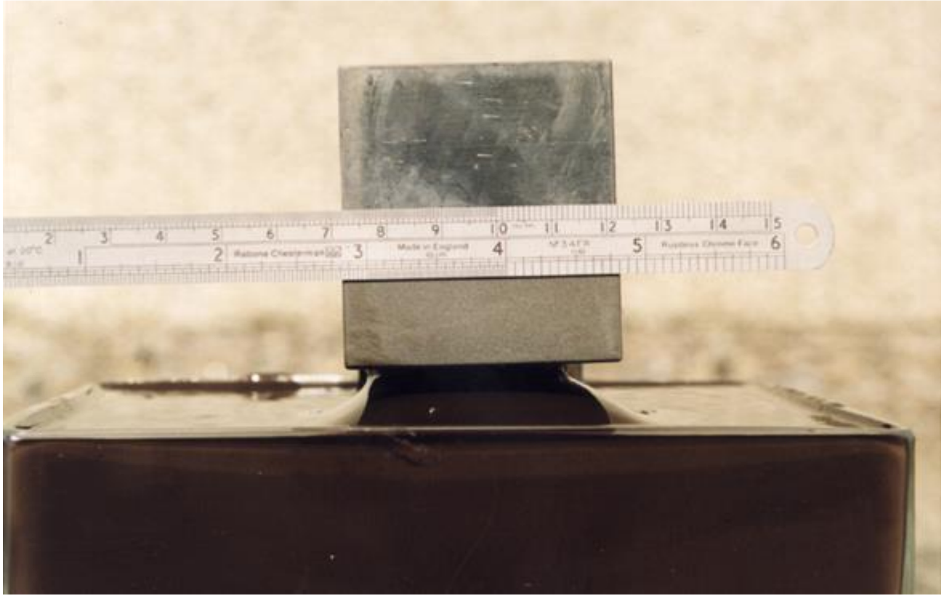


Figure 2: This drilling fluid contained initially no magnetic particles. The figure shows how the fluid is attracted into a vertical flux gap [4].

In some cases, the drilling fluid components also have a negative (diamagnetic) value. This negative value is normally very small. The magnetic shielding from the drilling fluid becomes a problem for the MWD directional tool when the value of the magnetic susceptibility, $|\chi|$, exceeds 0.01, when calculated in SI units. The magnetic shielding depends, in a non-trivial manner, on the magnetic susceptibility and is also dependent on geometry [11, 12].

Simple laboratory methods to measure the magnetic susceptibility accurately have been established for a long time. The methods are designed for dry powders and minerals. One method balances the magnetic force on a sample in an inhomogeneous magnetic field against the gravity to measure the magnetic susceptibility. On the other hand, the force balance methods cannot be used for fluids and slurries, including drilling fluids, as the hydrodynamic forces acting in the sample cannot be controlled. Electromagnetic methods that directly measures the induced magnetic effects, or microscopic methods like nuclear magnetic resonance (NMR), must instead be used to measure the magnetic susceptibility [2] if the concentration is known. Series of experiments conducted by Amundsen et al. (2010) [2], and Ding et al. (2008) [13] showed that magnetic shielding can have a pronounced dynamic behavior [5]. Figure 3 shows the dynamic behavior of magnetic shielding. First, the shielding increases with time before it is reduced slowly as time goes.

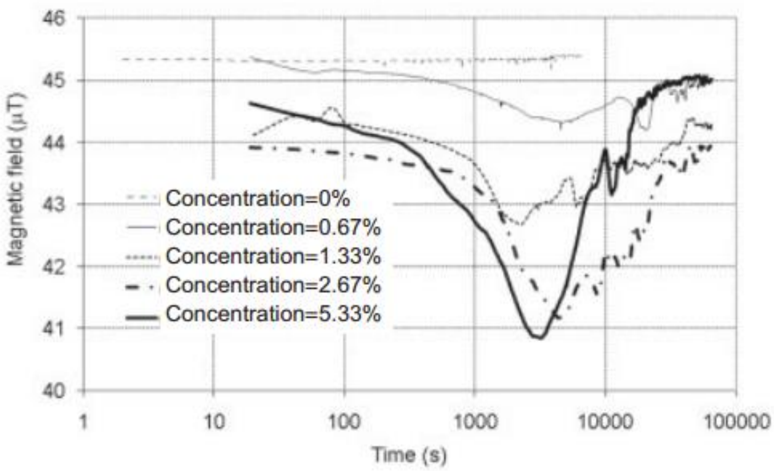


Figure 3: The dynamic behavior of magnetic shielding. Magnetic field as function of time for concentrations of magnetite [2].

The experiments were conducted by having magnetite added to a known solution of xanthan gum and water. Xanthan gum was added to the solution as it has the ability to keep magnetite with density 5.15 sg in suspension for a long period of time. As shown in Figure 3, the dampening of the magnetic field increases significantly as magnetite is added to the xanthan gum solution. At approximately 6000 seconds, the shielding effect reaches its maximum before it starts dropping again towards its initial value. This effect is anticipated to be cause by small magnetic fines aligning themselves to the external magnetic field. The dampening effect varies with the concentration of magnetite in the solution. Based on the work done by Amundsen et al. (2008) [2] and Ding et al. (2008) [13], Tellefsen et al. (2012) conducted several series of experiments with free iron ions mixed into the drilling fluid to investigate the effect on magnetic shielding. A series of experiments was also conducted using different clays and metallic waste particles from a specific well to analyze the effect on magnetic shielding. An important finding from the work was that magnetic contaminants taken from a ditch magnet showed a significant effect on magnetic shielding [5].

2.3.1 Measuring While Drilling (MWD) directional drilling tools

In order to drill a well with precision and in a cost effective way, advanced directional drilling tools have been developed. The directional drilling tools makes sure the pre-determined well path is followed by the use of magnetometers, accelerometers and/or gyroscopes. Magnetometers uses the magnetic field of the Earth as guidance to measure the azimuth angle of the well with respect to the magnetic north. Azimuth coordinates given relative to magnetic north can be converted to Grid – or True North. Accelerometers use the Earth's gravitational field to provide the inclination angle by measuring the gravitational field in the x, y and z plane. The accelerometers are used in both magnetometers and gyroscopes [3]. Gyroscopes measure the azimuth in the well by using its own spin and the rotation of the Earth. The gyroscope is very sensitive to external disturbances and due to harsh downhole environments during drilling, a solution is yet to be found where robust gyroscopes can be used permanently as directional drilling tools.

Magnetometers and accelerometers are the most frequently used directional drilling surveying tools to determine the course of the wellbore. The magnetometer and accelerometer inside the MWD tools measure the three orthogonal components of the local magnetic- and gravity fields and use these results to calculate the azimuth, well inclination and tool face orientation [4]. The data from the MWD tool is always being observed by the directional driller (DD) in case of survey data mismatch with the pre-calculated data. Abnormal values in azimuth readings might indicate distortions of the received values. These magnetic interferences may be caused by casing steel from nearby wells, solar activity, formation, steel drillstring components or the drilling fluid. All of them are capable of having the magnetic azimuth to be out of specification.

Wilson and Brooks (2001) described the measurement set-up. To keep the magnetometer away from magnetic interference sources caused by drillstring components, the tool is housed within a non-magnetic drill collar. In addition, several non-magnetic drill collars could be added, both on top and below the location of the MWD tool in order to reduce the degree of disturbance even further. On the other hand, the non-magnetic drill collars would in most circumstances, be inadequate to isolate the MWD magnetometer from the magnetic drill collars. Several correction techniques have been developed to eliminate the magnetic interference caused by the drillstring where the single-axis correction is the commonly used technique [4].

The single-axis correction is a frequently used technique to correct for magnetic interference where it is assumed that only the axial (z-axis) magnetometer measurement is corrupted by interferences from the drillstring. All the local field components from the Earth are determined independently using a magnetic site survey or geomagnetic charts or models. It is then reasonable to assume that the most likely value of z-magnetometer interference is the interference which results in the minimum vector distance between the post-correction total field components and the reference field. The single-axis correction has been used for three decades. Because the correction picks the point at which the data best fit the reference total field and dip angle, the residual errors in total field and dip are generally expected to be smaller than for well-spaced, uncorrected data [4].

The drillstring interference may also be corrected for by use of the survey method; Multistation Analysis (MSA). Multistation analysis provides drillstring magnetic interference compensation to magnetic surveys and improves the azimuth readings of the MWD directional tool. This method will not be elaborated any further and information can be found in the work done by Chia and Lima (2004) [14].

The presence of magnetic formations and solar activity to interfere with the downhole magnetometer is considered to be rare and nearby wells are avoided as far as possible to eliminate the effect of nearby casing steel interference. Any magnetic interference on the MWD is then assumed to be caused by the drilling fluid. There are no theoretical methods that implements the effect caused by magnetic contaminated drilling fluid in the MWD tools. The properties of the magnetic drilling fluid are highly variable and difficult to predict.

2.3.2 Water based drilling fluids

Water based drilling fluids (WBM) are commonly used while drilling the top-hole sections (conductor - and surface casing hole, as well as the first section drilled with return to the rig) due to the simple reason that it can be dumped straight back into the sea without being treated (as long as no harmful chemicals are used). For the top-hole sections, salt water or WBM with bentonite is frequently used. Bentonite, which is very often used in both WBM and oil based drilling fluid (OBM) to control fluid loss and viscosity, might contain significant amounts of magnesium (Mg) and iron (Fe). These ferrous components in the drilling fluid additives are the ones expected to cause the magnetic properties of the drilling fluid, and hence, causing the magnetic shielding of the measuring while drilling (MWD) directional tool. WBM has initially very low magnetic susceptibility [3], making it reasonable to assume that the shielding effect comes from magnetic contaminants in the drilling fluid. Tellefsen (2012) [5] conducted several experiments with WBM where different volumes of water was used, reducing the water/bentonite relationship in the mixture. It was found that WBM has the ability to shield the magnetic field in the experiment with a value of 2.2%, causing severe errors in the derived azimuth from 1° to 5° [9]. As bentonite clay was used, the structure of the bentonite is anticipated to capsule the ferrous components inside its structure, preventing the magnetic particles from aligning themselves with the external magnetic field. The viscosity and the gel structure of the drilling fluid will also diminish the ability of the magnetic particles to move freely. This prevents the magnetic particles in the experiment from having the time effects as described by Amundsen et al. (2008) [2]. Magnetic particles which are free to move tend to align themselves in the opposite direction of an external magnetic field and by this cancelling the field.

Amundsen et al. (2008) [2] also conducted experiments with WBM where magnetite powder was divided into fine fractions and course fractions to investigate if the size of the magnetic particles had any influence on the magnetic shielding. A xanthan gum WBM was used as drilling fluid as this fluid is non-magnetic and would not affect the results. Magnetite was added as magnetic additive as it is chemically stable. It was anticipated, from this setup, that the courser particles would precipitate and align faster in the drilling fluid compared to the finer particles. Figure 4 shows the results from the experiments.

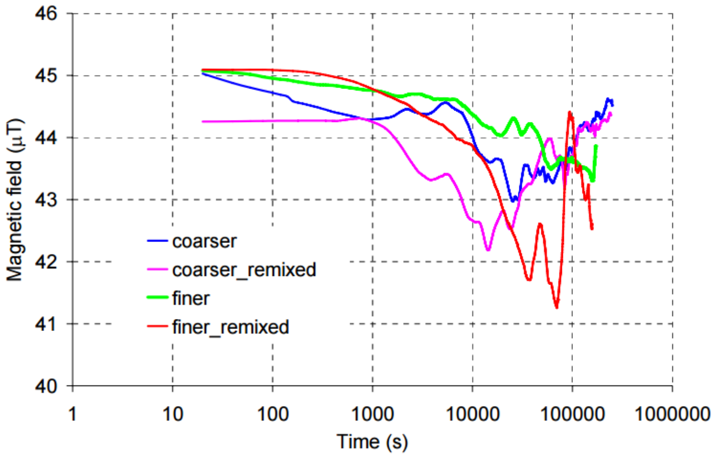


Figure 4: Time dependence of the magnetic field measured in particle suspensions with a magnetite concentration of 2.67% by weight with different particle size distributions [2].

As shown in Figure 4, the coarser magnetic particles give a more pronounced rise in the magnetic field after reaching its minimum value compared to the finer particles. These results agree well to the statement claiming that the large particles precipitate first from the drilling fluid. The finer particles show a time dependency were the magnetic field is dampened with time. This is also in good agreement with theory. Viscous forces are the dominating forces within the drilling fluid and will hinder alignment of both course and fine particles. The fine particles is however the particles that experiences the largest effect [2].

2.3.3 Oil based drilling fluids

Oil based drilling fluids (OBM) are a common used drilling fluid to drill the lower sections at the Norwegian Continental Shelf (NCS). OBM consists mainly of oil as the continuous phase, saltwater (from 0.1 – 50%), emulsifiers, organic clay, polymers and weight materials. All the mentioned ingredients need to be present to have a functioning OBM. The added clay and weight materials are the most decisive factors affecting the magnetic shielding of the Measurement While Drilling (MWD) directional tool. In oil based drilling fluids, organophilic clays are often used as they are oil dispersible. To make the clay oil dispersible, the clay is treated with oil-wetting agents during manufacturing [15]. Work done by Tellefsen (2012) [16], showed that freshly mixed oil based drilling fluid has little or no shielding effect on the Earth’s magnetic field. Based on the result, it was concluded that oil based drilling fluid additives such as organophilic hectorite clay Carbogel (Carbogel may also be made by other organophilic clays), had a negligible effect on the magnetic field as the synthetically made hectorite clay has little or no ferrous components.

An experiment where 1.5 kg of magnetic contaminants was added to a 10-liter sample of oil based drilling fluid was also conducted by Tellefsen et al. (2012) [5]. The result showed a 25% reduction in the measured magnetic field. This proved that magnetic contaminants, collected from the well, are capable of dampening the magnetic field of the Earth significantly. It is important to notice that the relationship between swarf and drilling fluid is not a realistic phenomenon in actual drilling operations. Figure 5 shows the actual dampening effect caused by the magnetic waste contaminants when added to the drilling fluid.

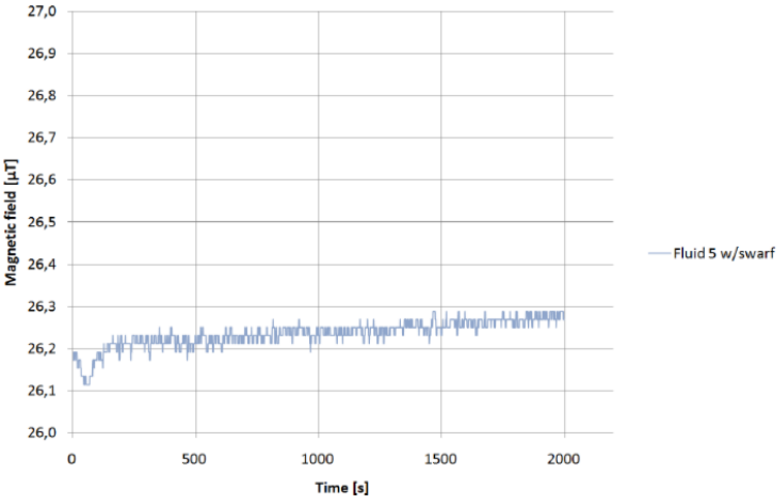


Figure 5: Magnetic field strength as a function of time for an oil-based fluid with swarf [16].

As the magnetic waste was added to the drilling fluid, an instant decrease in the magnetic field strength was seen before the strength slowly increased again. This trend could indicate that the magnetic waste particles precipitate from the drilling fluid and onto the bottom of the bucket as time goes.

Tellefsen (2011) [16] also investigated if used oil based drilling fluids had a larger dampening effect on the magnetic field. Experiments showed that the used drilling fluid had a slightly larger dampening effect compared to the fresh drilling fluids, but the effect was almost negligible. The results from the experiments carried out with the used drilling fluid are however highly unreliable as the used drilling fluid had been filtrated and cleaned before it was tested. Torkildsen et al. (2004) [9] found that used drilling fluids had higher magnetic susceptibility values than fresh drilling fluids. Based on results from these two experiments, it is anticipated that used drilling fluids have a larger dampening effect than new drilling fluids.

Cleaning and filtrating processes of the drilling fluid are not very accurate and strict at the drilling rigs. Foremost, OBM only gets cleaned and processed by the shale shakers and the ditch magnets before it re-enters the active mud pits and is circulated down into the well again. Only when a wellbore is drilled with an inappropriate drilling fluid and the wellbore conditions changes, a “new” drilling fluid is used. This “new” drilling fluid may have been used earlier. The “old” OBM is then pumped from the rig and onto a supply boat which in return, pumps “fresh” drilling fluid over to the rig. Used OBM is then transported back to shore for further processing. Onshore processing facilities remove any drill cuttings and debris left in the drilling fluid and make the fluid ready to be re-used. The “new” fluid is always made based on the operator’s specifications. If the drilling fluid is heavily contaminated, it will be treated as slop and not re-used. There are however no routines or methods onshore which clean the drilling fluid (which is going to be re-used) of magnetic waste contaminants [17]. It is anticipated that the smallest magnetic particles, which are not extracted by the ditch magnets, will still be a part of the drilling fluid as it is shipped from shore and back to the drilling rig after treatment. Based on experiments done by Torkildsen et al. (2004) [9] and Amundsen et al. (2008) [2], re-mixed (re-used) drilling fluids tends to shield the magnetic field of the Earth in a bigger way than fresh drilling fluids. In real time operations, the effect from not having the drilling fluid treated/cleaned by magnets onshore is anticipated to cause a significant increase in the total amount of magnetic contaminants in the drilling fluid as the fluid initially contains metallic particles when the drilling operation starts. Especially while drilling the reservoir sections where the accuracy of the directional drilling tools are most important, magnetic contaminated drilling fluids may prevent the directional driller (DD) from hitting the target.

2.4 Ditch magnets

As described in chapter 2.2, magnetic shielding of the Measurement While Drilling (MWD) directional tool is a known problem in the oil industry. To reduce, or eliminate the problem, the only solution (so far) is to remove the metallic waste material from the drilling fluid to ensure a low concentration of magnetic material. Different solutions to remove the metallic particles from the drilling fluid are available, but due to cost, rig space and easy handling, the ditch magnet is most commonly used today.

Ditch magnets are strong and powerful magnets placed in the flowline, upstream or downstream of the shale shakers. The main function of the ditch magnet is to extract magnetic waste particles from the drilling fluid and thereby prevent the particles from re-entering the drilling fluid return system. In conventional drilling, the drilling fluid is pumped from the mud pits, where the drilling fluid is stored when not used, and down into the well through the stand pipe. The drilling fluid is then circulated down the drill string, out through the drill bit, up the annulus and returns on the rig through the flowline, past the ditch magnets and through the shale shakers. Cleaned mud then returns to the mud pits before it is re-used and pumped back down into the well. As the drilling fluid is re-used and re-circulated, the drilling fluid tends to change its behavior as it slowly gets contaminated by drill cuttings, metallic wear products and other debris from the well. The shale shaker and ditch magnets are placed in the mud-return system to help get rid of this problem. Cuttings, debris and other large non-magnetic particles produced from the drilling operation are mainly removed by the shale shakers while magnetic particles are removed by ditch magnets installed upstream or downstream of the shale shakers. In theory, the ditch magnets are supposed to remove all the magnetic bi-products produced from the well and thereby obtain a clean drilling fluid with as few contaminants as possible. In order to solve the challenge, different vendors producing ditch magnets has tried to come up with different designs and solutions in order to have the most efficient system.

2.4.1 Block ditch magnets

One of the commonly used ditch magnets on drilling rigs/ships are the block ditch magnets constructed like a beam. The magnets are placed in the bottom of the flow line, either upstream or downstream of the shale shaker. The magnets may be placed in different locations, but the amount of magnetic particles collected by the magnets will be different based on the location. If the ditch magnets are placed upstream of the shale shakers, the largest quantities of metallic particles (in the fluid) are extracted from the drilling fluid before the particles reach the shale shaker.

On the other hand, if the magnets are placed downstream of the shale shakers, the largest metallic particles will first be separated by the shaker screens and then the finest particles that manage to pass through the screens, will continue to travel along with the drilling fluid until they are extracted by the ditch magnets downstream of the shale shakers. Figure 6 shows the design of a typical block ditch magnet.

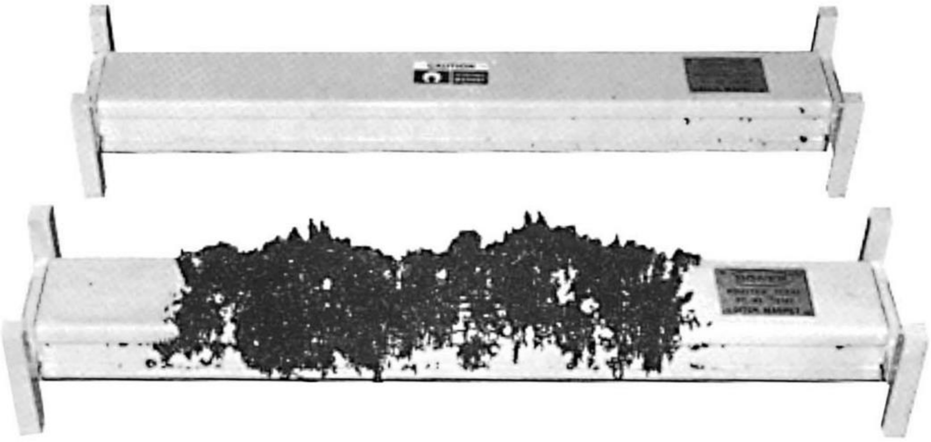


Figure 6: Bowen ditch magnet" from National Oilwell Varco (NOV) [18].

