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Relief Well Drilling Using Surface Seismic While Drilling (SSWD)

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Abstract

Magnetic survey methods are used to locate the blowing wellbore when drilling a relief well. If no magnetic material is present in the openhole section of the blowing well, the last set casing shoe is the deepest possible intersection point. A deeper intersection point will increase the hydrostatic head, increase the frictional pressure drop and allow a lower density kill fluid to be used.

A new potential method called surface seismic while drilling (SSWD), could make it possible to intersect the blowing well below the casing shoe. This method is not dependent of any casing or steel tubular present in the well to identify the relative wellbore positions. The SSWD method is based on a surface seismic source generator and a receiver array located on the seabed. Preliminary simulations indicate that it is possible to locate the wellpaths of the two wells on the seismic data. This method will allow real-time seismic monitoring of the well paths without interfering with the drilling operation. This can allow for more precise relative wellbore positioning.

To investigate the benefits of a deeper intersection, a simulation model was prepared. A vertical offshore well consisting of 2000 meters of casing, and a 1000-meter openhole section were used. The well was killed dynamically by circulating seawater at high rates into the blowing wellbore. Compared to a casing shoe intersection, simulations show that a bottom hole intersection would reduce the flow rate and pump pressure by approximately 48% and 55%, respectively. The required kill mud weight was reduced by 24 %.

The seismic method may also be used in conventional well killing operation to provide additional information of the position of the two wellbores and potentially reduce the time needed to drill the relief well. This paper presents the SSWD method and the potential improvements in relief well drilling and well killing.

Introduction

A blowout is by far the most severe consequence of loss in well control. Because of the tremendous powers at play, a blowout can rapidly become a disastrous event. Large volumes of hydrocarbons and toxic gasses can be released to the surface, potentially causing huge environmental damage and put human lives at jeopardy. Considering the resources required to stop the blowout, penalties imposed on the liable, reduction in share values, lost hydrocarbon resources, and destroyed reputation of companies involved, a blowout often becomes a dramatic and costly ordeal.

If loss in well control escalates to a blowout, it is important that the well is brought under control fast and safely, and in a terminal manner. This might require a relief well to be drilled to intersect the blowing well at a certain depth, and kill it by pumping liquid into the blowing wellbore until overbalance is retained.

Modern relief wells are drilled to directly intersect the blowing wellbore. The target is often smaller than 10 inches and the depth can be several thousand meters. Conventional surveying techniques do not offer the accuracy needed to accomplish this, and for that reason ranging tools that home in on steel tubular in the blowing well is used once the relief well is close enough. This often means that the last set casing shoe is the deepest point available for a relief well. If an extended openhole section

exists below the casing shoe, this cannot be utilized during the killing operation.

The SSWD method uses conventional seismic equipment together with specialized setup, procedure and processing to accurately display both wells on the seismic image. The method is based on the principle that the wellbores represent a reflective and refractive object for the seismic waves, and therefore is not dependent on the presence of steel in the wells. This means that the blowing well potentially can be intersected at a deeper point. A deeper intersection point will be favorable during both dynamic- and static killing because a lower flow rate and lighter fluid density are needed to balance the flowing pressure of the blowing well. This will reduce the pump requirements on the kill rig, and reduce the pressure in the openhole section of the blowing well.

Description of the SSWD method

Surface seismic is used for general mapping of the subsurface, identification of oil and gas accumulations and for monitoring of reservoir changes associated with production of oil and gas. When collecting surface seismic, the depth below the surface (z-axis) is measured in two-way travel time for the sound waves. Horizontal distances (x- and y-axis) are measured in meter. In drilling operations the depth (z-axis) is measured in meters. To convert between the two domains (depth conversion) the velocity of the subsurface rocks must be known. Velocity information is often uncertain and consequently drilling prognosis is also uncertain.

Surface seismic are low resolution data and the frequency content of the signal is reduced with burial depth. The assumed typical normal resolution is one quarter of a wavelength. With a typical center frequency of 50 Hz and a velocity of 2000 meters/sec the seismic wave length is 40 meters. This means that the bed resolution thickness is 10 meters. Seismic is also used in the borehole. The principle was investigated as early as in 1930. Today several techniques exist, with different application and limitations. A typical system consists of a source to create a seismic signal, and receivers to record these signals. All borehole seismic techniques utilize a setup where one component (source or receiver) is located on the surface, and the other in the borehole. Hence the "one-way travel time" of the waves is recorded in contrast to surface seismic where it is the waves that have travel both ways that is utilized. Today, borehole seismic is used extensively worldwide.

Here we use surface seismic for continuous seismic observation of a wellbore as it penetrates into the subsurface (Johansen et al., 2014). In this way the drilling operation can be monitored in real time on seismic displays as illustrated in Figure 1. Now, both the seismic reflectors representing rock formations boundaries and the seismic signals from the wellbore will be visible in the same seismic section. To achieve continuous imaging, a limited part of the original seismic survey must be repeated several times during drilling. The SSWD acquisition will not disturb ongoing drilling operations in any way.