The block ditch magnet shown in Figure 6 is primarily used when removing magnetic waste from the drilling fluid during milling operations. When milling the casing, in order to make path for a sidetrack, large amounts of swarf and metallic wear products are produced. During milling operations, the magnetic particles tend to be quite large and easy to extract from the drilling fluid. Larger particles have a higher capability to stick to the magnets due to the large mass to surface area of the particles. Smaller particles will also be removed by the block ditch magnet, but due to the size of the particles (1-500 µm) and the placement of the magnet (in the bottom of the flowline), only the particles closest to the block ditch magnet are extracted. Metallic particles contained in the drilling fluid flowing above the block ditch magnet are not extracted by the magnet due to the distance between the magnet and particles, the strength of the magnet itself and due to the hydrodynamic forces within the drilling fluid. As a result, all drilling fluid that flows a certain distance above the magnet will still contain large amounts of magnetic particles after passing the magnet. The block ditch magnet is therefore not considered to be optimal to use in order to remove the smaller magnetic particles from the drilling fluid.

In order to remove the magnet from the flowline, it must be lifted from the flowline and onto the ground before it may be cleaned. This process is time consuming, requires heavy lifting from the offshore personnel and a fresh or salt water hose need to be available to get rid of all the metallic particles from the magnet. In daily operation, where the magnets are cleaned up to 4 times a day, time and crew capacity are factors that contribute to decide how often and how properly the magnets are cleaned.

2.4.2 “Stick” ditch magnets

Another group of ditch magnets is the “stick” ditch magnet. This type of magnet is constructed like a magnetic stick/rod, and designed to be placed vertically down into the flowline. When the magnets are placed vertically down into the flowline with a number of magnetic rods set up in the horizontal direction, the coverage area of the magnets are maximized and the main part of the drilling fluid flow is exposed to the magnetic forces of the magnets. The efficiency of the magnets, and the total amount of magnetic particles extracted from the drilling fluid, is anticipated to increase as an effect of this design when compared to the block ditch magnet. More flow is exposed to the magnetic field from the magnets and a higher number of magnetic particles is then extracted from the drilling fluid. Figure 7 shows a typical “stick” ditch magnet solution were separate magnet rods are placed down into the flowline.

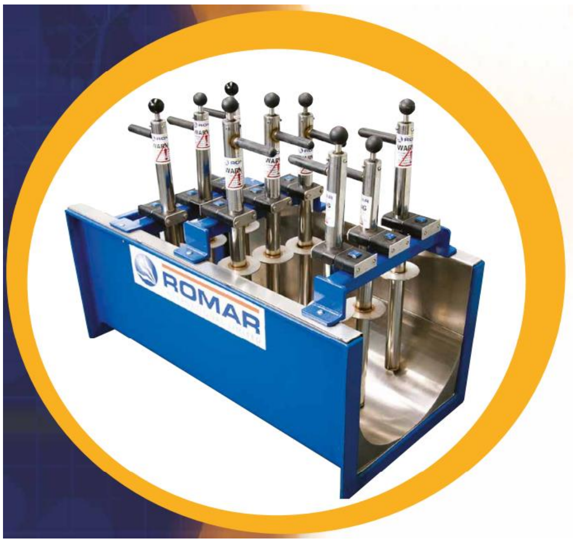


Figure 7: Romar International ditch magnet system, EZ-Clean ditch magnet [19].

Different factors contribute to determine the amount of magnetic material extracted from the drilling fluid. The strength of the magnets and the flow pattern of the drilling fluid through the magnets are important parameters. Magnetic attraction forces from the magnets (measured in Gauss, G. 1 Tesla = 10000 G) less than the viscous forces from the drilling fluid has restricted capability to extract all the magnetic material from the drilling fluid. The hydrodynamic forces tend to overcome the attraction force from the magnets and pulls the magnetic fines back into the fluid flow. The magnets also decrease in strength when moving away from the magnet surface. Closest to the magnet rod, the magnetic strength is highest and decreases for every millimeter when moving away from the magnet surface. At some point, the magnetic field lines from two or more magnets, superpose each other and ensures that the area between the magnets is covered. The magnetic strength of the field does not increase in this area, but the superpose effect helps the magnets to extract a larger volume of metallic particles from the drilling fluid.

Flow regime is also anticipated to affect the efficiency of the magnets. Laminar flow regime ($Re < 4000$) close to the magnet is anticipated to expose less drilling fluid to the magnet surface and reduce the possibility for having the particles extracted from the drilling fluid. Turbulent flow regime ($Re > 4000$) close to the magnets is anticipated to expose more of the magnetic particles to the magnet surface. From this, more magnetic particles is anticipated to be extracted from the drilling fluid as the magnetic field is strongest at the surface of the magnet.

2.4.2.1 EZ-Clean ditch magnet

The “stick” ditch magnets are fabricated in various designs and has different operating mechanisms depending on the vendor producing the magnet. Figure 7 shows Romar’s EZ-Clean ditch magnet solution which is a typical “stick” ditch magnet solution where all magnets are separately placed in a frame connected to the flowline. Each magnet rod is placed inside a non-magnetic metal tube, making it easy to remove the magnet and clean the tube. When magnetic waste material flows past the magnets, the material sticks to the non-magnetic tube due to the magnet inside. The magnet rod is then removed from the non-magnetic metal tube and the magnetic particles attached to the tube should fall off. Due to the sticky properties of the drilling fluid, the magnetic particles need to be scraped off using gloves. Figure 8 demonstrates how the magnets are cleaned at the semi-submersible drilling rig.

Figure 8: Cleaning of EZ-Clean ditch magnet. Picture taken at the semi-submersible drilling rig.

Every magnet can be removed separately from the frame when cleaned, making it simple for the operator to clean and handle the magnets as no heavy lifting is required. Each drilling rig also have its own setup of magnets due to space restrictions and geometry of the flowlines [20]. Figure 9 shows a typical setup of the EZ-Clean ditch magnet solution with three frames placed in the flowline with a total of ten magnet rods.

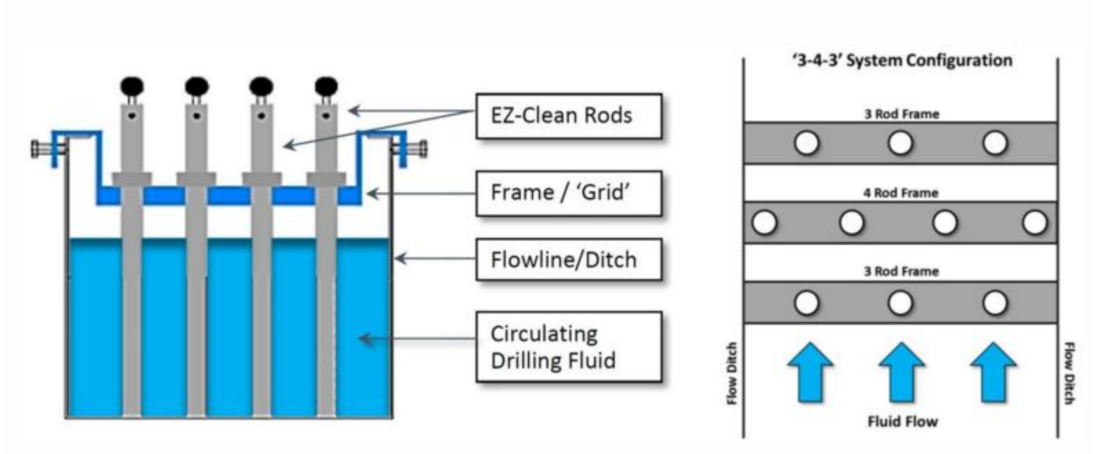


Figure 9: Typical setup of the EZ-Clean ditch magnet system [20].

2.4.2.2 Magnogrid ditch magnet

A second ditch magnet solution, also delivered by Romar International, is the Magnogrid. The Magnogrid ditch magnet tool is quite similar to the EZ-Clean ditch magnet, but all the magnet rods are suspended from one common frame as one unit. Each Magnogrid are designed specifically for each different flowline to ensure maximum coverage with the magnets. Often, two – three frames are used in combination to achieve maximum coverage [21]. When the magnets are cleaned, the whole frame is removed, including the magnets, before the magnetic waste is scraped and washed off. This is done by hand by the personnel handling the magnets. After washing, the Magnogrid is placed back into the flowline. Figure 10 shows a typical Magnogrid ditch magnet design.

Figure 10: Magnogrid ditch magnet solution from Romar International [21].

2.4.2.3 Magnetic Mud Filter™ ditch magnet

Another "stick" ditch magnet solution is the Magnetic Mud Filter™ developed by Innovar Solutions AS. Innovar's design is based on having separate ditch magnets mounted/welded to a plate which is placed in the bottom of the flowline. The plate and the magnets are permanently attached to the flowline. To collect the magnetic waste particles from the drilling fluid, an easily exchangeable filter bag is used. The filter bag covers the magnets and magnetic waste particles are extracted from the drilling fluid by the ditch magnets inside the filter bag. The bag functions as a filter and increases the exposure area of the magnets in order to extract even more particles from the drilling fluid. When the filter bags are full, the magnets are easily cleaned by removing the used exchangeable filter bags and new filter bags are installed on the cleaned magnet. When the magnets are cleaned, there should be no flow in the flowline to prevent magnetic particles from attaching to the ditch magnets while the filter is not installed. Figure 11 and 12 shows the Magnetic Mud Filter™ installed in the flowline and how magnetic particles attaches to the magnets.

Figure 11:Magnetic Mud Filter™ installation *[22]*.

Figure 12: Magnetic Mud Filter™ installation *[22]*.

2.4.3 Sapeg`s ditch magnet (Patent Pending)

A fourth "stick" ditch magnet solution is the Magnetic Active Particle Separator (M.A.P.S) developed by Sapeg AS. Sapeg's design consists of a metal frame which hosts an optional number of extractable magnet rods. The magnets are made of neodymium paramagnets covered and sealed into a stainless steel tube, making the magnets highly corrosion and wear resistant. There are simply no magnetic obstructions between the magnets and the drilling fluid which reduces the strength of the magnets. At the top of each magnet rod, a waste scraper is installed and designed to be used when the magnetic waste material shall be removed from the magnetic rods. At the bottom of each magnetic rod, a non-magnetic area of some centimeters is present to be able to remove the magnetic waste from the magnets. As the scraper is dragged down towards the non-magnetic area, the waste material below the scraper plate will fall off and into a sample/waste bucket. After removing all the magnetic waste from the magnet, the scraper plate is pulled back into its original position and the magnet rod is placed back into its frame in the flowline. Figure 13 and 14 shows how a saturated magnet is cleaned using the waste scraper.

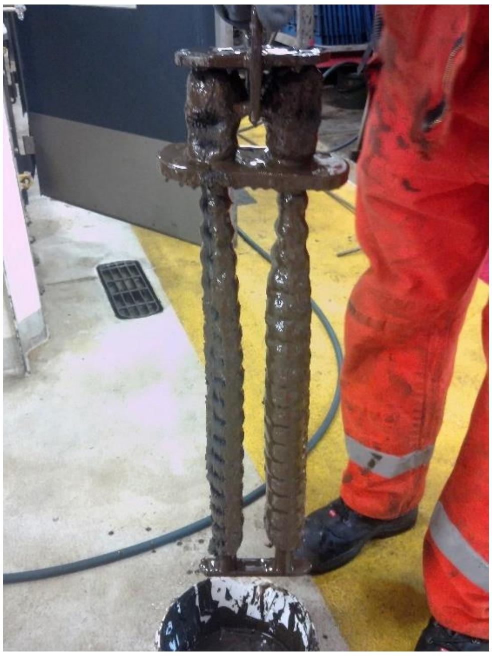


Figure 13: Saturated M.A.P.S ditch magnet rod. Picture taken offshore at the jack-up drilling rig.

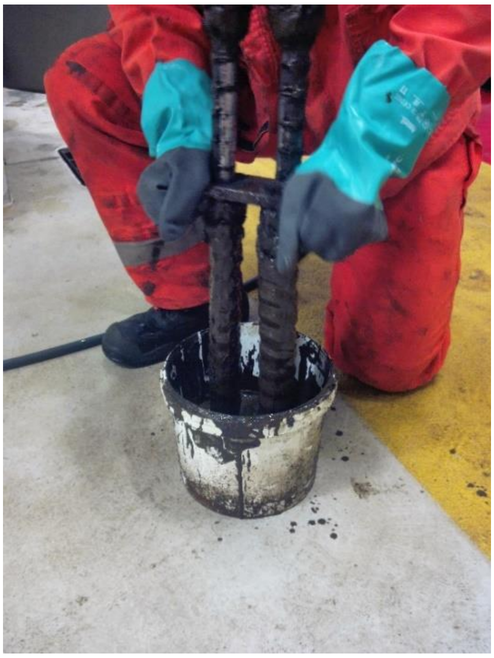


Figure 14: Cleaning of a saturated ditch magnet using the waste scraper. Picture taken offshore at the jack-up drilling rig.

The total number of magnets and number of frames installed in the flowline depends on the customer, and the magnet frame is customized to every single flowline. It is absolutely essential to have the possibility of having a customized flowline solution for the ditch magnet as there is no standard design for flowlines. This opportunity is also necessary in order to optimize the grid setup for each flowline and enhance the exposure level of the magnetic contaminated drilling fluid. The grid setup is carefully chosen as the flow pattern between the magnets is important in order to expose as much drilling fluid to the magnets as possible. Figure 15 shows a typical grid setup with a total of four magnet rows. This setup is designed to guide the fluid flow through the magnet grid in the best possible way, leaving no drilling fluid unexposed to the strong magnetic field.

Upstream and downstream of each magnet rod, a spoiler is placed in order to create turbulence in the region nearby the magnet's surface. The spoilers "break" off the fluid flow and increases the likelihood of having all the magnetic waste particles inside the drilling fluid exposed to the magnetic field from the magnets. Figure 15 shows a typical flow pattern with and without spoilers (in front of and behind the magnets) and how the magnet grid setup can be.

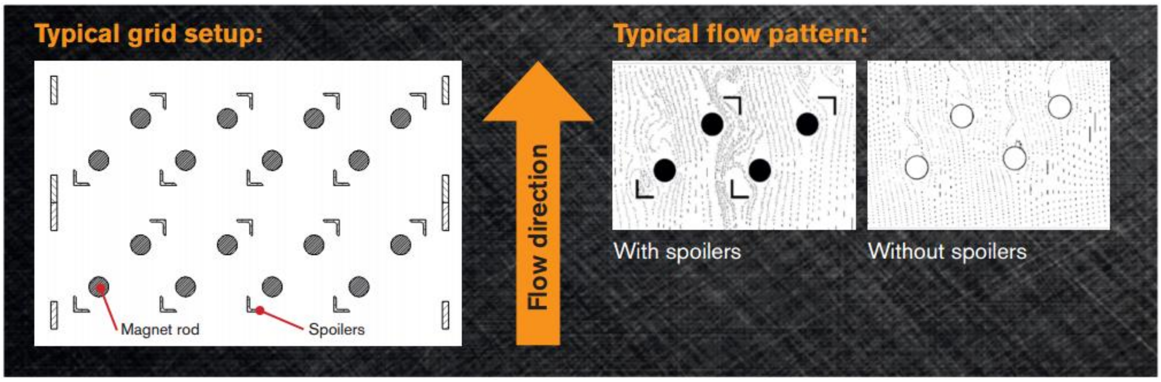


Figure 15: Typical magnetic grid setup and flow pattern with and without spoilers [23]. (Patent pending)

The flow simulation (in Figure 15, right hand side) clearly shows the difference with and without spoilers. With spoilers, the flow experiences a significant increase in turbulence in the region nearby the magnets. Without spoilers, the flow is not disturbed and turbulence flow is not present.

As described in chapter 2.4.2, the magnetic field strength is strongest at the surface of the magnets and decreases with every millimeter when moving away from the surface of the magnet. Direct contact between the drilling fluid and the stainless steel tube surface is crucial in order to accomplish a best possible extraction of magnetic particles from the drilling fluid. Figures 16 and 17 shows the magnetic field lines of M.A.P.S and how the strength of the magnets decreases as a function of distance.

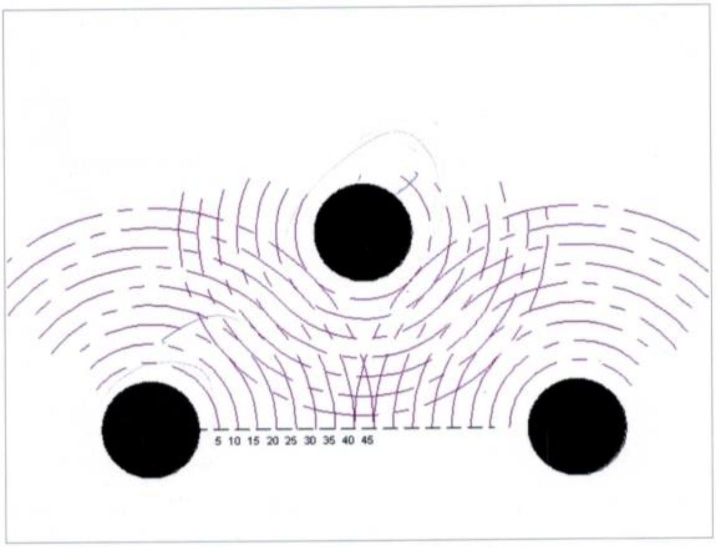


Figure 16: Magnetic field lines from simulation of the M.A.P.S ditch magnets. Picture provided by Sapeg AS.

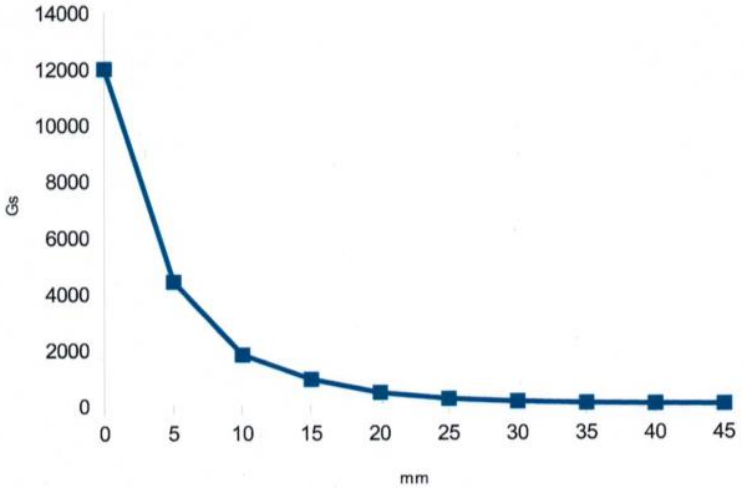


Figure 17: Magnetic field strength as a function of distance. Picture provided by Sapeg AS.

As seen from Figures 16 and 17, the magnetic field strength decreases drastically from the surface of the magnet to about 10 millimeters away from the magnet. The total drop is approximately 7500 gauss. From the 10 millimeter point and out to 45 millimeters the strength almost decreases to 0 gauss. The magnets are almost useless at a distance of 45 millimeters from the surface of the magnet. As the grid setup is based on having the field lines superimposing each other, the lowest magnetic field strength from the magnets inside the grid would be approximately 500 gauss at a distance of 25 millimeters from all the magnets. Based on the magnet grid setup, it is anticipated that no magnetic particles manage to travel between the magnets without (at worst) being exposed to a field strength larger than 500 Gauss. The spoilers in front of the magnets also help to “force” the smaller magnetic particles out from their original position (e.g. inside a gel structure) and expose them to a higher magnetic field than 500 Gauss.

2.4.4 Procedures for handling the ditch magnets offshore

Drilling rigs have different procedures for treating and handling the ditch magnets. This could be due to space restriction, placement of the magnets, and the magnet system itself. Different procedures for how the magnetic waste is treated and weighted are also developed individually at each rig as no mutual procedure has yet been developed. The two drilling rigs that were used in this study were a semi-submersible drilling rig and a jack-up rig, both operated by Det Norske Oljeselskap ASA.

On the semi-submersible drilling unit, the EZ-Clean ditch magnet solution is installed. The magnet system is placed in the header box upstream of the shale shakers where the flowline outlet is located. Just after the flowline outlet, the header box splits into two comparable flowlines and distributes the fluid flow onto the four shale shakers. One set of magnets is placed in each header box outlet in order to cover the fluid flow before it enters the shakers. The EZ-Clean ditch magnets at the semi-submersible drilling rig have a short region of approximately 30 centimeters which is magnetic, making the magnets susceptible to overflow. While drilling is commenced with flowrates ranging from 1500-3500 lpm, the magnets have no problems with overflow. If the flowrates are increased to 3500-4800 lpm, the fluid level in the header box increases and the magnets experience overflow. Large amounts of drilling fluid then flow straight past the magnets without being exposed to the magnetic field. Also, as seen from Figure 18, the magnets placed on the right side of the flowline outlet is not able to cover the entire fluid flow due to the width of the header box and the lack of extra magnet rods. In order to cover the entire fluid flow, a total of 6 magnets or more should be installed. As a consequence, (based on the above mentioned problems) less magnetic waste particles are extracted from the drilling fluid and a magnetic drilling fluid is obtained.

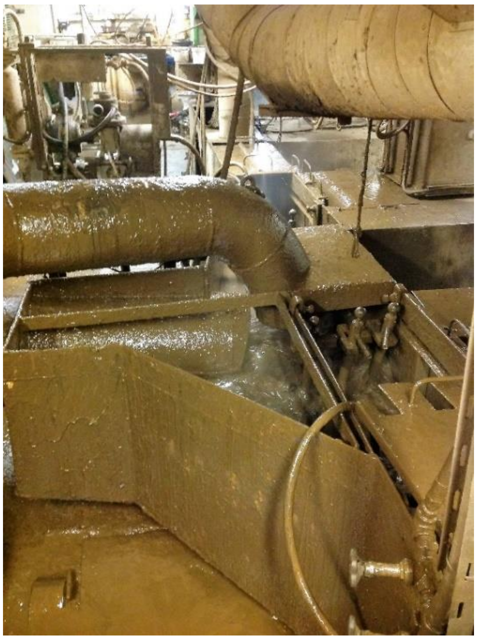


Figure 18: Header box geometry on the right side of the flowline outlet at the semi-submersible drilling rig.

Next to the flowline outlet, air is blown into the drilling fluid to prevent drill cuttings and metallic waste particles to precipitate and accumulate in the bottom of the header box. The air flow also ensures turbulence in the area around the magnets and ensures that large amounts of drilling fluid is exposed to the magnets. Figure 19 shows the turbulent flow regime created by the air blower and the placement of the three magnets (two magnets is shown).

Figure 19: Header box at the semi-submersible drilling rig showing the turbulent flow created by the air blower.

The cleaning routines of the magnets at the semi-submersible drilling unit is normally once every sixth hour. In special cases, where a cement plug or kick-off plug is drilled, the magnets are cleaned every third hour. This ensures that the magnets are clean at all times and not saturated with magnetic waste. The roughnecks are the ones responsible for cleaning the magnets. During each cleaning, the magnetic waste is dumped into a sample bucket and handed over to the sample catcher. The sample catcher is the person responsible for weighing the magnetic material collected from the well. At first, the sample is discharged into a sieve with a mesh size of 2 millimeters and placed on the shaker to get rid of the smallest particles and the drilling fluid leftovers. After this, the sample is washed with base-oil (if oil based drilling fluids are used) to remove the rest of the drilling fluid leftovers and the smaller particles which are less than 2 millimeters. In the end, the remaining particles represent the total amount of magnetic waste collected from the given clean-up.

At the jack-up rig, the Magnetic Active Particle Separator (M.A.P.S) is installed. The M.A.P.S system is installed in the flowline upstream of the shale shakers. At this rig, the drilling fluid arrives in one mutual flowline and does not split before it hits the ditch magnets, leaving the entire fluid flow to be processed by the M.A.P.S setup. The magnets have the same configuration as the one shown in Figure 15, consisting of a total of 16 single magnet rods divided on two frames standing next to each other. Recently, only six magnet rods have been used (Oct. 2015 – April 2016) due to problems related to cutting accumulation downstream of the magnets. The configuration with six magnets obviously affects the performance of M.A.P.S and the total amount of magnetic contaminants extracted from the drilling fluid.

Due to the total number of magnets installed in the flowline when using M.A.P.S, an analysis was done (by Fedem Technology AS) to anticipate the likelihood of having the fluid flow exceed its maximum allowable level in the flowline. Based on the simulations, no overflow problems were observed as the maximum increase in upstream height was recorded to be 0.56 millimeters which is considered to be a very small change in fluid height. The Bernoulli equation was applied to determine the increase in upstream fluid level using a drilling fluid with density 1.3 [sg], viscosity 0.091 [Pa s] and a flowrate of 4500 lpm. Figure 20 shows the results from the flow simulations. The specific velocities of the drilling fluid in the different areas around the magnets are also described where blue color represents low fluid velocity and red color represent high fluid velocity.

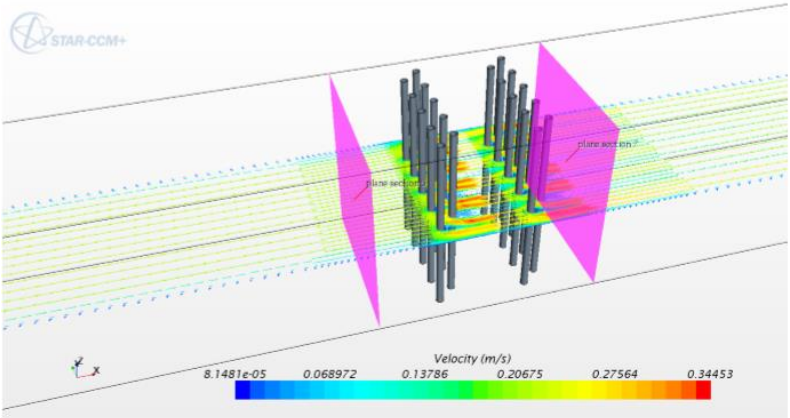


Figure 20: Velocity vectors and vertical planes from the Fedem Technology simulation [24].

The flow pattern in between the magnets is predominantly laminar as the flowline hits the magnets head on. On the other hand, the spoilers installed in front of the magnet rods, break off the laminar flow and creates turbulence around the magnets and help forcing the magnetic particles out from the drilling fluid (see Section 2.4.3 and figure 15 for demonstration of the spoilers). This is anticipated to have a positive effect in the manner of exposing more magnetic particles to the magnetic forces of the magnets.

The magnets are cleaned at six hour intervals, having a total of four ditch magnet cleanups per day. At the jack-up rig, the roughnecks are the ones responsible for having the ditch magnets cleaned at the given time (same as for the semi-submersible drilling rig). The magnetic waste is removed from the magnets with the waste scraper as described in chapter 2.4.3, and then dumped into a sample bucket which is handed over to the sample catcher. At each shift, the sample catcher weighs the bucket after each clean-up and documents the total amount of magnetic material collected. No treatment of the magnetic waste is done before the total weight is noted. At the end, the total weight of the collected magnetic waste includes both the weight of the drilling fluid which sticks to the waste, the bucket and the magnetic waste particles. The main reason for not cleaning the ditch magnet sample at the jack-up drilling rig was the possibility of having the finest magnetic waste washed out from the sample and not included in the total weight.

2.5 Other swarf extraction solutions

Romar International has developed the Swarf Handling System for magnetic waste handling. The Swarf Handling System is a large unit, installed on the rig site as a separate installation, and used to separate magnetic waste particles from the drilling fluid. The system consists of a "scalping" unit which is located just in front of the flow trench where the drilling fluid enters the system. Large non-magnetic and magnetic particles is separated from the rest of the drilling fluid by use of a course grid at the inlet of the "scalping" unit. Separated fluid then travels down into the flow trench where the drilling fluid is exposed to the "Magnoveyor". The "Magnoveyor" unit consists of several pipe-loops with strong movable magnets inside. The pipe-loops are partially submerged down into the flow trench to ensure contact with the drilling fluid. Inside the pipe-loop, the magnets are attached to each other in one continuous chain and constantly circulates around in the loop. When the magnets are immersed down into the drilling fluid, the magnetic waste particles attach to the magnets and travel along the "Magnoveyor" towards an enclosure face plate where the magnetic particles fall off and into a chute. From the chute, the particles are discharged into a skip for further processing. In between the magnets, some non-magnetic areas are installed to make sure the magnetic waste will detach from the magnets when they reach the enclosure face plate. Figure 21 shows the chain link rotation and the enclosure face plate:

Figure 21: Chain link rotation and enclosure face plate [25]

After the Magnoveyor, the drilling fluid flows through the EZ-Clean ditch magnets for a final "polish". The EZ-Clean ditch magnets are placed in the flow trench to make sure the drilling fluid is free of magnetic waste particles before the drilling fluid enters the shakers and goes back into the system [25]. Figure 22 shows the Swarf Handling System and its main components.

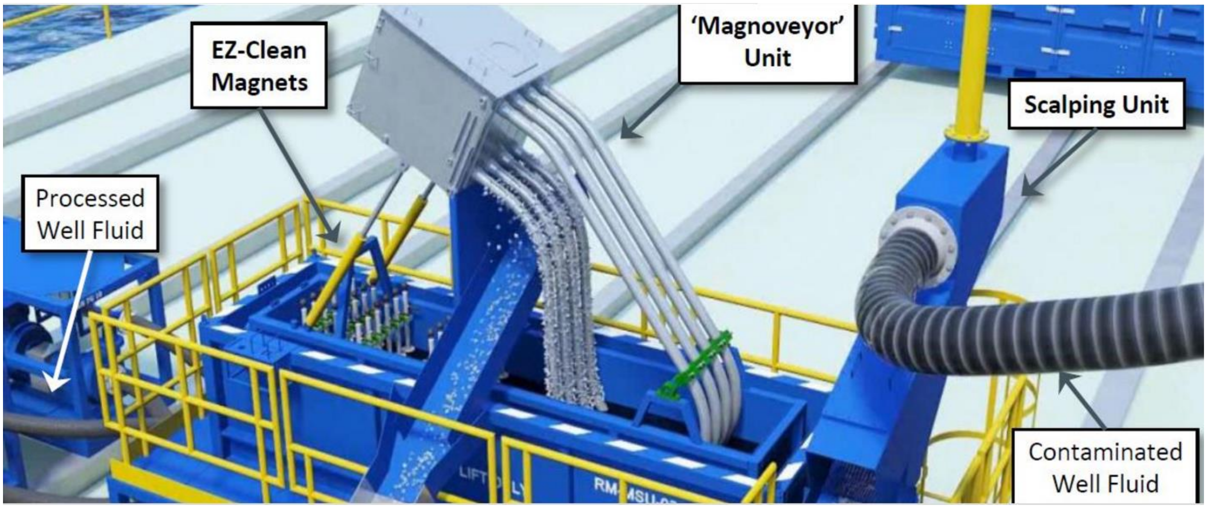


Figure 22: Swarf Handling System by Romar International [25].

2.6 Material extracted from the drilling fluid by the ditch magnets

The location of the magnets, their field strength, currents in the specific area and the configuration of the magnets are all parameters that affects what material that is extracted from the drilling fluid by the ditch magnets. Some ditch magnets are placed upstream of the shale shakers and other, downstream of the shale shakers. The location of the magnets plays a large role in determining which particles they manage to collect. When the magnets are placed in front of the shale shakers, all sorts and sizes of magnetic waste are collected. The magnets then work as a "filter" before the drilling fluid is processed further by the shale shakers. Magnets placed downstream of the shale shakers is anticipated to collect more of the fine magnetic particles as all the larger particles already have been removed by the shale shakers (depending on the mesh size of the screens). On most of the drilling rigs, it is challenging to have the ditch magnets placed downstream of the shale shakers due to the lack of space and accessibility to the flowline.

The material extracted from the ditch magnets tends to contain large amounts of drilling fluid additives and not only magnetic particles. As more and more magnetic particles are attached to the magnets, the particles tend to create a "sieve" which collects both magnetic and non-magnetic particles. By having this "sieve", drilling fluid additives and other non-magnetic particles also become a part of the material extracted by the ditch magnets. Figure 23 and 24 show pictures of two ditch magnet samples taken offshore which includes the drilling fluid. Both ditch magnets are placed upstream of the shale shakers but has removed different sizes of particles. The magnetic material in Figure 23 is hard to observe as the magnetic particles seem to have the same size and color as the drilled cuttings and additives. From Figure 24, the magnetic material is quite easy to locate as the pieces are very big (0.005 – 3cm). Figure 25 shows a picture of the same sample as shown in Figure 24 after it has been washed with base oil and then sieved with a mesh size of 2 millimeters to wash out the smallest fines particles. The large particles in the sample was collected while initiating a sidetrack below the casing shoe and is the main reason for the difference in particle size in the two pictures. When sidetracks are initiated, the inclination of the downhole directional tool is quite high and causes large steel particles to be scratched off the lower part of the casing due to erosion.

Figure 23: Magnetic waste taken from M.A.P.S ditch magnet on the jack-up drilling rig.

Figure 24: Ditch magnet sample taken from EZ-Clean ditch magnet at the semi-submersible drilling rig.

Figure 25: Ditch magnet sample from the semi-submersible drilling rig cleaned with base oil and sieved with a 2mm mesh size.

2.7 Flow pattern

The flow pattern through the ditch magnets is anticipated to have a considerable effect on the total amount of magnetic waste particles extracted from the drilling fluid. In most cases, the flow pattern through the magnets is rectilinear due to high flow rates during drilling and narrow flow lines. When the flow regime next to the magnets is laminar, the velocity of the fluid and the velocity of the magnetic contaminants suspended in the drilling fluid, increases. The viscous forces within the drilling fluid, in combination with the high velocities of the particles, makes it challenging for the ditch magnets to clean the drilling fluid properly for magnetic fines. To catch the finest particles, the magnets need to be extremely strong as the magnetic forces scale with the volume of the particles, while the fluid drag forces scale with the surface area of the particles [3]. For the smaller particles, the drag forces dominate and move them away from the magnets again. This “linear” flow regime also causes less particles to be exposed to the magnets as no magnetic particles are “forced” out from the fluid. To optimize the quantity of magnetic contaminants exposed to the magnets, it is crucial to “break” the flow and generate large scale turbulence. Turbulent flow creates currents which “forces” the magnetic contaminants out from their gel and flow structures and expose them to the magnets.

2.8 Treatment of drilling fluid after being used

As drilling fluids are used offshore and shipped back to shore for treatment and re-use, no methods are used to remove any magnetic waste leftovers from the drilling fluid. If the drilling fluid is heavily contaminated with cement or other contaminants, the fluid is treated as slop and terminated. Drilling fluids without any contaminants are cleaned and re-used. Before the drilling fluid is sent offshore again, new specs are added to satisfy the wellbore conditions. There are however, no methods onshore which are designed to remove magnetic contamination from the drilling fluid. It is anticipated that “new” drilling fluids arriving offshore, after being treated onshore, may contain large amounts of magnetic waste particles even before drilling starts.

3 Ditch magnet performance

3.1 Field case background

The effects from having a drilling fluid contaminated with magnetic particles are, as previously mentioned, elements that contribute to additional wear of downhole tools, casing/drillstring, mud pumps, and magnetic shielding of the measuring while drilling (MWD) directional tools. Magnetic waste particles inside downhole tools may cause failures in vital bottom hole assembly (BHA) parts and mis-readings from logging tools, causing inadequate logging data, and hence, increased costs and extended drilling time. Mud pumps may experience more frequent breakdowns due to wear of pistons and gaskets caused by friction forces from the magnetic fines and the drillstring/casing is anticipated to experience additional erosion. In order to eliminate the problem, the performance of the ditch magnet is crucial to be able to remove as much magnetic contaminants from the drilling fluid as possible. Wilson and Brooks (2001) [4], Torkildsen et al. (2004) [9], Amundsen et al. (2008) [2], Waag et al. (2012) [26] and Tellefsen et al. (2012) [5], all stated that the only solution so far to diminish the magnetic shielding problems, is to remove the magnetic contaminants from the drilling fluid.

To better understand the importance of the ditch magnet performance and its ability to remove magnetic waste from the drilling fluid, some experiments and one analytical study has been conducted. The total volume of magnetic waste collected from the drilling fluid by the ditch magnets and differences between two systems are evaluated.

Eight wells, drilled by Det Norske Oljeselskap ASA, were used in the analysis. Three of the wells were drilled by a midwater semi-submersible drilling rig, capable of drilling at water depths of 450 meters. This drilling rig had the EZ-Clean ditch magnet system installed. The other rig was a harsh environment jack-up rig, capable of drilling at water depths of 150 m. This rig had the new ditch magnet system, Magnetic Active Particle Separator (M.A.P.S) installed. All eight wells that are used in the investigation are drilled with oil-based drilling fluids, ensuring similar conditions.

3.2 Field sample evaluation

Drilling fluid field samples collected from the two drilling rigs have been analyzed in order to see if there are any measurable differences in the amount of magnetic waste contained in the drilling fluids. One sample is collected upstream and one downstream of the ditch magnets. In order to observe the differences, it was decided to have the density of the drilling fluids measured. The densities have been measured by the use of a TRU-WATE™ Fluid Density Balance weight. Any noticeable difference in the drilling fluid density taken upstream and downstream of the magnets could indicate the performance of the ditch magnets. The density of the drilling fluid is measured and compared to the actual drilling fluid density given in the daily drilling reports (DDR) from the given time.

In order to identify the size of the smallest particles collected from the ditch magnets and the different elements in the particles contained in the drilling fluid, three small field samples have been investigated by the use of a Zeiss Supra VP35 Scanning Electron Microscope (SEM). Two of the samples were taken directly from the ditch magnet waste and prepared for the SEM analysis. The third sample has been extracted from the drilling fluid by having a 50 milliliter sample boiled in a retort. The third sample was investigated to investigate if there were any visible magnetic particles contained in the given drilling fluid sample. The two ditch magnet waste samples were prepared for the SEM analysis by having the samples mixed with base oil in order to remove the largest amount of drilling fluid attached to the particles. After the samples were washed, a magnet rod was used to extract the clean magnetic particles from the samples. The magnetic particles were dried by the use of a simple oven and prepared for the SEM. From the analysis, the composition of elements in the magnetic waste was determined and the size of the particles that were investigated in the samples was determined. The element analysis presents the answer in weight percent and atomic percent. Weight percent represents the weight of the elements in the investigated area and the atomic percent represents the percent of atoms in the investigated area.

3.2.1 Experimental setup, TRU-WATE™ Fluid Density Balance

A TRU-WATE™ Fluid Density Balance weight has been used to measure the density of the drilling fluid. The method minimizes the uncertainty caused by air bubbles in the drilling fluid. Air bubbles contained in the drilling fluid lower the measured density of the drilling fluid and should be removed as far as possible. The setup consists of the TRU-WATE™ Fluid Density Balance arm placed on top of a base. A cup to fill the drilling fluid inside are placed in one end of the arm while a counterweight is placed on the other end. On top of the cup, a lid with gaskets, inlet and a nut is placed. The lid and nut are in place to be able to pressurize the cup. When the cup is pressurized, the volume of potential air inside the drilling fluid test sample is neglected. Pressure is applied using a pump filled with drilling fluid. A rider is used to balance the counterweight and the weight of the cup. When the two are in equilibrium (seen from a level bubble on top), the density can be noted from the rider. The accuracy of the weight was checked in advance of the measurements by measuring the density of known deionized water (1.00 sg). The weight showed a density of 0.999 sg, giving an uncertainty of ± 0.001 sg. Figure 26 show the experimental setup and the different components of the TRU-WATE™ Fluid Density Balance weight.

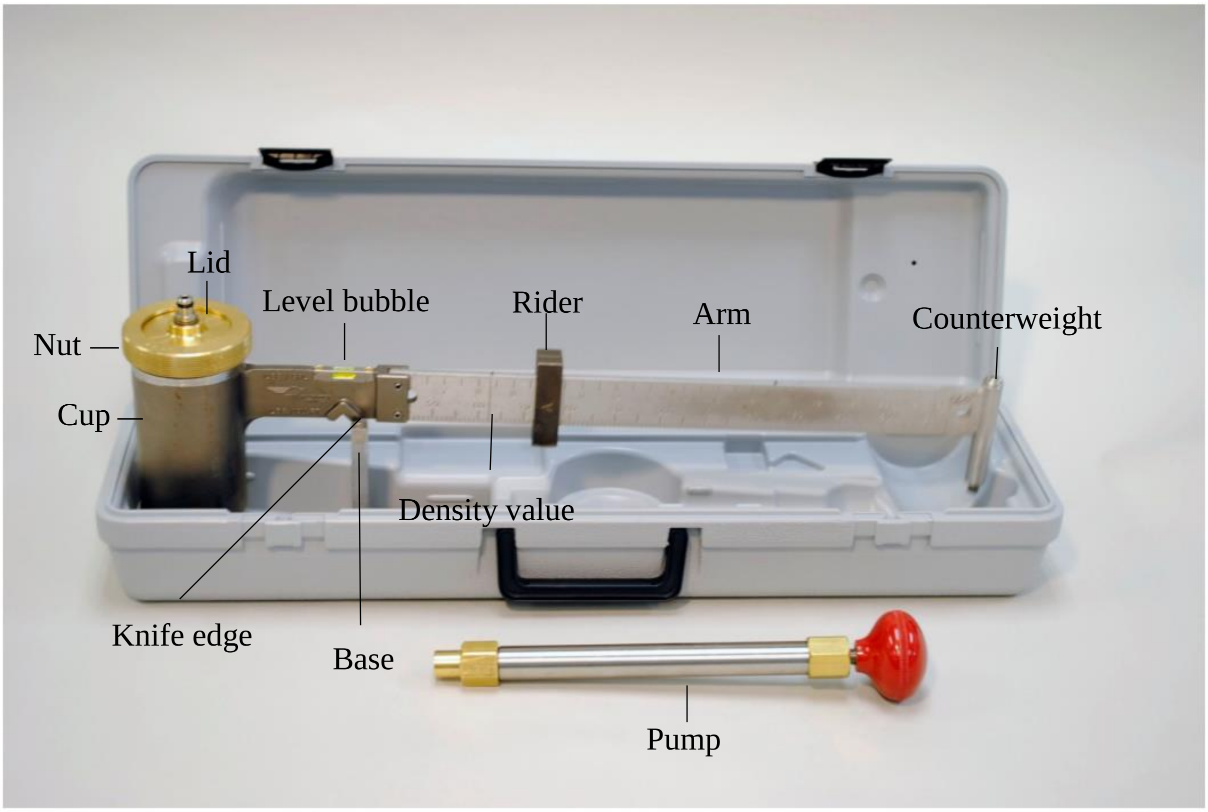


Figure 26: TRU-WATE™ Fluid Density Balance weight and its components [27].

3.2.1.1 Density measurements, jack-up drilling rig

The density upstream and downstream of the ditch magnets are measured by use of the TRU-WATE™ Fluid Density Balance weight. All samples are collected offshore at the given rig and shipped back to shore for testing. One sample upstream and one sample downstream of the ditch magnets are investigated. All density measurements were performed once.

The experiments were conducted by having the samples mixed for 30 seconds inside the 1-liter test bottles in order to achieve a homogenous mixture. Gel structures and settlements in the bottom of the bottle were also removed as far as possible. From the test bottles, the drilling fluid was filled inside the cup shown in Figure 26 and the lid was placed on top and tightened by the use of the nut. All excess fluid was pressed through the top of the lid and removed. In order to neglect the air bubbles in the sample, the pump was filled with drilling fluid, placed on top of the lid and drilling fluid was injected into the cup. The pump was removed after pressurizing the cup. Drilling fluid spill was cleaned and the arm was placed on top of the knife edge. In order to achieve equilibrium, the rider was used to adjust the balance between the counterweight and the cup filled with drilling fluid. Equilibrium condition was showed by the level bubble on top of the arm. The density of the drilling fluid was noted from the values given next to the rider. Table 1 shows the results from the tests that were conducted.