We see from the example mentioned above that a borehole is below the normally assumed resolution for surface seismic. In addition it complicates the case that long sections of the bore hole is vertical and will for this reason not easily reflect seismic energy back to the surface. However, it has been shown that it is *theoretically* possible to see a thin object like a borehole on surface seismic (Arntsen et al., 2014).

To test if the SSWD concept has the potential to be used in practical drilling operations forward seismic modeling was used. A two-layered earth model including one vertical well was used to verify the general concept, see Figure 2. To illustrate how the well can be displayed on a more realistic seismic section we modeled a section with a vertical borehole in a detailed geological model based on exposed geology from outcrops as illustrated in Figure 3.

Matlab was used to build the flat-layered models, and Petrel was used to build the more complex model. To construct the final impedance models representative P-wave velocities, S-wave velocities, and densities from strata drilled in the North Sea were used, and a water layer was added on top of the model, see Figure 3. The simulated seismic sections were generated by a 3D elastic wave propagation modeller that uses a high order space and a second-order time finite-difference scheme. The inputs to the modeller are grids of P-wave velocity, S-wave velocity, and density from the geological models.

The result from the forward seismic modeling of the conceptual model is shown in Figure 2. The formation boundary is imaged as expected. The bottom of the well and the point where the borehole crosses the formation boundary are also clearly visible on the seismic image. But, also the vertical part of the well is visible. This result is promising since the well is far below what is normally considered a detectible object by standard surface seismic techniques. The response from the borehole will be reduced with depth. The reason for this is that a seismic signal travelling through the subsurface is attenuated and the amplitudes reduced with depth. The high frequency signals have lower penetration depth than the low frequency signals. This also means that the expected accuracy of the method is reduced with depth as the high frequencies content is gradually decreased with increasing depth.

If the SSWD method works in practice as indicated on the simulated seismic, it will allow for direct and continuous positioning of the well path on the seismic section or in the seismic cube. This opens for a wider use of surface seismic in drilling operations.

Blowout control

A blowout is brought under control in three stages. These are detection and response, containment of harmful liquids and finally control. First the rig and all equipment must be shut down, any fires put out, rigs in danger must be moved and personnel evacuated. Secondly the oil spill must be contained to minimize environmental damage. Thirdly the blowout must be killed (Adams & Kuhlman, 1994). Several different methods are used to bring the well back to overbalance, and hence stop the inflow from the reservoir. The method that is going to be used must be evaluated according to its success factor, the time and cost of implementation, and the safety of the operation. Often several methods are deployed to secure the fastest and safest termination of the blowout.

A blowout is brought under control by retaining a pressure overbalance in the blowing wellbore. Once the wellbore pressure is higher than the pore pressure in any exposed permeable formations there cannot be any fluid inflow. This overbalance is obtained by displacing the blowing wellbore to a kill fluid. If the kill fluid has a sufficient density to balance the formation pressure in static conditions, the blowout is statically dead. If the fluid is circulated at a certain rate to create a supplementary frictional backpressure to reach overbalance, the blowout is dynamically dead (Adams & Kuhlman, 1994).

Killing techniques can be classified as either top kill- or bottom kill techniques. Top kill refers to techniques where the blowing well is entered at the surface, whereas a bottom kill refers to techniques where the blowing well is entered at a certain depth. The most common top kill techniques are capping- or surface stinger operations. Capping is performed by replacing the wellhead and blowout preventer stack, shut in the well and subsequently bullhead a heavy fluid into the wellbore to obtain static overbalance. A stinger operation is performed by forcing a stinger assembly with a packer into the blowing well and set the packer hydraulically at a predetermined depth. At this point kill fluid is bullheaded through the stinger and into the blowing well in a similar manner as during a capping operation (Adams & Kuhlman, 1994).

Top kill techniques require access to a casing string with the required integrity to handle the forces from the blowout and the killing operation. This is to prevent rupture of a weak casing string or fracturing of openhole formations, both potentially causing an underground blowout. In addition to this the surface conditions must allow work to be performed in close proximity to blowing well. If this is not the case, a bottom kill might be the only alternative.

A bottom kill requires a relief well to be drilled and obtain hydraulic communication with the blowing well at some point along the wellpath. Hydraulic communication between the wells is obtained through direct intersection, hydraulic fracturing, acid or fluid squeeze, perforating or with the use of explosives (Wright & Flak, 2006). Heavy fluid is pumped into the blowing well to increase the bottom hole pressure. A bottom kill operation can be less complicated because the fluid does not have to be pushed against the direction of flow, as opposed to a top kill operation.

Today relief wells are commonly drilled to directly intersect the blowing wellbore, establishing full hydraulic communication between the two wells. This minimizes fluid- and pressure loss during the killing operation. The uncertainty regarding the absolute position of the both wellbores makes it necessary to utilize some method to establish the relative distance and direction between the relief well and target. Modern relief wells have a very high success factor (de Wardt et al. 2013). However, a bottom kill is a time-consuming process. The relief well will normally take a longer time to drill than the blowing well because of the time required to home-in on the target, and potentially because of the required relief well trajectory. This causes a relief well operation to be more expensive than top kill techniques.