Table 1: Drilling fluid density measurements upstream and downstream of the ditch magnets.

Date of sample	MW from DDR (sg)	Magnetic waste collected (kg)	MW upstream ditch magnets (sg)	MW downstream ditch magnets (sg)
20.03.2016	1.40	18.6	1.441	1.435
21.03.2016	1.40	16	1.42	1.418
22.03.2016	1.40	6	1.421	1.421
23.03.2016	1.40	4.2	1.428	1.428
24.03.2016	1.43	21.6	1.45	1.448

*MW = Mud Weight

From Table 1 it is shown that the measured density of the drilling fluid from the daily drilling reports (DDR) is less than the measured density in the laboratory. This is explained by the effect from the drill cuttings generated while drilling the wellbore. Drill cuttings increase the density of the drilling fluid as more particles are added to the fluid and adds extra weight.

Table 1 also shows the difference in density upstream and downstream of the ditch magnets. From the samples taken 20th, 21st and 24th of March, the density of the drilling fluid is less downstream than upstream of the magnets. This effect could be caused by having the samples taken at different levels in the flowline, increasing/decreasing the content of drill cuttings inside the test sample. There are however no reasons to anticipate that the decrease in density upstream and downstream of the ditch magnets is caused by the removal of magnetic waste from the drilling fluid. As these measurements are taken with the TRU-WATE™ Fluid Density Balance weight, the volume of air inside the sample is negligible. On the other hand, several other uncertainties would affect the results. Mixing time, measurement accuracy from the rider (human error), gel-structures, oil/water content, volume of drilling fluid inside the cup and the content of drill cuttings in each sample are all parameters affecting the final results.

3.2.1.2 Density measurements, semi-submersible drilling rig

As described in chapter 3.2.1, the density measurements upstream and downstream of the ditch magnets are conducted by the use of a TRU-WATE™ Fluid Density Balance weight. The same procedure is used for the test samples from the semi-submersible drilling rig. All samples are collected offshore at the given drilling rig and shipped back to shore for testing. One sample, taken both upstream and downstream of the ditch magnets has been investigated. All density measurements were performed once.

The experiment was conducted by having each sample, contained inside a 1-liter bottle, mixed for 30 seconds to ensure a homogenous mixture. This removed any settlements or gel structures in the sample as far as possible. Each test was done by having the cup in Figure 26 filled with drilling fluid. The lid and nut was then placed on top and tightened. Additional drilling fluid was then injected through the lid by use of a pump to neglect the volume of air bubbles. The arm was then placed on the knife edge and balanced until equilibrium between the cup and counterweight. From the rider, the density of the drilling fluid could be noted. Table 2 shows the results from the experiments.

Table 2: Drilling fluid density measurements upstream and downstream of the ditch magnets.

Date of sample	MW from DDR (sg)	Magnetic waste collected (kg)	MW upstream ditch magnets (sg)	MW downstream ditch magnets (sg)
11.05.2016	1.39	3.64	1.391	1.391
12.05.2016	1.40	3.56	1.40	1.40
13.05.2016	1.40	1.95	1.41	1.41
14.05.2016	1.40	4.2	1.41	1.41
15.05.2016	1.42	1.35	1.42	1.43

*MW = Mud Weight

From Table 2 it is shown that the density given in the daily drilling reports (DDR) is practically identical to the density measured in the laboratory. This observation could be explained from the look of the drilling fluid. While pouring the drilling fluid from the test bottle to the cup, it seemed to contain very small amounts of drill cuttings. The density measurement for the last test (15.05.16, downstream of ditch magnets) shows an increase in density of 0.01 sg compared to the sample taken upstream of the ditch magnet and the given value from the DDR. It is anticipated that the content of drill cuttings in the last sample could be slightly higher, resulting in a higher density.

There are however no indications from this experiment, conducted on the samples taken upstream and downstream of the ditch magnets at the semi-submersible drilling rig, that the ditch magnet performance is possible to verify by the use of density measurements. If there are any noticeable differences in the magnetic waste content, it is not possible to be determined by the use a fluid density weight. It is also seen from Table 2 that the total amount of magnetic waste collected from the ditch magnets is rather small, giving further reasons to anticipate that the ditch magnet performance is impossible to be measured in such an interval. The experiment involved identical uncertainties as those described in section 3.2.1.1.

3.2.2 SEM analysis of drilling fluid material

The drilling fluid sample that was investigated in the Scanning Electron Microscope (SEM) was collected upstream of the Magnetic Active Particle Separator (M.A.P.S) ditch magnets. This was done to ensure that magnetic contaminants still were a part of the investigated sample. From the Zeiss Supra VP35 Scanning Electron Microscope (SEM), it was found that some larger parts of the dry drilling fluid (drilling fluid particles) contained some kind of magnetism. Individual "colonies" of particles were investigated as it was difficult and time consuming to observe any particles that differentiated from one another and that looked "magnetic" (contain iron). The investigated "colonies" are shown with red markings in Figure 27.

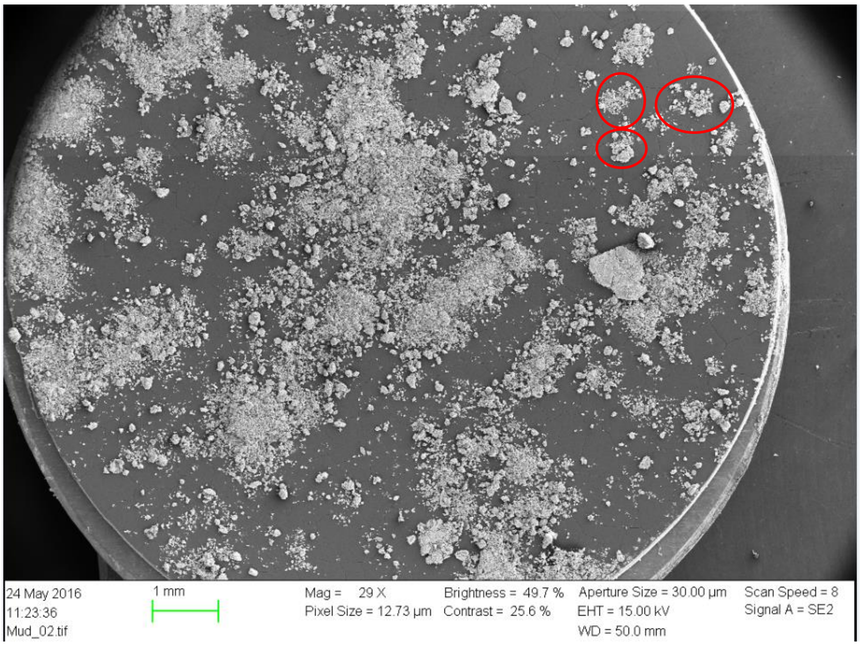


Figure 27: Overview of the particles contained in the drilling fluid.

From the "colonies" shown in Figure 27, a few element analyses were taken of some larger area of the sample in order to see if it was possible to identify single particles that contained iron (Fe). This showed to be difficult as no particles in the pictures implied to be magnetic. No single magnetic particles were found. However, Figure 28 and 29 show a closer look at one of the investigated "colonies" and the element analysis of the particles in the given area. The larger particles in Figure 28 showed themselves to be formation (rock) as they consisted of large amounts of silica.

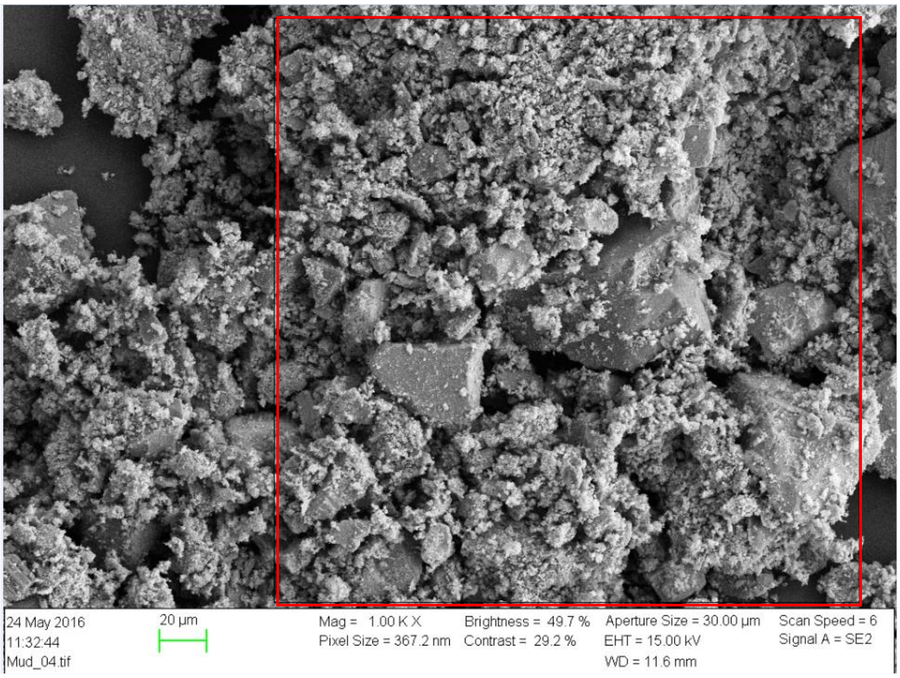
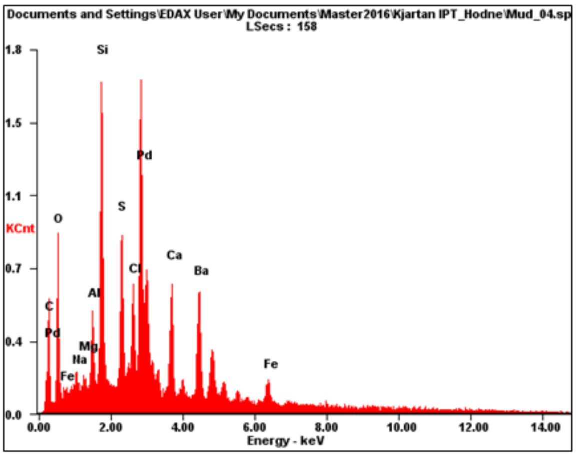


Figure 28: The investigated area of the "colony".



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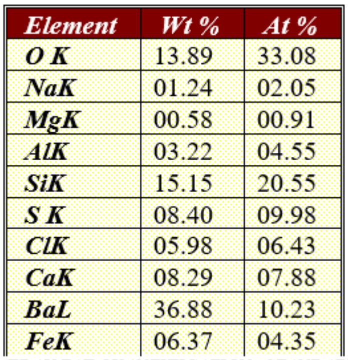

Element	*Wt %*	*At %*
O K	13.89	33.08
NaK	01.24	02.05
MgK	00.58	00.91
AlK	03.22	04.55
SiK	15.15	20.55
S K	08.40	09.98
ClK	05.98	06.43
CaK	08.29	07.88
BaL	36.88	10.23
FeK	06.37	04.35

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Figure 29: Element analysis of the investigated area of the "colony".

The element analysis in Figure 29 show that the investigated area contained large amounts of Barium and Silica (Oxygen is not considered). Barium is commonly used in drilling fluid additives (Barite) and Silica is naturally present in the formation (rock). In addition, some iron (Fe) is detected by the SEM analysis, verifying that the drilling fluid (with additives etc.) might be magnetic. There could, however, be single magnetic particles “hiding” in the sample, causing the detected iron peak in the graph. Some attempts were made in order to detect the magnetic particles without results.

3.2.3 SEM analysis of the ditch magnet waste collected from the EZ-Clean ditch magnet

The investigated sample collected from the EZ-Clean ditch magnet consisted of unwashed material. No prewash of the sample had been done offshore before it was investigated at the laboratory. This was required as the smallest particles in the sample were the ones to be investigated. From the Zeiss Supra VP35 Scanning Electron Microscope (SEM) sample, it was found that some of the smallest magnetic particles collected by the EZ-Clean ditch magnet measured 0.8 µm in size. Figure 30, 31 and 32 show pictures of the investigated sample received from the SEM analysis and the investigated particle.

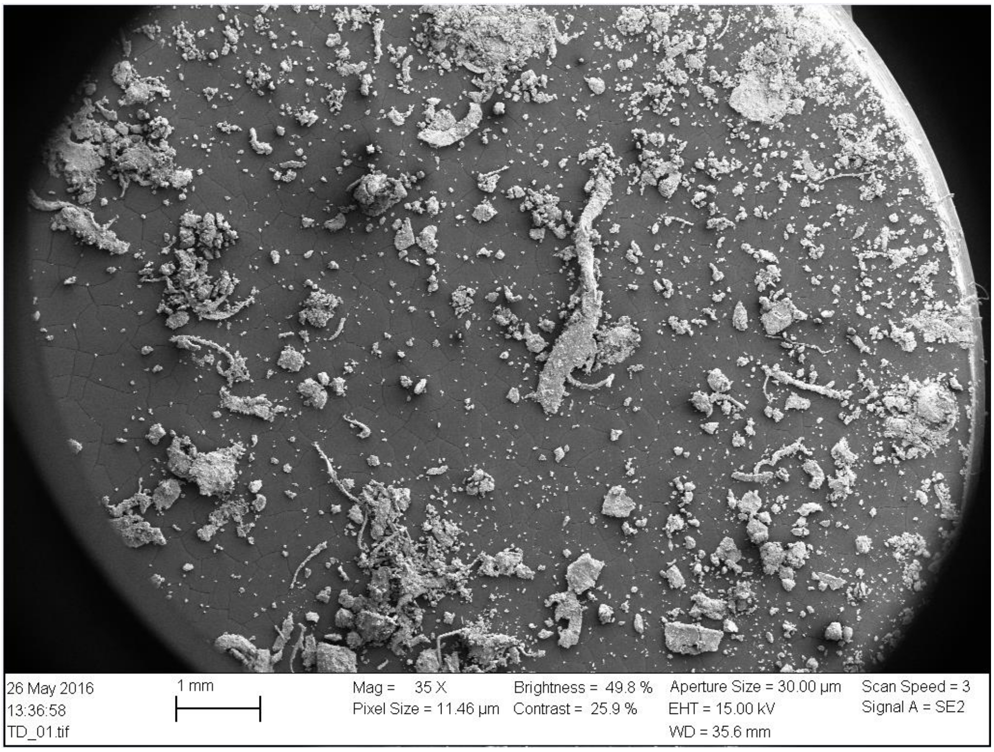


Figure 30: Overview of the particles collected by the EZ-Clean ditch magnets.

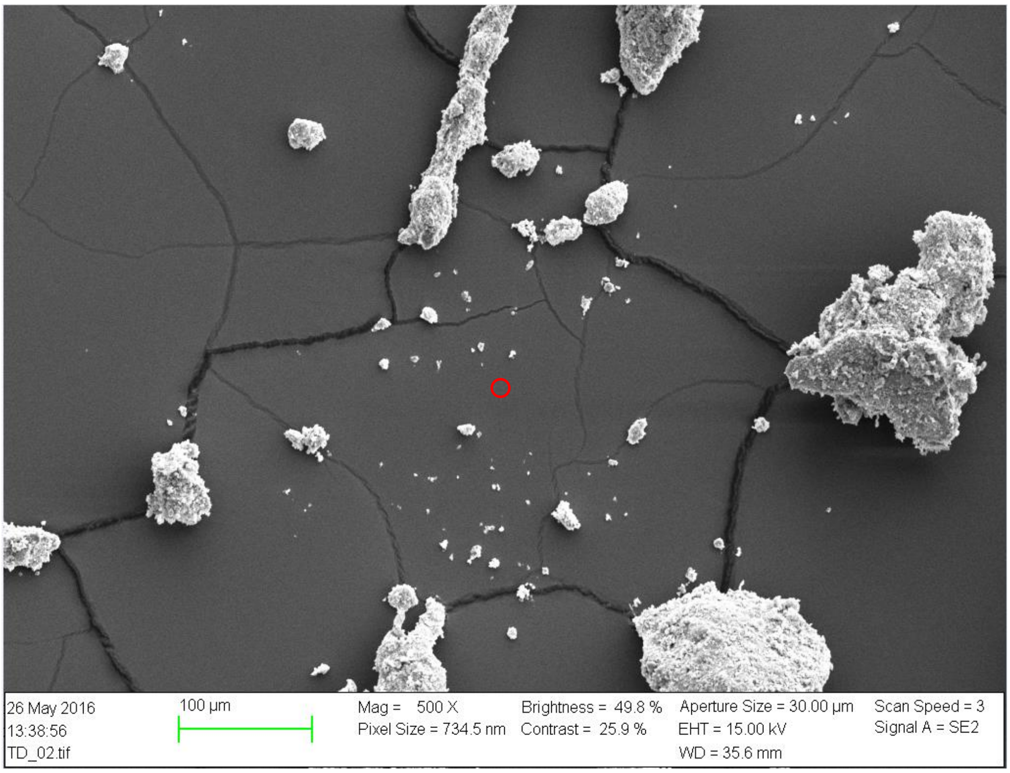
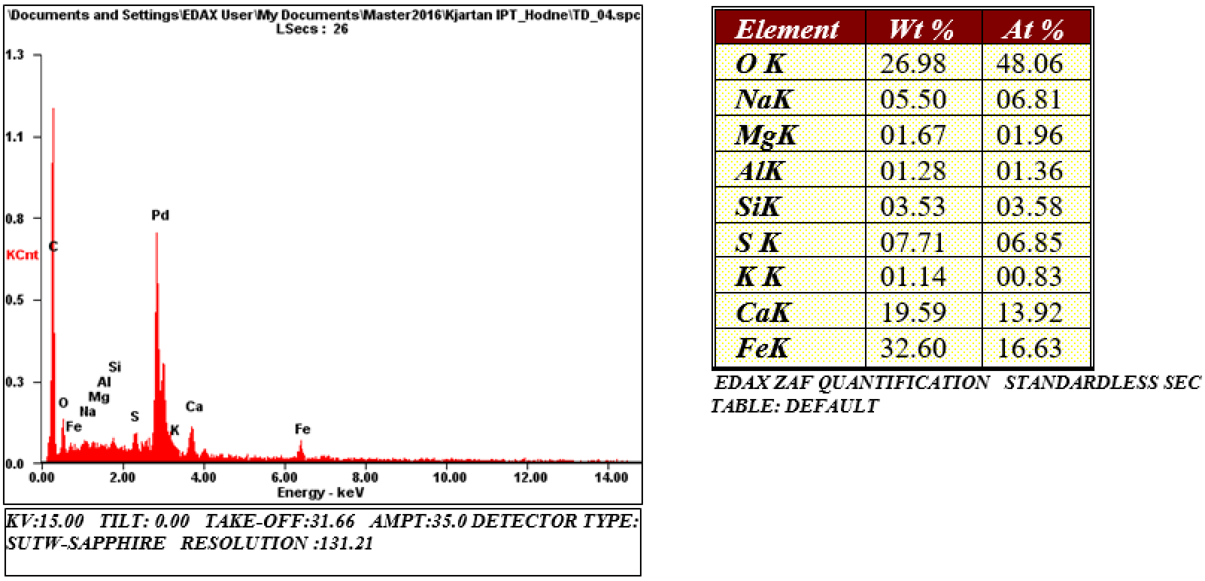


Figure 31: Overview of some of the smallest particles in the given sample.

Figure 32: Magnetic particle collected by the EZ-Clean ditch magnet

The analysis showed that the EZ-Clean ditch magnet is capable of catching relatively small magnetic particles from the drilling fluid. From one SEM analysis, it is however impossible to determine the quantity of the smallest particles and the actual number of magnetic particles in the investigated sample.

Figure 33 show the results from the element analysis taken of the particle shown in Figure 32.



KV:15.00 TILT: 0.00 TAKE-OFF:31.66 AMPT:35.0 DETECTOR TYPE: SUTW-SAPPHIRE RESOLUTION :131.21

Element	***Wt %***	***At %***
O K	26.98	48.06
NaK	05.50	06.81
MgK	01.67	01.96
AlK	01.28	01.36
SiK	03.53	03.58
S K	07.71	06.85
K K	01.14	00.83
CaK	19.59	13.92
FeK	32.60	16.63

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Figure 33: Element analysis of the given particle in Figure 32.

As observed from the table shown in Figure 33, the element analysis shows that the content of iron (Fe) is relatively high compared to the content of the other elements. From the table, the weight percent of iron is 32.60 Wt. % while the atomic percent is 16.63 At. %. It is anticipated that the high content of Fe causes the particle to be magnetic. The source of the particle was though not investigated and could origin from formation, casing, drillstring or drilling fluid additives.

3.2.4 SEM analysis of the ditch magnet waste collected from the M.A.P.S ditch magnet

From the Zeiss Supra VP35 Scanning Electron Microscope (SEM), it was found that some of the smallest magnetic particles collected by the Magnetic Active Particle Separator was measured to be 0.5 µm in size. This result shows that the magnet is capable of collecting magnetic fines even smaller than the EZ-Clean ditch magnet. It is anticipated that removal of the smallest magnetic particles, reduces the magnetic shielding of the measurement while drilling (MWD) directional tool [2]. Logging tool failures are also anticipated to be reduced and the quality of the logs may improve as less disturbance is caused to the tools by magnetic fines [28]. Figure 34 and 35 show two of the pictures received from the SEM analysis. One of the smallest particles found in the sample is represented in Figure 35.

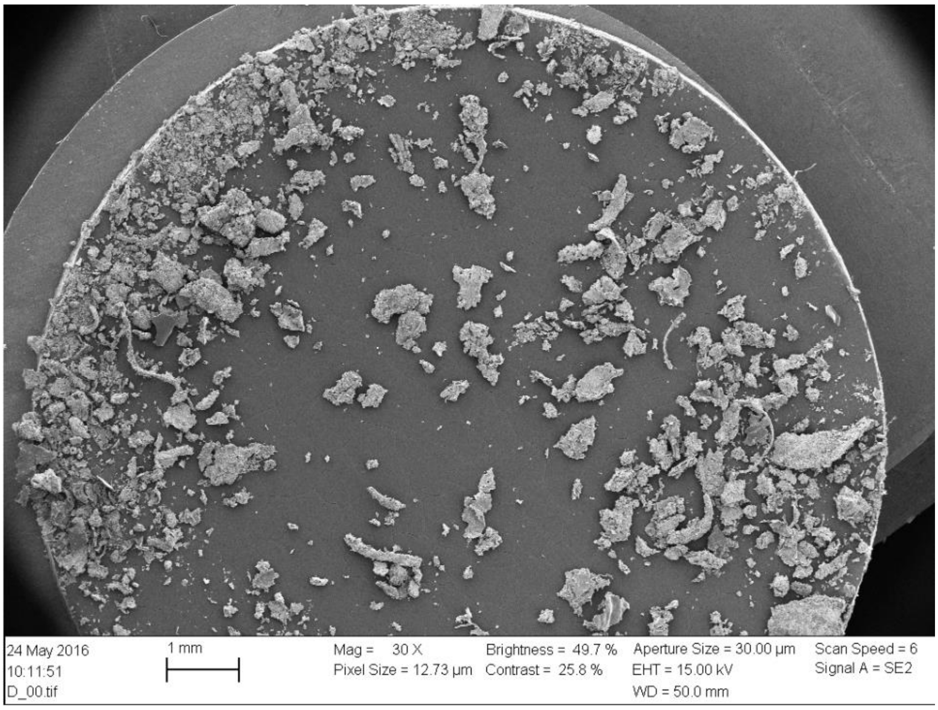


Figure 34: Overview of the particles collected from the M.A.P.S ditch magnet.

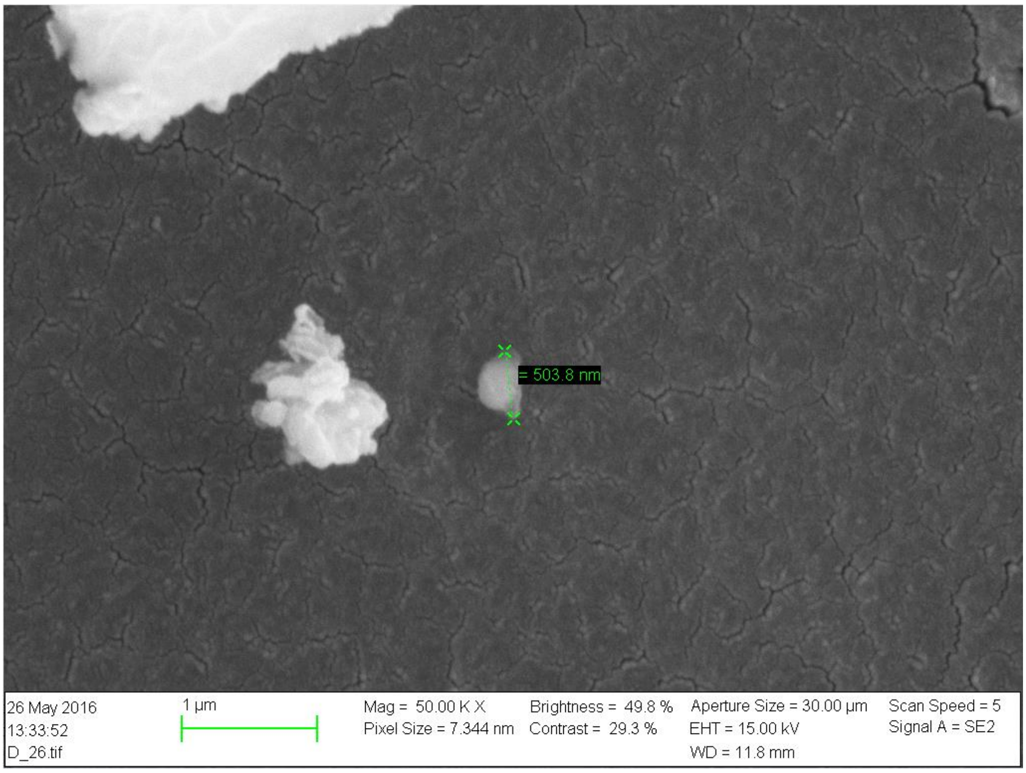
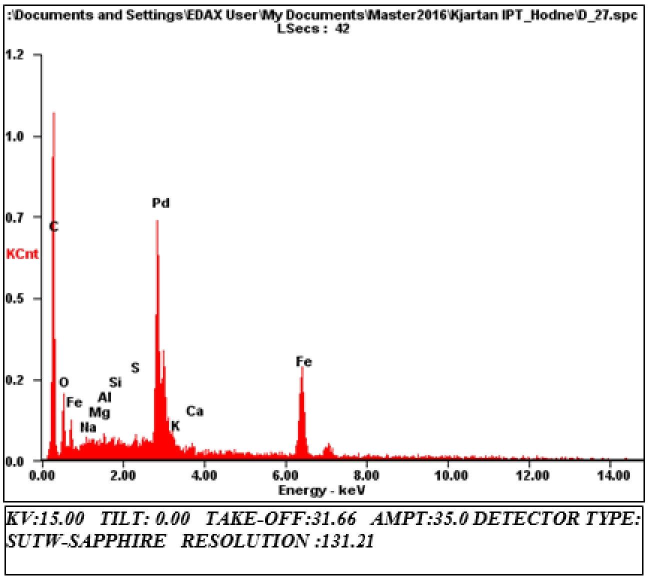


Figure 35: Scanning Electron Microscope image of one of the smallest magnetic particles extracted by the M.A.P.S ditch magnet.

In order to determine the elements in the particles, a small spot of the particle was investigated. The analysis of the different elements within a specific area of the particle is shown in Figure 36 and the element analysis results are presented in Figure 37.

Figure 36: The investigated area of the magnetic particle marked with a cross. Only a small spot was investigated.



KV:15.00 TILT: 0.00 TAKE-OFF:31.66 AMPT:35.0 DETECTOR TYPE: SUTW-SAPPHIRE RESOLUTION :131.21

Element	Wt %	At %
O K	08.97	23.87
NaK	01.84	03.42
MgK	01.30	02.28
AlK	01.38	02.18
SiK	01.31	01.99
S K	01.16	01.55
K K	00.27	00.30
CaK	01.89	02.01
FeK	81.86	62.41

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Figure 37: Element analysis of the investigated spot of the magnetic particle extracted by the M.A.P.S ditch magnet.

As observed from the graph in Figure 37, the element analysis shows relatively high values for Carbon and Palladium. Carbon is present in high quantities as the sample was washed with base oil and palladium is present as the sample was coated with palladium before it was analyzed in the Scanning Electron Microscope (SEM). From the table presented in Figure 37, the weight percent and atomic percent are shown. As observed, the atomic percent of Iron (Fe) in the investigated area is 81.86 At. % and the weight percent is 62.41 Wt. %. The two values show that particles extracted from the drilling fluid by the ditch magnets are highly magnetic. If a known metal sample from e.g. casing or drillstring were investigated, an element analysis of the given samples could have been performed. Based on the results, the elements found in the casing and drillstring analysis could have been compared with the samples collected from the drilling fluid in order to determine the source of the particle.

3.3 Analysis of performance

Eight different wells have been investigated in order to analyze and identify any correlation between the total amount of magnetic waste collected from the drilling fluid and the performance of the ditch magnets. From the two studied ditch magnet systems, the performance of the Magnetic Active Particle Separator (M.A.P.S) has been observed particularly. M.A.P.S was developed in close collaboration with Det Norske Oljeselskap ASA and Sapeg AS in order to develop a ditch magnet system which enhanced the extraction of magnetic waste particles from the drilling fluid. Survey data from each well has been seized from the daily drilling reports (DDR) provided by Det Norske Oljeselskap ASA. All the eight wells that are analyzed are drilled in the time period May 2015 until April 2016 as M.A.P.S was installed at the jack-up rig in advance of the drilling campaign which started in December 2014. Drilling of the production and injection wells through the permanent rig structure (the given oil field is a permanent installation) did not start before August 2015. Three of the eight wells have been drilled by the semi-submersible drilling rig and the remaining five are drilled by the jack-up drilling rig. The given semi-submersible drilling rig was used in the analysis as no other drilling rig was hired by Det Norske Oljeselskap ASA at the time of the study.

To better understand the performance of the ditch magnets and the different parameters affecting the amount of magnetic waste collected from the drilling fluid, the total amount of magnetic particles collected from the ditch magnets as a function of total drilling length (all lengths refer to the rotary kelly bushing (RKB)) has been investigated. In addition, the total amount of magnetic waste collected as a function of inclination and drilling length are implemented in the results. The study was carried out in order to see if there is any correlation between inclination, drilling length and magnetic waste collected from the drilling fluid. Each drilling interval is divided into separate runs in order to differentiate between the total amount of magnetic waste collected from each section. Large variations in the ditch magnet performance have been observed and are discussed.

3.3.1 Ditch magnet performance, semi-submersible drilling rig

The ditch magnets installed at the semi-submersible drilling rig are, as previously mentioned, the EZ-Clean ditch magnets from Romar International. For the ditch magnet performance, data from the daily drilling reports (DDR) are evaluated and plotted in graphs using Microsoft Excel. The survey of ditch magnet collection starts after installing the conductor casing for each wellbore. Return of drilling fluid to the rig is present while drilling the top sections as riserless mud recovery systems have been used. Drill cuttings are then transported onto the rig, through the ditch magnets and shakers, and not dumped onto the sea bed. From the three wells that are drilled with the semi-submersible rig, two wells have performed milling operations. Milling operations are anticipated to add large amounts of magnetic particles to the drilling fluid. All magnetic waste collected by the ditch magnets, the downhole drillstring magnets and the shale shakers during milling operations is excluded from the final weight results as the ditch magnet performance is not represented by these values. Hence, it is anticipated that the milling operations conducted in the two wellbores contribute to obtain a more contaminated drilling fluid, causing additional magnetic shielding of the Earth's magnetic field [4], less accurate directional drilling and larger quantities of magnetic waste collected by the ditch magnets.

From the three wells drilled with the semi-submersible drilling rig there are one three-lateral, one dual-lateral and one single-lateral wellbore, all very different from one another.

The statements and assumptions in the following three sections are all related to the EZ-Clean ditch magnet at the semi-submersible drilling unit and the procedures at the rig. It is important to consider the fact that all samples taken from the ditch magnets are cleaned with base-oil and then sieved though a 2mm mesh size before the total weight of the sample is measured. Magnetic particles less than 2mm are removed from the sample and not added to the final weight result. On the other hand, drilling fluid additives and other "junk" particles from the well are removed from the sample, leaving only the magnetic particles left to be weighted. The different procedures for handling the magnetic waste from the ditch magnets before the results are implemented in the daily drilling reports (DDR) is important to consider when the final results are compared with the M.A.P.S ditch magnet results.

Drilling of well A-1

Drilling of the multilateral oil producer, well A-1, involved one milling operation, two pilot holes and one sidetrack operation. The well had a total drilling length of 12421.8 mMD, excluding the drilling length of the conductor casing. Seen from the well survey data, the wellbore is rather complicated, involving high dog leg severities (DLS) and rapid inclination changes. These are parameters that are anticipated to make the wellbore prone to produce magnetic waste particles. Magnetic waste generated from the given milling operation are anticipated to increase the general content of magnetic fines in the drilling fluid and affect the performance of the ditch magnets. The milling operation is considered as an error and removed from the results. In total, 46.2 kg of magnetic waste was collected from the ditch magnets after completing drilling. Figure 38 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different sections based on drilling length.

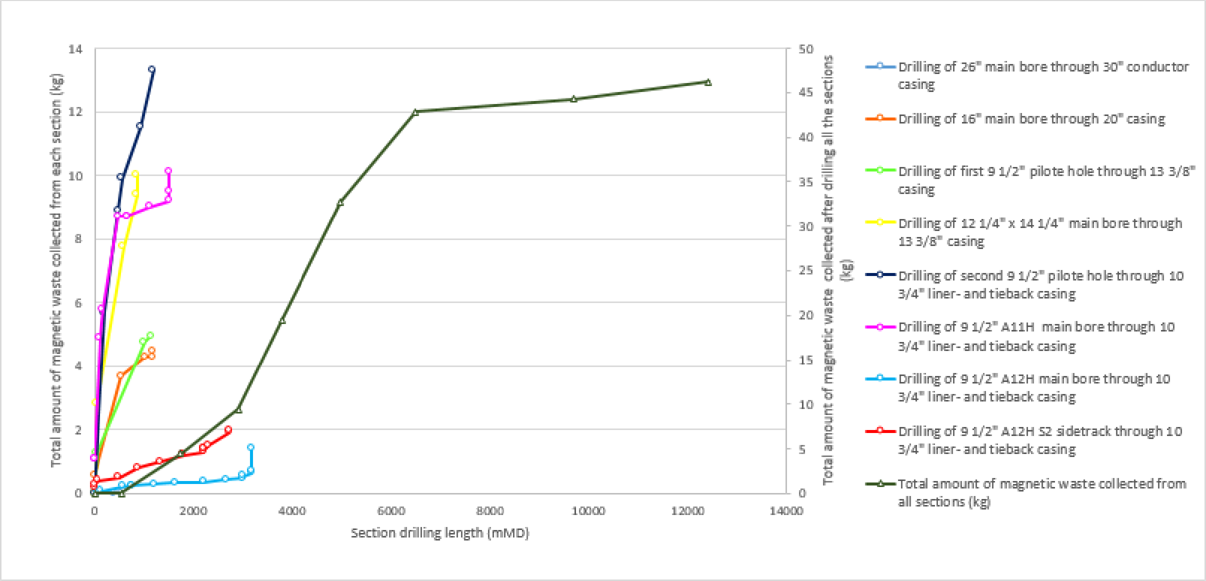

Figure 38: Magnetic waste distribution in the different section as a function of drilling length in well A-1.

The dark green curve represents the cumulative amount of magnetic waste collected after drilling all the well sections. The other eight graphs show the total amount of magnetic waste collected by the ditch magnets from each individual section. Figure 39 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. Inclination surveys for each individual section with additional drilling length is also shown.

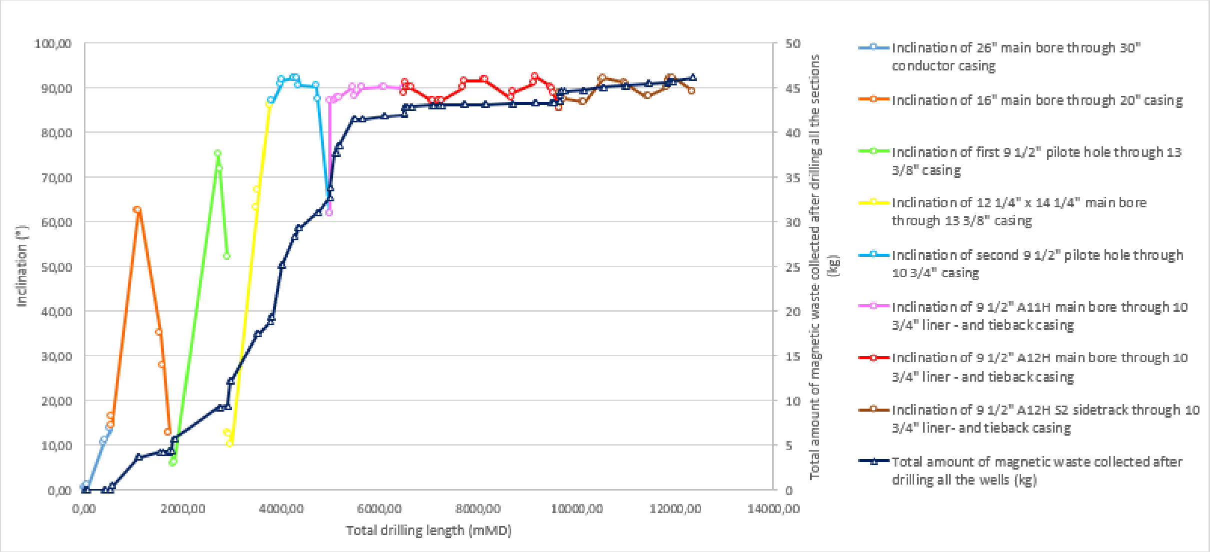

Figure 39: Magnetic waste distribution as a function of inclination and drilling depth in well A-1.

The graphs shown in Figure 38 and 39, representing well A-1, show that the ditch magnets collect more magnetic waste from the drilling fluid when the inclination increases and the well path varies, i.e. more bends. The graphs also show that the ditch magnets collect more magnetic waste upon drilling the 16” hole section, the first pilot hole, the 12 ¼” x 14 ¼” section, the second pilot hole and the first lateral section compared to drilling of the 26” section, the second lateral section and the lateral sidetrack section. This may imply that drilling of the middle sections, i.e. the 16” hole section, the first pilot hole, the 12 ¼” x 14 ¼” section, the second pilot hole and the first lateral section, produces more magnetic waste compared to drilling of the other sections. The middle sections are also drilled with relatively high inclination variations ranging from 15° to 90°. It is anticipated that inclination in this area increases the total amount of magnetic waste produced in the well. Thus drilling of the two lower lateral sections (A12H and A12H S2) produces close to negligible amounts of magnetic waste (the lateral wellbore sections are named based on well name and the lateral number). In these two sections the inclination is steady around 90° and the drilling lengths are 3181.8 mMD for A12H and 2736 mMD for A12H S2.

Drilling of the A12H and A12H S2 sections was conducted after the milling operation. This was anticipated to generate additional magnetic waste to the drilling fluid and hence, increase the ditch magnet performance. There are however no indications from the results presented in Figure 38 and 39, showing any significant increase in magnetic waste collected by the ditch magnets after the milling operation. The dark blue line, representing the cumulative amount of magnetic waste collected from the ditch magnets after drilling all the sections, rather show a decrease in magnetic waste collected by the ditch magnets after the milling operation. It is, however, important to know that the ditch magnet results during the milling operation is not included in the presented results. Magnetic waste collected during milling operations does not represent the ditch magnet performance. The observation does not support the claim anticipating that milling operations increases the content of magnetic fines in the drilling fluid.

Drilling of well A-2

Drilling of the three lateral oil producer, well A-2, involved two milling operations and drilling of three pilot holes. The total drilling length, excluding the drilling length of the conductor section was 14266.5 mMD. Well A-2 is, in the same way as well A-1, a complicated wellbore which is prone to produce large amounts of magnetic fines. High DLS and inclination changes are present upon drilling well A-1 and two milling operations are performed. In total, 54.6 kg of magnetic waste particles were collected from the ditch magnets after drilling the well sections. Figure 40 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different sections based on drilling length.

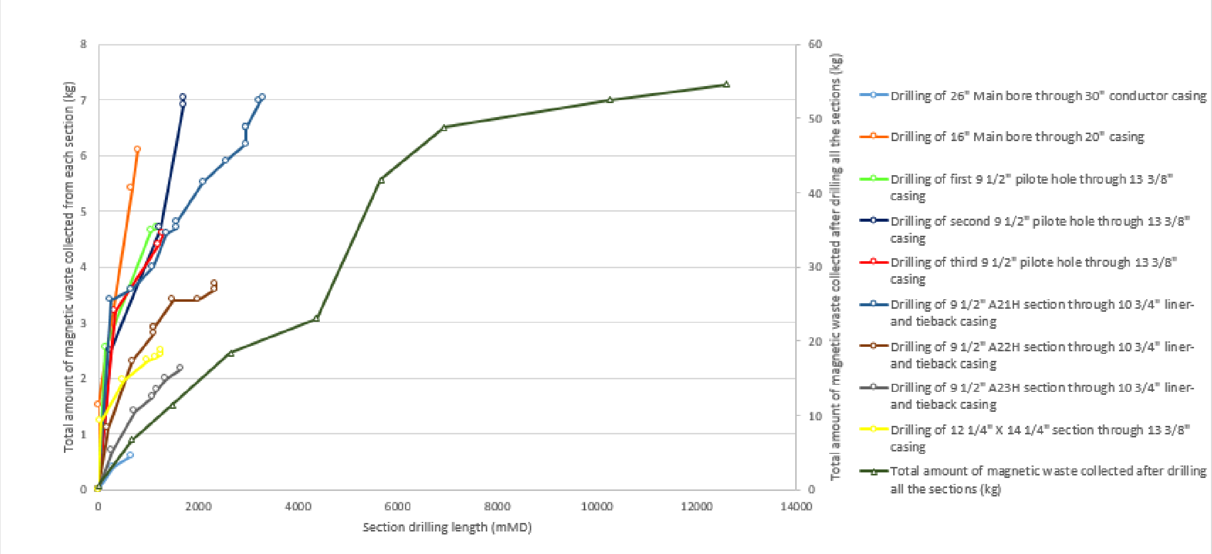

Figure 40: Magnetic waste distribution in the different section as a function of drilling length in well A-2.

The dark green curve represents the cumulative amount of magnetic waste collected after drilling all the well sections. From the other nine graphs, the total amount of magnetic waste collected by the ditch magnets from each individual section is shown. Figure 41 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. Inclination surveys for each individual section with additional drilling length is also shown.

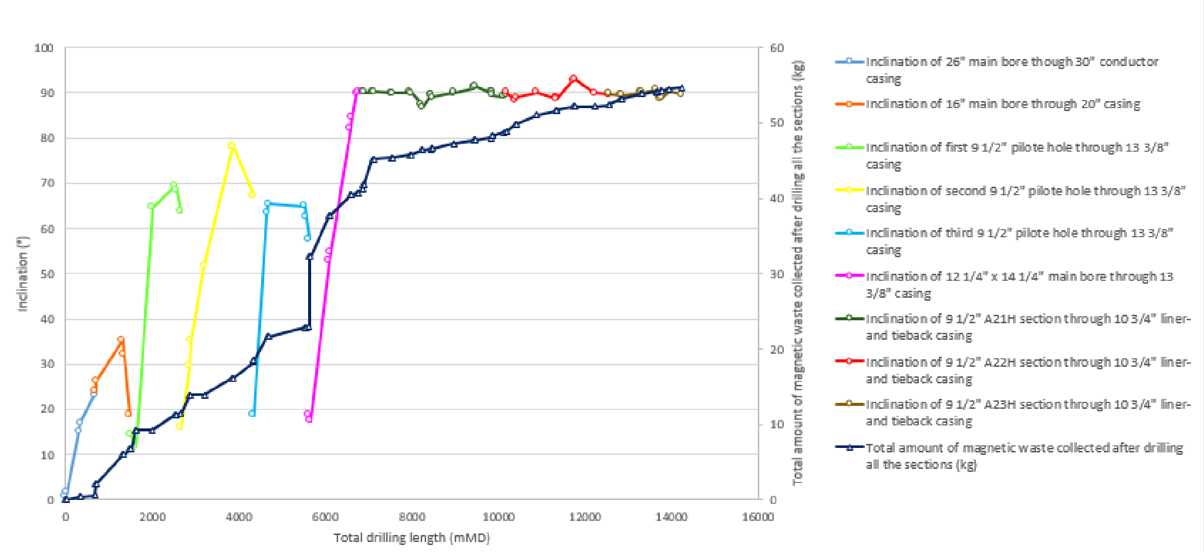

Figure 41: Magnetic waste distribution as a function of inclination and drilling depth in well A-2.

The graphs shown in Figure 40 and 41, representing well A-2, show similar trends as observed in well A-1. The ditch magnet collection from the drilling fluid increases as inclination increases and the well path varies i.e. more bends. Especially for intervals where the well inclination is within the area of 20 - 90°, the ditch magnets collects considerable amounts of magnetic waste from the drilling fluid. From Figure 41, the trend is clearly observed and shown by the dark blue line, representing the cumulative amount of magnetic waste collected from the ditch magnets throughout the whole well. The same results were observed in wellbore A-1.

Drilling of the 16” section produced 6.1 kg of magnetic waste. This result is not analogous with the amount of magnetic waste that was collected in the 16” section in well A-1. The drilled section in well A-2 is both shorter and the inclination variations are less, however, more magnetic waste is collected from the drilling operation.

Drilling of the two lateral well sections, A22H and A23H, are both drilled with an inclination of approximately 90°. As for well A-1, the ditch magnet performance in the given sections is not as extensive as expected considering the inclination and drilling length of the sections. In addition, drilling of wellbore A22H and A23H is commenced after performing one and two milling operations. The ditch magnet collection results presented in Figure 40 shows however, no indications that milling operations affect the total amount of magnetic waste collected from the ditch magnets. Magnetic waste collected during the milling operation is not included in the final weight results for well A-2 either.

Drilling of well A-3

Drilling of the single lateral wellbore, well A-3, was completed after drilling a total of 5766 mMD, excluding the length of the conductor casing. The drilling operation included drilling of one pilot hole section. The pilot hole section was drilled from the 13 3/8" casing shoe and down to 3248 mMD. No milling operations were conducted in well A-3, having no additional magnetic waste particles added to the drilling fluid due to milling operations. In total, 31.1 kg of magnetic particles were collected by the ditch magnets after drilling all well sections. Figure 42 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different sections based on drilling length.

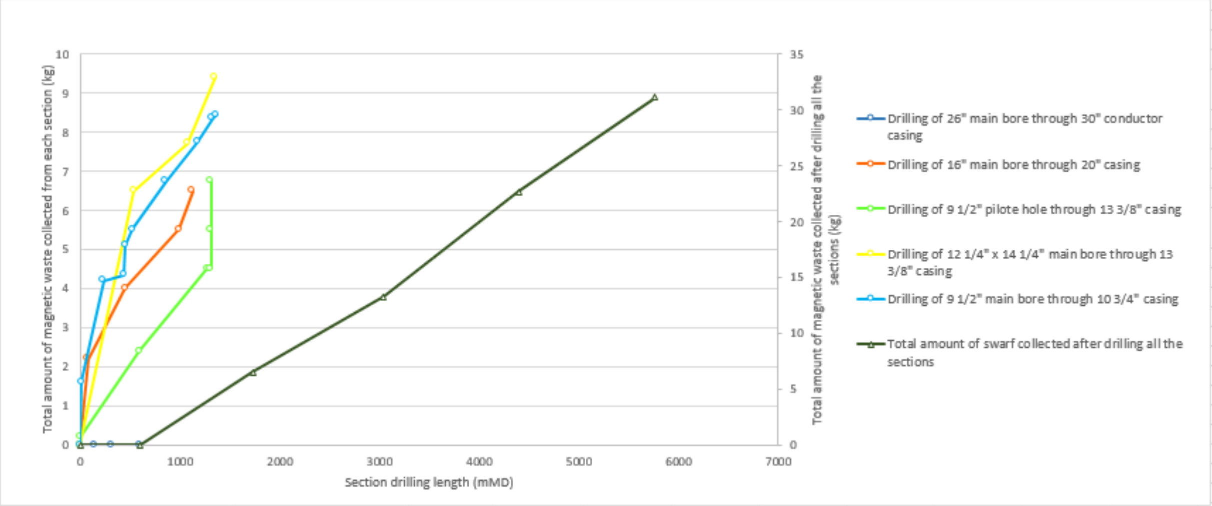

Figure 42: Magnetic waste distribution in the different section as a function of drilling length in well A-3.

The dark green curve represents the cumulative amount of magnetic waste collected after drilling all the well sections. From the other five graphs, the total amount of magnetic waste collected from the ditch magnets in each individual section is shown. Figure 43 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. The inclination survey for each section as a function of drilling length is also shown.

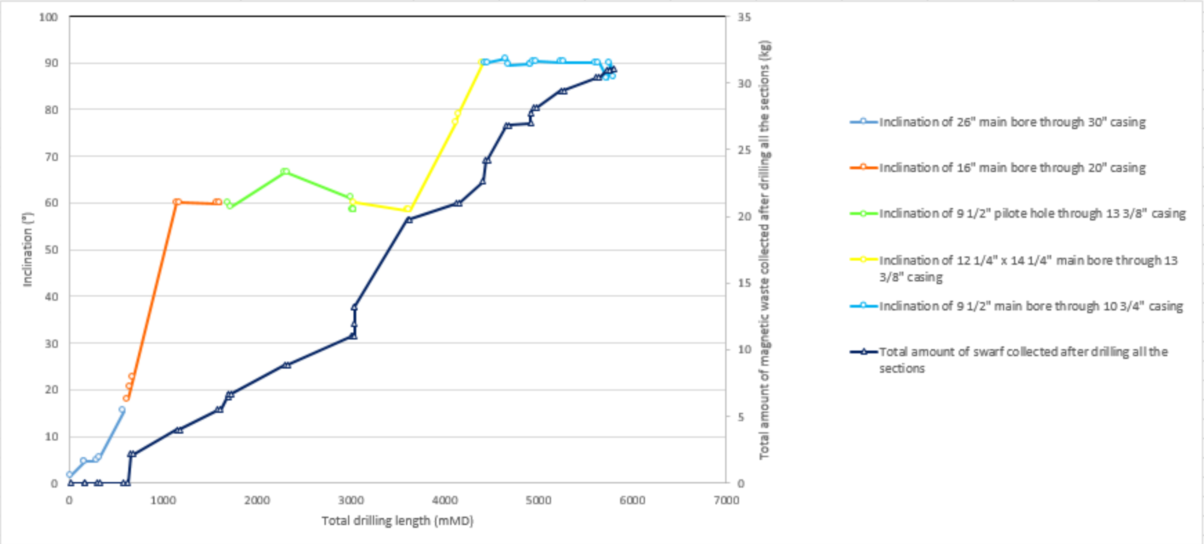

Figure 43: Magnetic waste distribution as a function of inclination and drilling depth in well A-3.

Based on the graphs shown in Figure 42 and 43, representing the ditch magnet results from well A-3, the same trend as seen in well A-1 and A-2 are observed. The 16” section, the pilot hole and the 12 ¼” x 14 ¼” sections, all drilled with inclinations within the area of 20 – 80°, are the sections that produce the highest quantity of magnetic waste. Figure 42 shows that the last reservoir section produces 8.45 kg of magnetic waste. This section is drilled with an average inclination of 90°, making the results agree with the assumption indicating that inclinations between 20° and 90° produce the largest amounts of magnetic waste.

If a closer look is taken on the reservoir sections in well A-1 and A-2 from Figure 39 and 41 (wellbore A11H and A21H) it is seen that the ditch magnets collect weights (A11H = 10.1 kg and A21H = 7.02 kg) of magnetic material similar to the well A-3 reservoir section. It is anticipated, from the results, that drilling of the first reservoir sections is prone to produce considerable amounts of magnetic waste. The need for appropriate ditch magnet performance while drilling the reservoir sections is anticipated to be crucial in order to collect as much magnetic waste from the drilling fluid as possible.

3.3.2 Ditch magnet performance. Jack-up drilling rig

The ditch magnets installed at the jack-up drilling rig are, as previously mentioned, the Magnetic Active Particle Separator (M.A.P.S) ditch magnet system developed by Sapeg AS.

For the ditch magnet performance, data from the daily drilling reports (DDR) are evaluated and plotted in graphs using Microsoft Excel. Collection of survey data from the ditch magnets is initiated after drilling and cementing of the conductor casing. Ditch magnet data from two of the 16” surface hole sections are absent in the DDR, having no value for the given sections. Full drilling fluid return is present at any time as the jack-up rig operates with a dry blowout preventer (BOP) and a high pressure riser (HPR). No milling operations are conducted while drilling the five investigated wells. This is anticipated to affect the ditch magnet collection as less magnetic waste (in theory) is added to the drilling fluid and collected by the ditch magnets.

The five wells that are used in the analysis are well B-1, B-2, B-3, B-4 and B-5. All five are single lateral wells. Well B-1 is drilled with a 17 ½” surface hole while the rest is drilled with a 16” surface hole. In well B-5, no 9 5/8” casing is installed.

Statements and assumptions in the following five sections are all related to the M.A.P.S ditch magnet at the jack-up rig and the procedures at the given rig site. All ditch magnet samples taken on the jack-up rig includes the weight of the drilling fluid additives and other “junk” attached to the magnets. This ensures that no magnetic waste is left out from the total weight of the sample. On the other hand, the drilling fluid and “junk” increases the total weight of the sample and presents an error in the final results. The wells are presented chronological, starting with the wellbore that was drilled first.

Drilling of well B-1

Drilling of the single lateral oil producer, well B-1 was a rather simple and unproblematic operation. No pilot holes or milling operations were conducted. The presence of pilot holes is anticipated to increase the total amount of magnetic waste collected from the drilling fluid as the total drilling length of the well is expanded. Milling operations are anticipated to increase the number of magnetic particles collected by the ditch magnets as more magnetic waste is added to the drilling fluid. Thus, without drilling of pilot holes and milling operations, a total of 122.07 kg of magnetic waste was collected after drilling a total of 4227 mMD. Figure 44 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different well sections based on drilling length.

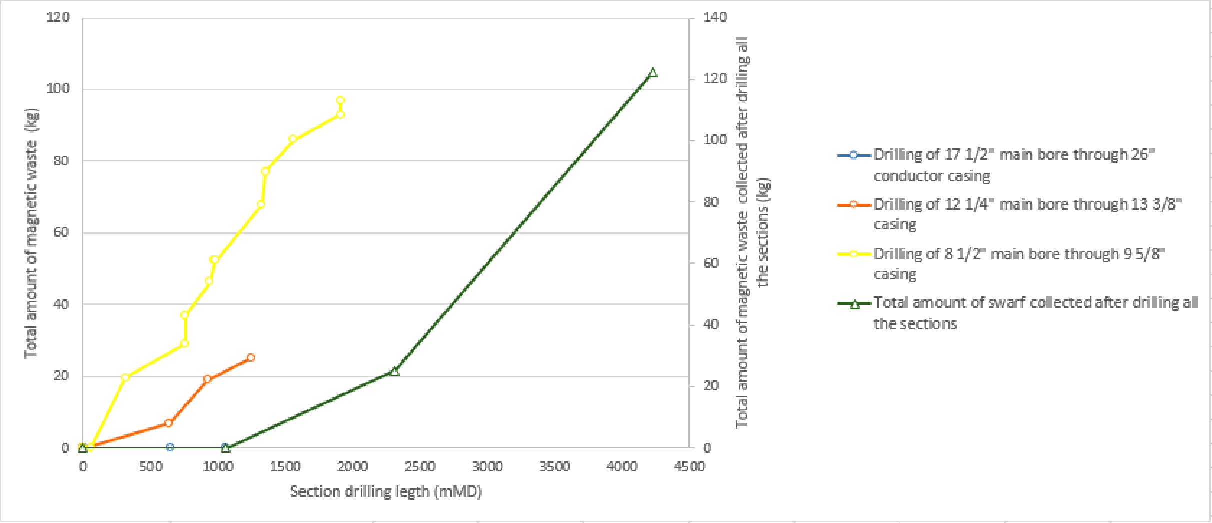

Figure 44: Magnetic waste distribution in the different sections as a function of drilling length in well B-1.

The dark green line represents the cumulative amount of magnetic waste collected by the ditch magnets after drilling all the well sections. From the other three graphs in Figure 44, the total amount of magnetic waste collected by the ditch magnets in each individual section is shown. Figure 45 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. The inclination survey for each section as a function of drilling length is also shown.

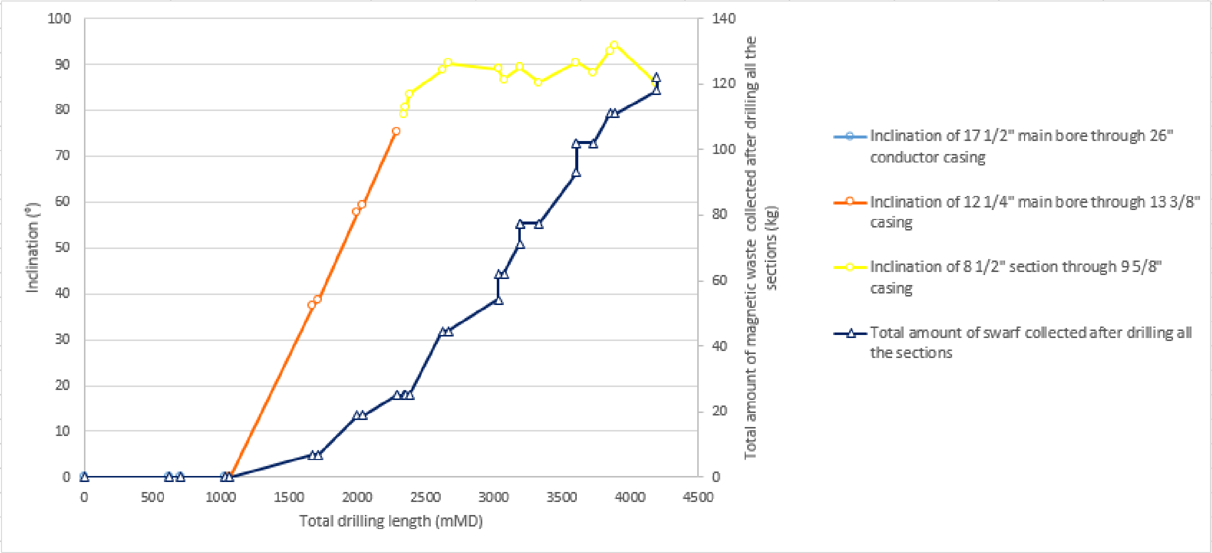

Figure 45: Magnetic waste distribution as a function of inclination and drilling depth in well B-1.

From the two graphs shown in Figure 44 and 45, representing well B-1, a correlation is observed between section drilling length, the casing section being drilled through and the amount of magnetic waste collected by the ditch magnets. From Figure 44 it is seen that drilling of the first 17 ½” section did not produce any magnetic waste. In the daily drilling reports (DDR), no data from the 17 ½” section is recorded, giving the value zero in the graphs. The inclination in the hole section was however 0° (vertical hole section), giving reasons to anticipate that the section would not have produced that much magnetic waste anyway.

Drilling of the 12 ¼” hole section produced in total 25.07 kg of magnetic waste. The inclination in the 12 ¼” hole section starts at 0° and ends at 75.44° according to the last survey point. According to results collected from the ditch magnets at the semi-submersible drilling rig, the inclination interval from 20-90° was the part of the well where highest amounts of magnetic waste was collected.

Drilling of the 8 ½” section produced 97 kg of magnetic waste. The collection of magnetic waste in the 8 ½” section is almost four times the value collected from the 12 ¼” hole section. The wellbore inclination varies from 78 – 94°. Wellbore B-1 indicates that inclinations in the area of 70 – 90°, in combination with drilling of an 8 ½” hole section through a 9 5/8” casing produce considerable amounts of magnetic waste. It is anticipated that the inclination of the 9 5/8” casing and the total length of the casing is one of the reasons for having this amount of magnetic waste collected by the ditch magnets. The dark blue line in Figure 45 represents the cumulative amount of magnetic waste collected after drilling all the well sections with respect to inclination and total drilling length.

In addition, the M.A.P.S ditch magnet system installed at the jack-up drilling rig is developed in close collaboration with Det Norske Oljeselskap ASA and Sapeg AS in order to enhance the collection of magnetic waste from the drilling fluid. It is anticipated that the ditch magnet system could have a positive impact on the final collection result. This will be shown in the following analysis.

Drilling of well B-2

Drilling of the single lateral oil producer, well B-2, was conducted drilling one pilot hole section through a 9 5/8” casing and no milling operations. In total, 376.4 kg of magnetic waste was collected after drilling a total of 5839 mMD, excluding the length of the conductor hole section. Figure 46 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different well sections based on drilling length.

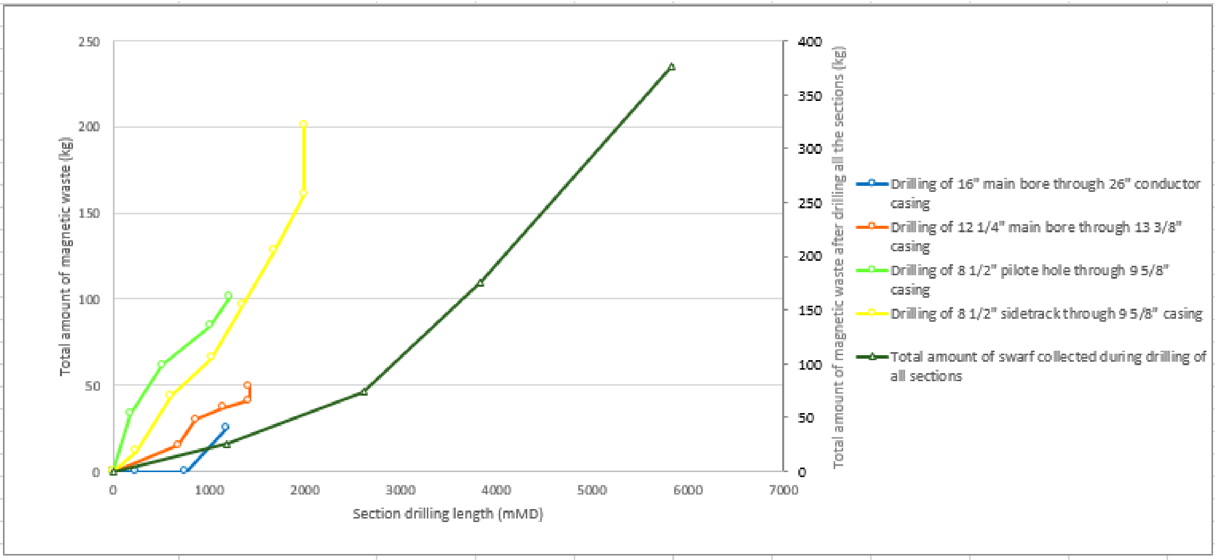

Figure 46: Magnetic waste distribution in the different sections as a function of drilling length in well B-2.

The dark green line in Figure 46 represents the cumulative amount of magnetic waste collected from the ditch magnets after drilling all the well sections. From the other four graphs, the magnetic waste collected by the ditch magnets after drilling each individual section to its total depth (TD) is shown. Figure 47 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. The inclination survey for each section as a function of drilling length is also shown.

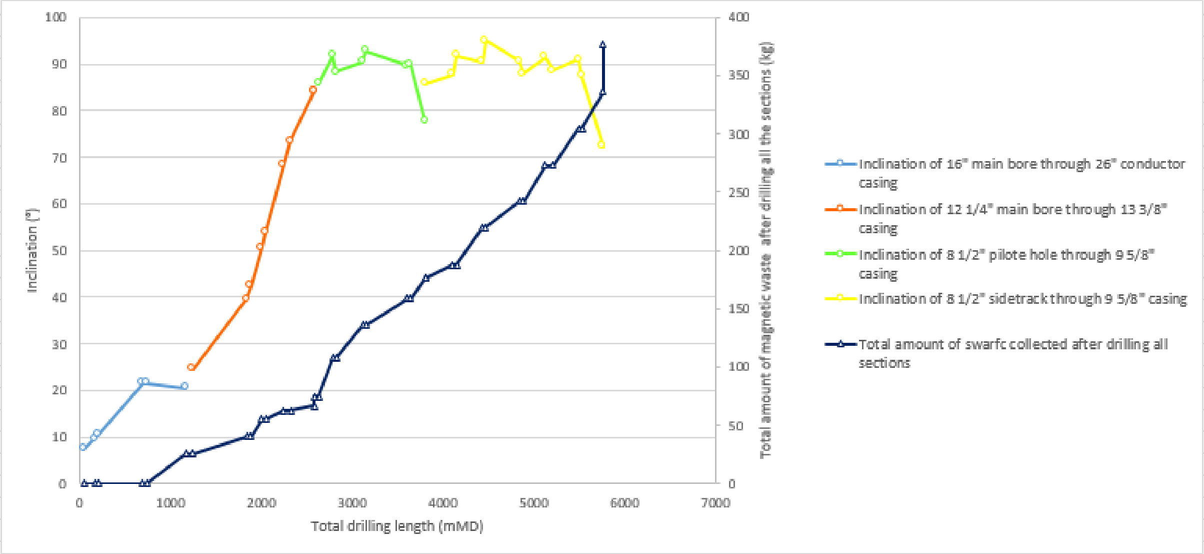

Figure 47: Magnetic waste distribution as a function of inclination and drilling depth in well B-2.

The two graphs shown in Figure 46 and 47, representing well B-2, show that drilling of the first 16” section produces relatively large amounts of magnetic waste. A total of 25.4 kg of magnetic waste is collected from the ditch magnets as the section is drilled. From the survey data in the daily drilling report (DDR) and the graph shown in Figure 47 it is shown that the 16” well section is drilled through a conductor casing having an inclination of 7.35° at the casing shoe. In addition, the 16” well section is drilled with some inclination variations, creating potential edges and corners inside the casing where magnetic material may be eroded.

Upon drilling the 12 1/4” section, 49 kg of magnetic waste was collected from the ditch magnets. The inclination varies from 25 – 84° with a total drilling length of 1428 mMD. Upon drilling of the 8 ½” pilot hole, a total of 101.5 kg of magnetic waste was collected from the ditch magnets. This turned out to be nearly the same amount as collected while drilling the 8 ½” section in well B-1. After cementing back the 8 ½” pilot hole, further drilling of the 8 ½” main bore section collected 200.5 kg of magnetic waste. This value represents nearly twice the amount of magnetic waste as collected from the pilot hole and the main bore in well B-1. It is anticipated that the increase in collected material from the ditch magnets is due to the slight increase in drilling length, larger inclination variations and the length of the installed 9 5/8” casing. The efficiency of the M.A.P.S ditch magnets is anticipated to affect the increase in collected material for well B-2 as well.

Drilling of well B-3

Drilling of the single lateral oil producer, well B-3, was conducted drilling three wellbores, excluding the conductor hole. No pilot hole operation or milling operation was conducted. A 16”, 12 ¼” and one 8 ½” wellbore was drilled in order to reach the total depth (TD) at 6217.2 mMD. In total, 109.8 kg of magnetic waste was collected after drilling 5765.2 mMD. Figure 48 shows the magnetic waste distribution (kg) collected from the ditch magnets in the different sections based on drilling length.

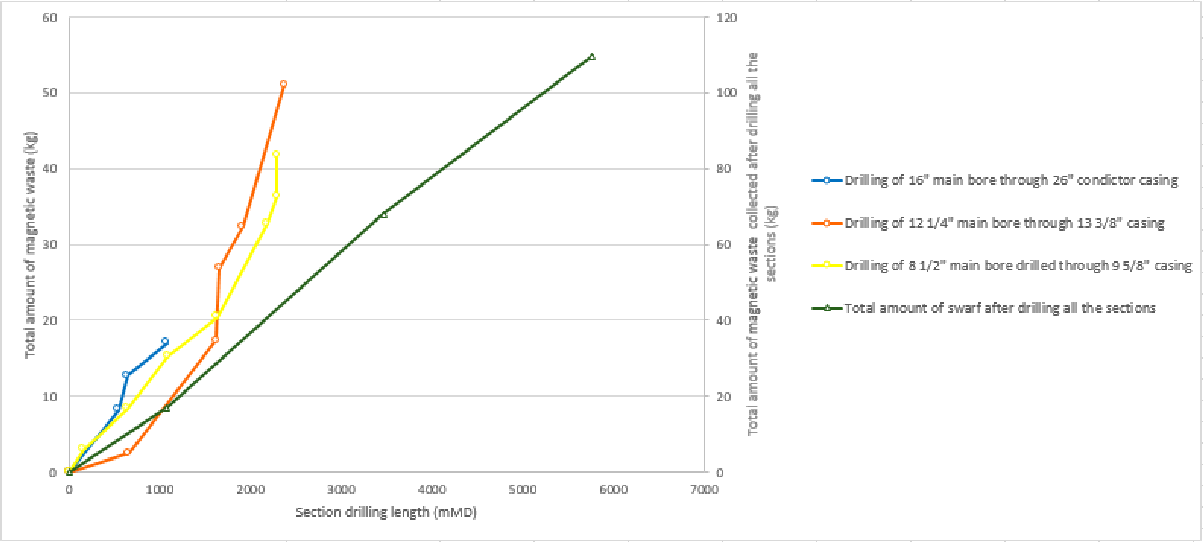

Figure 48: Magnetic waste distribution in the different sections as a function of drilling length in well B-3 with three magnets installed in the flowline.

The dark green line represents the cumulative amount of magnetic waste collected from the ditch magnets after drilling the well to TD at 6217.2 mMD. From the other three graphs in Figure 48, the total amount of magnetic waste collected in each section is shown. Figure 49 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. The inclination survey for each section as a function of drilling length is also shown.

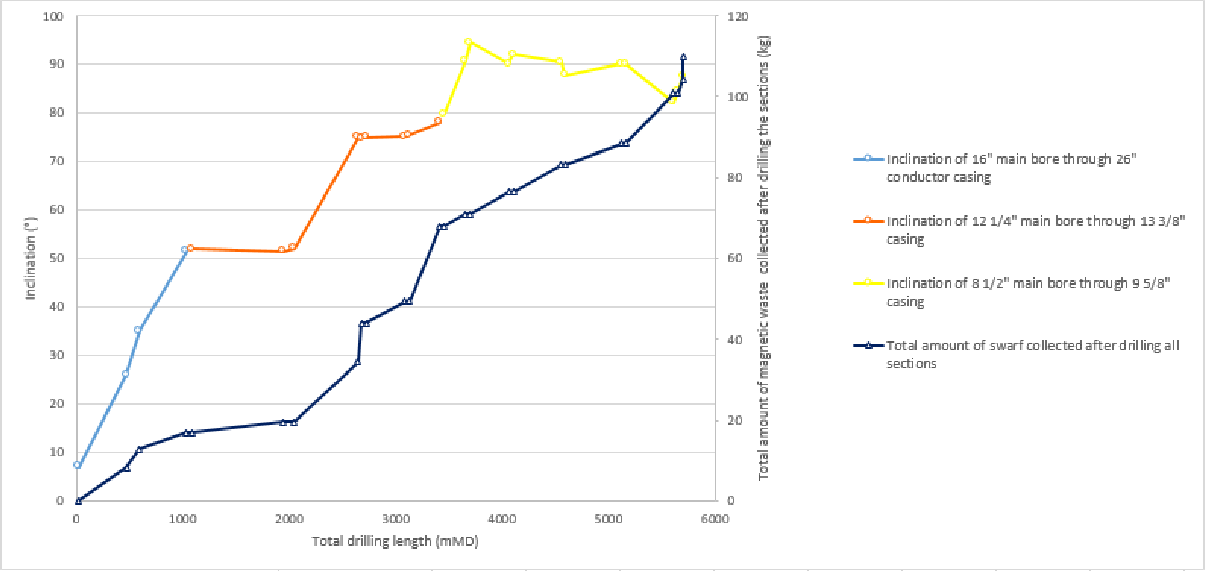

Figure 49: Magnetic waste distribution as a function of inclination and drilling depth in well B-3.

From the graphs shown in Figure 48 and 49, representing well B-3, a correlation is observed between total drilling length, inclination and amount of magnetic waste collected. From the 16” section, 17 kg of magnetic waste was collected by the ditch magnets. A total of 1085 mMD was drilled and the inclination variation ranged between 7 – 51° in the 16” section. The 12 ¼” section is however the section where the most magnetic material is collected by the ditch magnets. In total, 51 kg of magnetic waste was collected. From Figure 49 it is seen that the 12 ¼” section is drilled with inclinations ranging from 51 – 75°, and the total drilling length is 2382 mMD. The section is drilled through a 13 3/8” casing with high inclination, making the well prone to produce magnetic waste.

In total, 41.8 kg of magnetic waste were collected from the ditch magnets while drilling the 8 ½” well section through the 9 5/8” casing. The 8 ½” wellbore represents the well section where the largest amounts of magnetic waste are collected by the ditch magnets based on the results from well B-1 and B-2. However, well B-3 deviates slightly from these results as less magnetic waste is collected from the 8 ½” section compared to the 12 ¼” section.

Another observation that needs to be considered for well B-3 is that only three ditch magnets were installed in the flowline as the wellbore was drilled. This is anticipated to affect the overall ditch magnet performance and reduce the total amount of magnetic waste collected from the ditch magnets.

Drilling of well B-4

Drilling of the single lateral oil producer, well B-4, was conducted without drilling of pilot holes or milling operations. Based on observations from the survey data collected from well A-1, A-2, A-3 and B-2, pilot holes tend to increase the total amount of magnetic waste collected from the ditch magnets. No magnetic waste is logged in the daily drilling reports (DDR) while drilling the 16” main bore. It is anticipated that the data are left out from the reports. In total, 73.3 kg of magnetic waste was collected from the ditch magnets after drilling 4393 mMD, excluding the drilling length of the conductor hole section. Figure 50 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different sections based on drilling length.

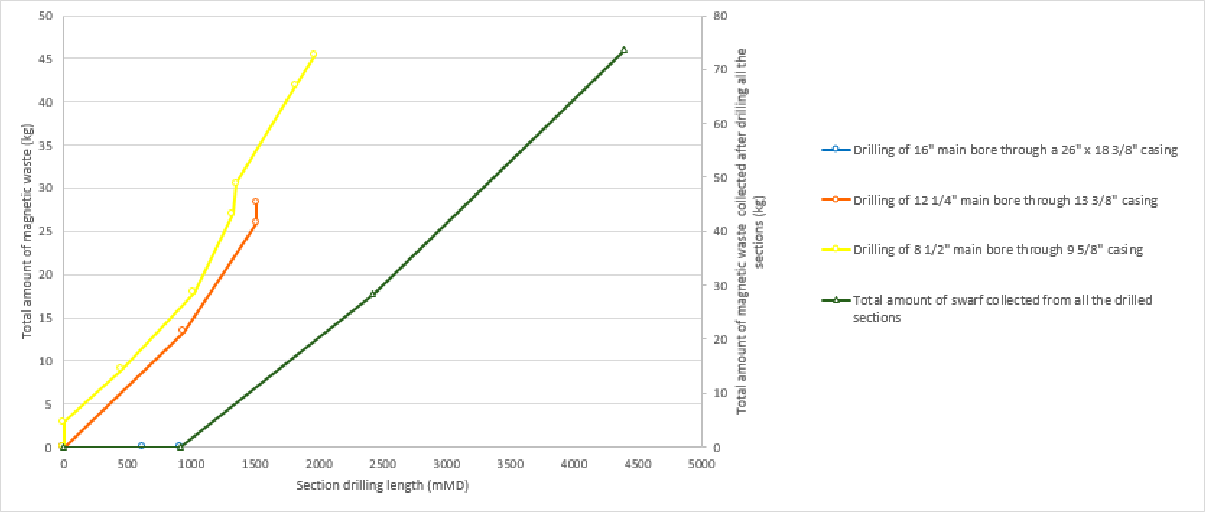

Figure 50: Magnetic waste distribution in the different sections as a function of drilling length in well B-4 with three magnets installed in the flowline.

The dark green line represents the cumulative amount of magnetic waste collected from the ditch magnets after drilling 4825.4 mMD. From the other three graphs, the total amount of magnetic waste collected in each section is shown. Figure 51 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. The inclination survey for each section as a function of drilling length is also shown.

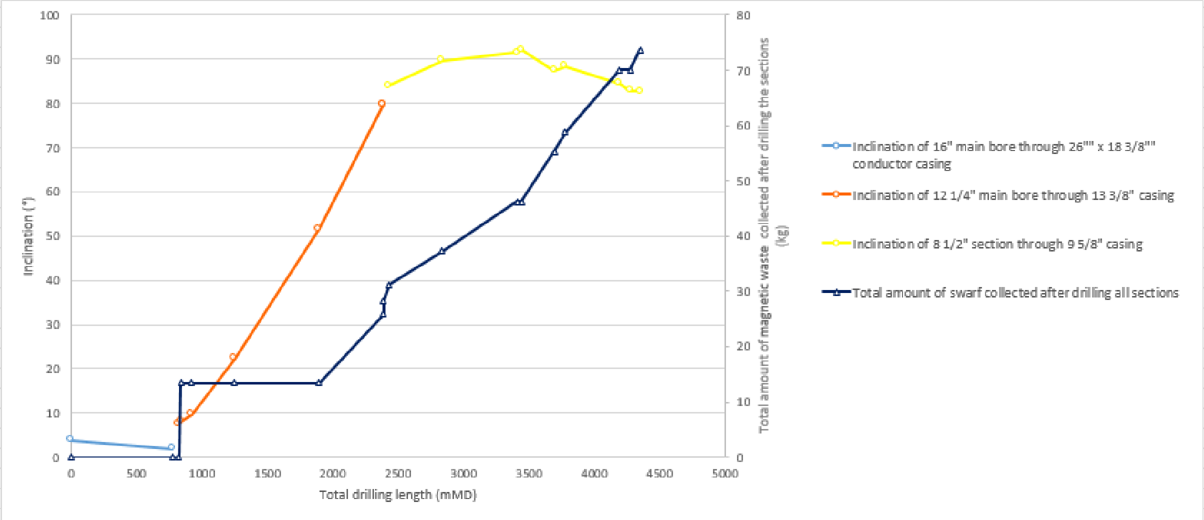

Figure 51: Magnetic waste distribution as a function of inclination and drilling depth in well B-4.

The two graphs in Figure 50 and 51, representing well B-4, show the results from the DDR. From the dark blue line in Figure 51, the correlation between inclination, total drilling length and the magnetic waste material collected by the ditch magnets is shown. The ditch magnets collected 0 kg of magnetic waste when drilling the 16” hole section. No rapid change in inclination or irregularities are present while drilling the 16” hole section, giving reasons to anticipate that this section would have produced relatively small amounts of magnetic waste anyway. Thus the lack of data has an impact on the final weight result.

From the 12 ¼” section, 28.3 kg of magnetic waste was collected. The section was drilled with inclinations varying from 7 - 80° and with a total drilling length of 1512 mMD. Similar conditions are observed in well B-1 where 25.07 kg of magnetic waste was collected.

Drilling of the 8 ½” section produced 45.4 kg of magnetic waste and represents the highest amount of collected magnetic particles in the wellbore. Based on the graphs in Figure 50 and 51, it is anticipated that drilling through the 9 5/8” casing i.e. the reservoir section, produces the highest amount of magnetic waste. This observation was made in both well B-1 and B-2.

Again, while drilling well B-4, only three magnets were placed in the flowline, reducing the exposure area of the drilling fluid and the amount of magnetic waste collected from the drilling fluid.

Drilling of well B-5

Drilling of the single lateral oil producer, well B-5, was conducted by drilling one 16” main bore, one 8 ½” pilot hole and one 8 ½” sidetrack operation. Due to the 8 ½” pilot hole, additional magnetic waste material is expected to be collected from the ditch magnets. No milling operations have been conducted. In total, 368.2 kg of magnetic waste were collected by the ditch magnets after drilling 6857 mMD, excluding the conductor hole section. Figure 52 shows the magnetic waste distribution (kg) collected by the ditch magnets in the different sections based on drilling length.

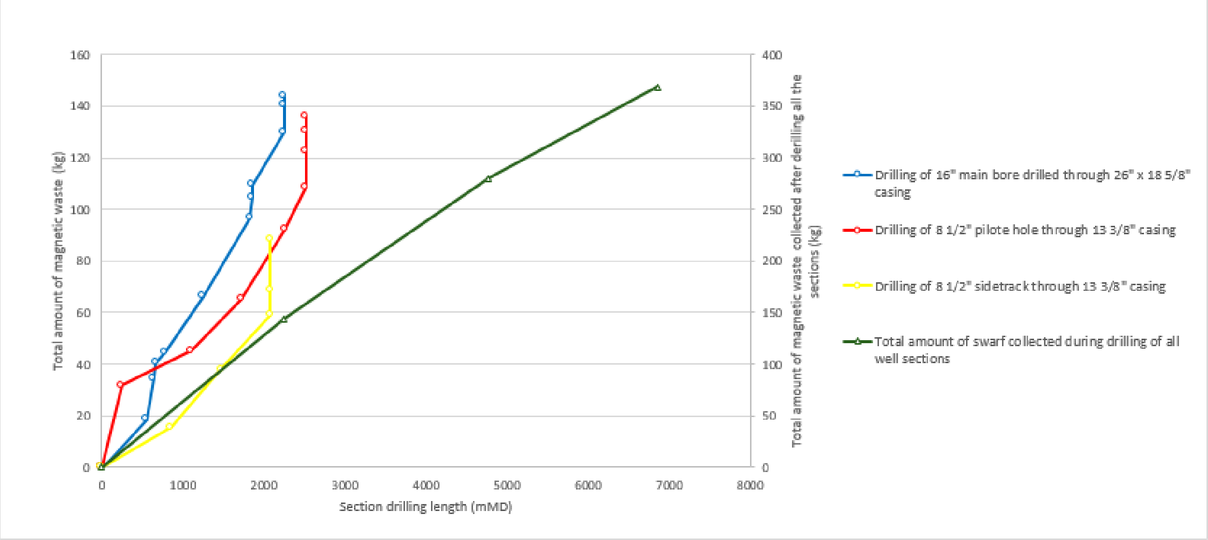

Figure 52: Magnetic waste distribution in the different sections as a function of drilling length in well B-5 with three magnets installed in the flowline.

The dark green line represents the cumulative amount of magnetic waste collected from the ditch magnets after drilling all the well sections to TD. From the other three graphs, the total amount of magnetic waste collected in each section is shown. Figure 53 shows the total amount of magnetic waste collected from the ditch magnets as a function of inclination and total drilling length. The inclination survey of every section as a function of drilling length is also showed.

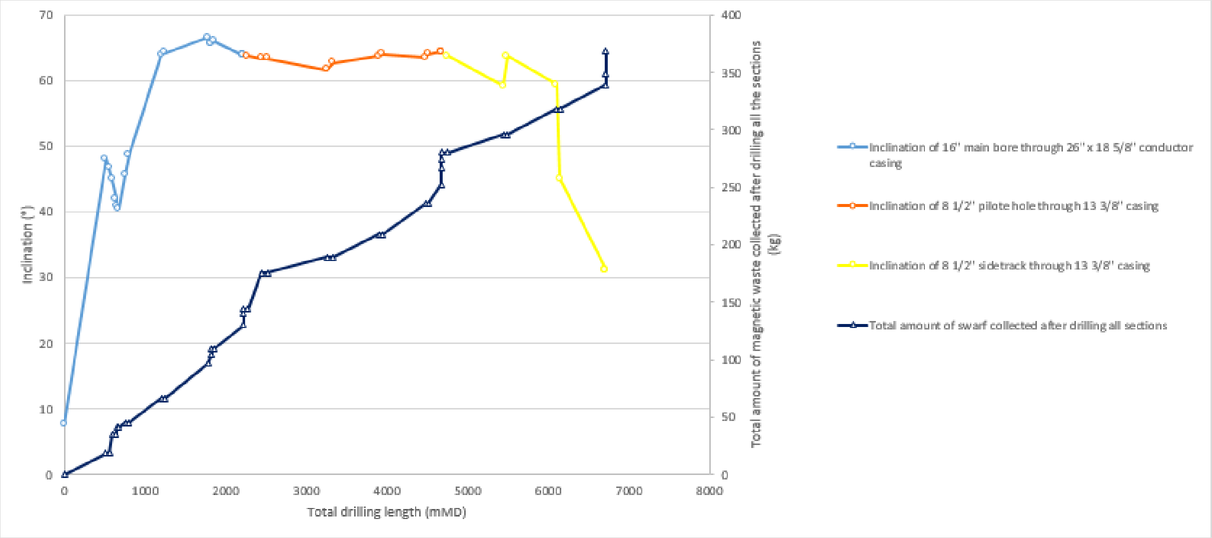

Figure 53: Magnetic waste distribution as a function of inclination and drilling depth in well B-5.

The two graphs shown in Figure 52 and 53, representing well B-5, show the correlation between inclination, drilling length and magnetic waste collected by the ditch magnets. From Figure 52 it is observed that the 16" hole section produces the largest amount of magnetic waste. Drilling of the 16” hole section is however commenced with high inclination variations in a drilling interval of 2253 mMD. In total, 143.8 kg of magnetic material was collected from the ditch magnets while drilling the 16” hole section. The inclination varied from 7.5 - 65.9° and is shown in Figure 53. A 26” × 18 5/8” conductor casing is used as conductor casing, decreasing the inner diameter of the casing at the bottom of the well section. It is anticipated that the inner diameter of the conductor casing, in combination with inclination variations throughout the well section, contributes to produce enormous amounts of magnetic waste from the 16” section.

The 8 ½” pilot hole section is drilled with a constant inclination in the area of 62-64° through the 13 3/8” casing. A total of 136.2 kg of magnetic waste was collected by the ditch magnets after drilling 2523 mMD. The 8 ½” sidetrack section collected 88.2 kg of magnetic waste, showing a decrease in the amount of collected magnetic material. However, if a closer look is taken on the inclination data from the two 8 ½” wellbore sections, it is seen that the inclination in the sidetrack section is less than in the pilot hole section. This may affect the difference in collected magnetic material from the two sections and may explain why less magnetic material is produced from the sidetrack section. In addition, the two 8 ½” hole sections were both drilled through the 13 3/8” casing, giving reasons to anticipate that the first run (pilot hole) experienced a smaller inner diameter than the 8 ½” sidetrack as metal of the casing could have been eroded in advance of drilling the sidetrack section.

Only three ditch magnets were installed in the flowline while drilling well B-5. This is anticipated to affect the overall ditch magnet performance.

3.4 Performance of the two ditch magnet systems

Based on the results presented in chapter 3.3, a further discussion is presented in order to better understand the performance of the two different ditch magnet systems and the difference between them. The effect from different parameters will be discussed and evaluated.

3.4.1 Ditch magnet performance with respect to drilling length

The effect from total drilling length on the performance of the ditch magnets has shown some miscellaneous results. According to the ditch magnet results collected from the semi-submersible drilling rig, there are no results indicating any correlation between the total drilling length of a well section and the ditch magnet performance. Well A-1, represented in Figure 38, shows that drilling of the longest well sections i.e. A12H and A12H T2, produced the smallest amounts of magnetic waste based on drilling length. Well A-2, represented in Figure 40, shows that drilling of well section A21H, A22H and A23H produced small amounts of magnetic waste compared to the total drilling length of the sections. Well A-3 showed results that didn't match with the previous two wells where similar amounts of magnetic waste was recorded from each well section. In addition, it was difficult to interpret the results in well A-3 as the well sections produced close to the same amount of magnetic waste based on drilling length. However, in the five wells drilled by the jack-up drilling rig, i.e. well B-1, B-2, B-3, B-4 and B-5, a correlation between the total drilling length and collected magnetic waste was observed. When the length of the drilled section was extended, an increase in the ditch magnet collection was observed for all the wells. This effect is illustrated in Figures 44, 46, 48, 50 and 52, representing the wells drilled by the jack-up drilling rig.

Based on the results from the two different ditch magnets, it is anticipated that the EZ-Clean ditch magnet installed at the semi-submersible drilling rig has a significant reduced recovery factor compared to the Magnetic Active Particle Separator (M.A.P.S) ditch magnets installed at the jack-up drilling rig. Well A-1 and well A-2 both have significant drilling lengths (12421.8m and 14266.5 m) and complicated well paths. These are all parameters which are anticipated to make a well prone to produce large amounts of magnetic waste. However, less magnetic waste is collected from these wellbores. Drilling of well A-3 did also produce small amounts of magnetic waste when total drilling length is considered and compared with the wellbores drilled by the jack-up drilling rig. Table 3 shows a summary of the ditch magnet performance from the two drilling units where average ditch magnet collection per meter is presented. In addition, the total amount of magnetic waste and drilling length are shown. The average ditch magnet collection is calculated by having the total amount of magnetic waste collected divided by the total drilling length of the well, excluding the length of the conductor casing.

Table 3: Average collected magnetic waste per meter from eight offshore oil wells.

Well name:	Total number of magnets in place:	Total drilling length (mMD)	Magnetic waste collected (kg)	Average collected magnetic waste (kg/mMD)
A-1	6 sticks	12421.8	46.231	0.00372176
A-2	6 sticks	14266.5	54.6	0.00382715
A-3	6 sticks	5766	31.1	0.00539369
B-1	8 double sticks	4227	122.07	0.02887864
B-2	8 double sticks	5839	376.4	0.06446309
B-3	3 double sticks	5765.2	109.8	0.01904531
B-4	3 double sticks	4393	73.7	0.01677669
B-5	3 double sticks	6857	368.2	0.05369695

From Table 3, the difference in collection ratio between the two ditch magnet setups is shown. All collection ratio values, representing the M.A.P.S ditch magnet, has a value of 0.016 kg/mMD or more while the collection ratio for the EZ-Clean ditch magnet has a maximum value of 0.0054 kg/mMD. The number of magnets installed in the flowline is also presented to demonstrate the effect of having more magnets installed in the flowline. Column number four shows the significant difference between the two systems when evaluating the total amount of magnetic waste collected from the ditch magnet. Although, it is important to take into consideration that the magnetic waste collected from the EZ-Clean ditch magnet is sieved through a 2 millimeter mesh size and washed with base oil before the sample is weighed. The magnetic waste from the M.A.P.S ditch magnet is not treated this way, leaving drilling fluid and other “junk” to be implemented in the final weight result. All wellbore data are presented in Figure 54 to better show the difference in total amount of collected magnetic waste from the different wellbores based on drilling length.

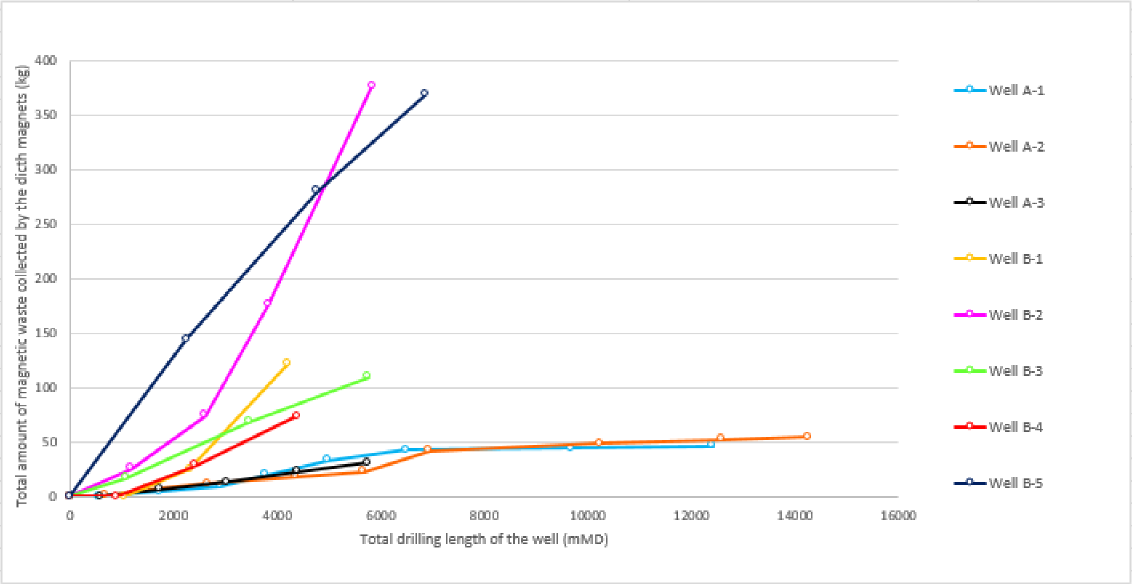

Figure 54: Total amount of magnetic material collected from each of the eight investigated wellbores.

3.4.2 Ditch magnet performance with respect to inclination

The effect of well inclination on the ditch magnet performance has shown itself to be significant for each of the eight investigated wells. Wellbore sections drilled with inclinations within the 20-90° interval has shown themselves to be the sections that produces the largest amount of magnetic waste. High inclination variations and bends in the wellbore generate regions where drillstring and casing wear may occur. This is anticipated to increase the production of magnetic waste material in the well and increase the ditch magnet collection performance.

Magnetic waste collection results from the eight investigated wellbores all support the statement indicating that inclination affects the total amount of magnetic waste produced in the wellbore. The EZ-Clean ditch magnets installed at the semi-submersible drilling rig increase the collection rate as the inclination increases above 20°. This trend is also observed for the M.A.P.S ditch magnets installed at the jack-up drilling rig. However, the M.A.P.S ditch magnets collect more magnetic waste (in kg) as the inclination increases above 20° than the EZ-Clean ditch magnet. This effect is represented in Figures 39, 41 and 43 for the EZ-Clean ditch magnet. The inclination effect for the M.A.P.S ditch magnets is represented in Figure 45, 47, 49, 51 and 53.

3.4.3 Ditch magnet performance with respect to casing size

Based on the results, a correlation between the size of the casing that is being drilled through and the total amount of magnetic waste collected from the ditch magnets is observed. The results are presented in Figures 38, 40, 42, 44, 46, 48, 50 and 52. The graphs in the figures show that as the diameter of the casing that is being drilled through decreases, the total amount of magnetic waste collected from the ditch magnets increases. The ratio of tool diameter to hole diameter is anticipated to affect the ditch magnet collection performance. A brief summary of these results is presented in Figure 55, 56 and 57 with one section drilled through the conductor casing, surface casing and production casing for each well.

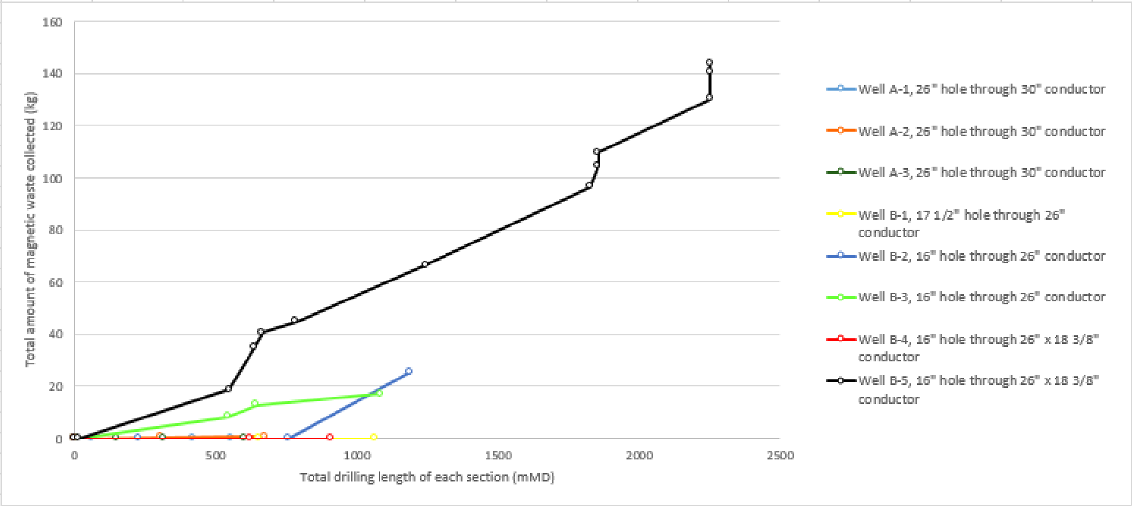

Figure 55: Drilling of the surface hole section through the conductor casing for the eight investigated wells.

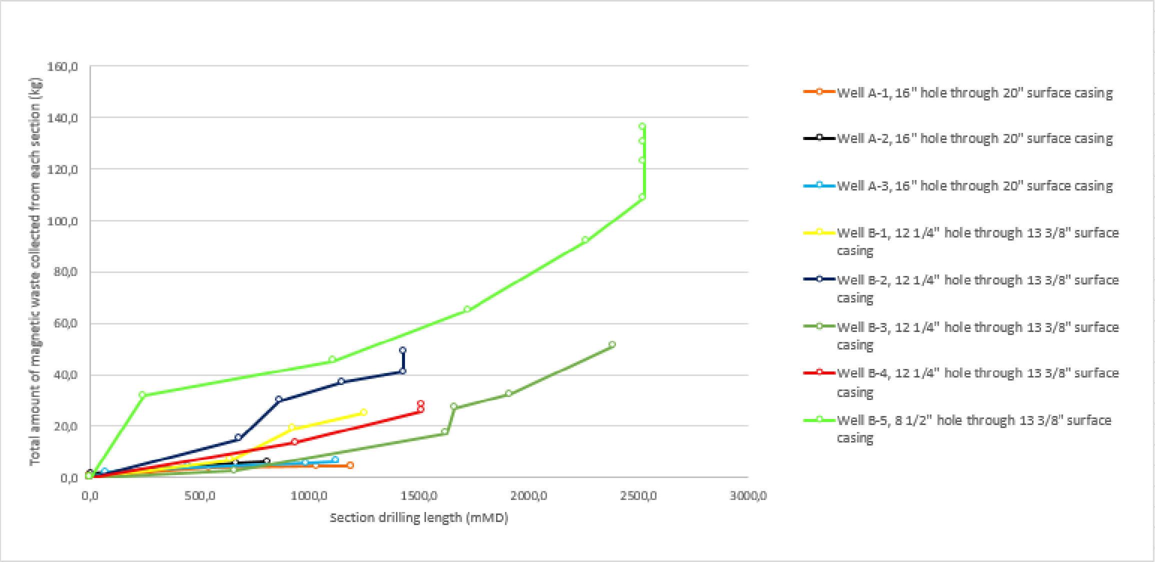

Figure 56: Drilling of the intermediate hole section through the surface casing for the eight investigated wells.

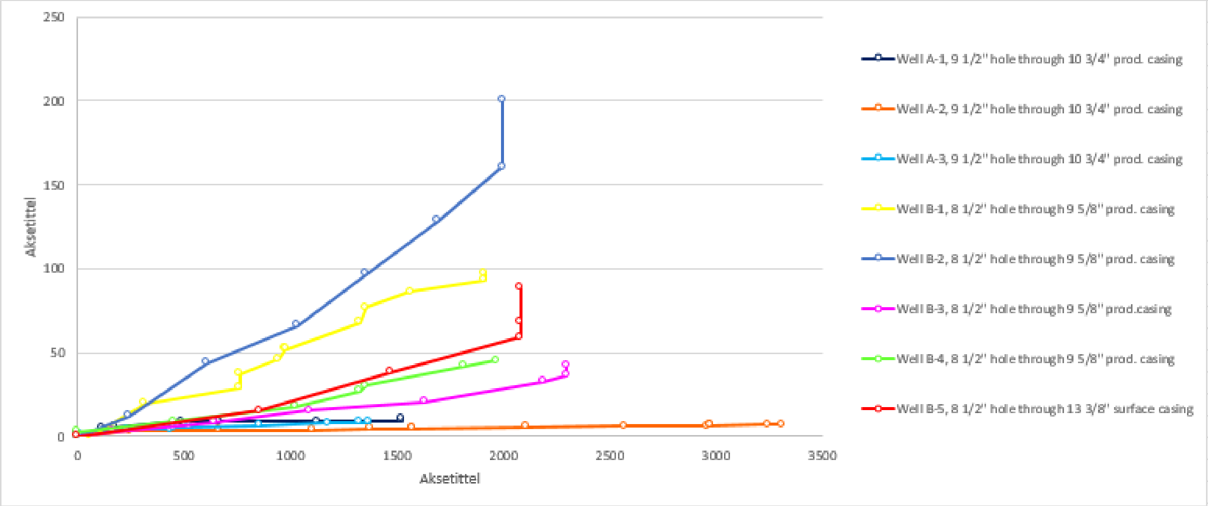

Figure 57: Drilling of the reservoir section through the production casing for the eight investigated wells.

From the graphs shown in Figures 55, 56 and 57, the effect of casing diameter on the ditch magnet performance, due to the ratio of tool diameter to hole diameter, are observed. A decrease in the inner cross sectional area of the casing reduces the space between the drillstring and the casing. This is anticipated to increase the probability of having contact between the casing and drillstring, causing wear to the system. For well B-5, an opposite trend has however been shown. Drilling through the largest casing section, the 26” × 18 3/8” conductor casing, showed itself to be the interval where the ditch magnets collected the largest amount of magnetic waste. It is, despite this result, anticipated that casing sizes less than or equal to 13 3/8” has a higher probability of producing larger amounts of magnetic waste than casings with larger cross-sectional areas as the distance between casing and drillstring is reduced.

3.4.4 Ditch magnet performance with respect to parameters affecting the final weight result

From the analysis there are observed several different errors to the final weight of the magnetic waste material collected from the two different ditch magnet systems. As described in chapter 2.4.4, there are different procedures for handling the ditch magnets and how the samples are weighed. At the semi-submersible drilling rig, the magnetic waste collected by the ditch magnets is washed with base oil and sieved through a 2 millimeter mesh size sieve before the final weight is noted. The weight of the sample bucket is also subtracted. At the jack-up drilling rig, there is no pre-wash of the sample, having both drilling fluid and other “junk” added to the final weight results. The weight of the bucket (150 gram), representing a very small value, is also included. This is anticipated to increase the overall ditch magnet performance of the M.A.P.S ditch magnet and increase the uncertainty connected to the performance as the weight of the drilling fluid and “junk” are added to the final result. On the other hand, no accurate formulas are developed yet where the “junk” and drilling fluid additives are implemented and subtracted from the final weight results. The effect from having the drilling fluid and “junk” added to the final weight of the M.A.P.S ditch magnet is not defined and therefore not evaluated. However, it is important to be aware of this uncertainty in advance of making any conclusions.

Which type of drilling fluid that is used and if it is a re-used drilling fluid or not, is anticipated to affect the overall ditch magnet performance. Based on experiments done by Torkildsen et al. (2004) [9] and Tellefsen (2012) [5], it has been found that used drilling fluids have a slightly larger dampening effect than fresh drilling fluids on the measurement while drilling (MWD) directional tool. In general, used drilling fluids contain initially more magnetic waste than fresh drilling fluids. It is anticipated that used drilling fluids increase the performance of the ditch magnets as more magnetic particles are suspended in the drilling fluid. From chapter 2.8 it is described that drilling fluids that are transported onshore for treatment have no procedures for removal of the remaining magnetic waste particles from the drilling fluid before they are transported back offshore. There are however no data available to confirm which sections are drilled with used drilling fluids and which sections are drilled with fresh drilling fluids. The effect from this factor is therefore not discussed any further.

As discussed for well A-1 and A-2, milling operations are anticipated to increase the general content of magnetic waste in the drilling fluid and by this, increase the overall ditch magnet performance. There are however no indications from the two wells, A-1 and A-2, which both conducted milling operations, that the ditch magnets performance increased after conducting the milling operation.

3.5 Summary of the two ditch magnet performances

Table 3 shows the significant difference in total amount of magnetic material collected by the two different ditch magnet systems. From the two highest collection rates, representing 376.4 kg for the Magnetic Active Particle Separator (M.A.P.S) and 54.6 kg for the EZ-Clean ditch magnet, a total of 321.8 kg differentiates the two results. This substantial difference is anticipated to be related to the efficiency of the magnets. The uncertainty, represented by the weighing method of the ditch magnet waste from the EZ-Clean ditch magnets, is anticipated to be small compared to the value representing the fines washed away from the EZ-Clean ditch magnet samples. Based on the SEM-analysis and the analysis of data, the M.A.P.S ditch magnet is anticipated to collect much more fines (small magnetic particles) than the EZ-Clean ditch magnet. The smallest magnetic fines are however the particles that are anticipated to cause the magnetic shielding of the Measurement While Drilling (MWD) directional tool [2, 4, 5, 13, 29] and have shown to be the hardest to remove. For this purpose, the M.A.P.S ditch magnets have showed to perform at a significant higher level than the EZ-Clean ditch magnet.

3.6 Benefits from having optimal removal of magnetic waste from the drilling fluid

An optimization of the ditch magnet performance, where the main objective is to increase the total amount of magnetic waste collected from the drilling fluid, is anticipated to improve the overall drilling operation up-time and cause significant cost reductions to the drilling operation. The wellbore may be drilled in a shorter time, errors to the MWD directional tools may be avoided and the accuracy of the directional tools may increase as the shielding effect from the drilling fluid is anticipated to be eliminated. In addition, it is anticipated to reduce damage to mud pumps, downhole tools and lessen wear on drill pipe/casing. There has, in the past years, been conducted experiments in order to develop a new cleaning method for drill cuttings by the use of microwaves [30]. If the drill cuttings, and the oil surrounding the cuttings, contain metallic and magnetic particles, there may be a risk of forming sparks and ignition of the cuttings. Optimal removal of the magnetic particles from the drilling fluid would eliminate this risk.

4 Conclusion

From the presented analyses and experiments, the performance and the importance of the ditch magnets have been discussed and some characteristics are found.

It was found that the Magnetic Active Particle Separator (M.A.P.S) is able to extract magnetic particles with a size of 0.5 micrometers from the drilling fluid. The SEM analysis of the particles collected from the EZ-Clean ditch magnet showed that particles with a size of 0.8 micrometers are extracted from the drilling fluid. The quantity of these magnetic fines are however not known and should be investigated further.

From the analysis of performance, the studies of the two different ditch magnet systems installed at the jack-up rig and the semi-submersible rig showed an evident difference in performance. From the investigated wellbore sections, it has been found that the Magnetic Active Particle Separator (M.A.P.S) collected more magnetic waste from the drilling fluid than the EZ-Clean ditch magnet in total weight per drilled length. This is both with respect to the total drilling length, inclination and size of the drilled through casing. The M.A.P.S ditch magnet system collects in average above 0.016 kg/mMD of magnetic waste from the drilling fluid during drilling. From the EZ-Clean ditch magnet, an average of 0.0054 kg/mMD or lower, of magnetic waste was collected from the drilling fluid. There are however several uncertainties to be considered in the presented results. Measurement accuracy of each ditch magnet sample, how much magnetic waste is left after the cleaning process, lack of data in the daily drilling reports (DDR) and the total volume of “junk” in the sample must all be considered.

It has been found that the performance of the ditch magnets, based on differences in drilling fluid density upstream and downstream of the ditch magnets, is impossible to observe by the use of a TRU-WATE™ Fluid Density Balance weight. The extent of uncertainties involved in the measurements makes no data trustworthy. In addition, the volume of magnetic waste collected from the drilling fluid in a 1-liter sample is extremely small when using the fluid balance weight. This makes it impossible to quantify the amount of magnetic waste particles using this technique. More accurate and reliable methods need to be used in order to determine if there are differences in the content of magnetic waste in the drilling fluid upstream and downstream of the ditch magnets.

Procedures for how the magnetic waste samples are weighed, the total drilling length of each section, the length of each casing, inclination etc. have been found to be parameters that affects the final weight results significantly. Methods used to weigh the samples are considered to be a decisive factor when the final weight result is evaluated. Still it is found that the M.A.P.S ditch magnet recover more steel material than the other investigated ditch magnet system.

Nomenclature

χ = magnetic susceptibility

B = magnetic field vector

H = magnetic field strength vector

F = Force

q = electric charge

T = magnetic torque

v = velocity

m = magnetic moment

j = current density

μ_0 = magnetic permeability of vacuum

V = volume

M = magnetization

ρ = mass density

A = molecular mass

BHA = bottom hole assembly

DD = directional driller

DLS = dog leg severity

M.A.P.S = magnetic active particle separator

mMD = meter measure depth

MD = measure depth

MW = mud weight

MWD = Measurement While Drilling

NCS = Norwegian Continental Shelf

OBM = oil based mud (oil based drilling fluid)

sg = specific gravity

TD = total depth

TVD = true vertical depth

WBD = water based mud (water based drilling fluid)

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