Conventional relief well planning and execution

A minimum of two surface positions for a potential relief well should be present before drilling of any well, or cluster of wells. Accurate information about water depth, seabed and sub-surface drilling hazards, seabed topography, anchor holding capacities and obstructions must be present. The shallow gas risk must be acceptable and seismic interpretations of the subsurface must be available. Wind and current considerations must be taken into account so that toxic and flammable fluids or gasses do not pose any dangers to the relief well drilling operation (NORSOK standard D-010, 2013).

During planning, the last set casing shoe is often set as the deepest point reachable utilizing conventional ranging techniques. This is because the drill pipe might be at a higher point when the inflow takes place, or because blowing fluids may move the drill string. Further local legislations may dictate how many planned relief wells can be utilized to bring the blowing well to overbalance. These limitations might put severe limitations on casing design or hole dimensions during planning of an offshore well.

A relief well is spudded with a certain horizontal offset from the blowing well. This is to ensure that surface conditions at the relief well site are not affected by the blowout, and to fulfill certain trajectory requirements. Relief wells often have a S-shape. Once the kick off point has been reached the well angle is built to the planned inclination to move in on the target. The incident angle between the two wells at the intersection point should be between 1 and 5° (JWCO, 2009). This gives the greatest ability to make trajectory adjustments, increases accuracy and reduces the possibility of a sidetrack if the wellbore is missed. Depending on the trajectory of the blowing well this usually means that the relief well must be dropped back to a lower angle before intersecting.

One of the most challenging aspects of relief well drilling is to determine the position of the two wellbores with high enough accuracy to be able to perform a direct intersection. Errors inherent to conventional wellbore positioning tools, related to running procedures and borehole environment adds up with depth and create an ellipse of uncertainty around each well. Further, once the two wells are within a certain distance of each other, magnetic interference from steel tubular in the blowing well will corrupt measurements while drilling (MWD) readings, potentially increasing the positional uncertainty of the relief well. Because of this, north-seeking gyros are commonly used in this stage if the uncertainty becomes too large (Oskarsen et al. 2003).

Before the relief well has progressed to the point where the uncertainty ellipsoids overlap, and the chance of premature intersection exists, ranging tools are deployed to evaluate the relative distance and direction to the target (de Wardt et al, 2013). These specialized tools measure the magnetic signal from steel tubular in the blowing well, and subsequently home in on the target. However, these have a certain detection range and it is essential that conventional borehole positioning surveys can position the two wells within this distance of each other without the risk of premature intersection.

Conventional borehole positioning surveys

As a well is being drilled positioning surveys are being performed at fixed intervals to determine the true path of the wellbore. According to NORSOK standard D-010 (2013) at least one survey should be performed for every 100 meters drilled. At every survey point depth, azimuth, inclination and toolface angle is measured. The position of the wellbore is determined by taking the sum of these vectors. The measured wellbore positions are tied together using different methods, depending on the assumed shape of the well, to create the wellpath.

The depth measurement is usually determined by finding the total length of drill pipe or wireline that has been run into the hole. However, the length of the steel can change as a result of pipe stretch, temperature effects or other environmental or operational effects. In addition, some uncertainty exists in the measured length of each pipe segment. Because of this, the uncertainty regarding the measured depth of the well is highly dependent on the running procedures and operator skills and is reported to be between 0.5 to 2% (Wolff and de Wardt, 1983).

Magnetic surveying tools are used together with accelerometers to find azimuth, inclination and toolface angle. Magnetic tools are robust and have been integrated into the bottom hole assembly (BHA). This means that a survey can be completed during a connection when the pipe is at rest, and the results can be transmitted to surface using mud telemetry. Since magnetic tools measure the local magnetic field, they are also very susceptible to environmental disturbance. Any steel present, from casing, drill pipe, drill collars, nearby wells, crustal anomalies or magnetic storms can cause large errors in the survey. Magnetic tools also show poor results when used in near vertical boreholes. This is because the horizontal component of the earth's magnetic field becomes small, and difficult to measure. When drilling in east-west direction, the accuracy of magnetic tools is also reduced (Samuel & Lui, 2009).

Gyroscopic surveying tools consist of a highly balanced spinning wheel, mounted on a gimbal. Because of the high spinning rate applied to the wheel a moment of inertia is created. This will keep the wheel at a given position, regardless of the position of the surveying tool itself (Samuel & Lui, 2009). The direction of the gyro wheel is set at the surface, and this will act as the reference point when the survey is performed downhole. Once the gyro is back at the surface, the direction is measured to account for any gyro drift (Wolff & de Wardt, 1981). Wrong setting of the gyro at surface or wrong calculation of the operational drift will cause errors in the survey.

The gyro is a high precision instrument and is very sensitive to mechanical shocks and vibrations as this may knock the wheel out of its initial position. Since a small amount of friction will act between the wheel and the gimbal, some drift will be experienced during the running of the gyro tool. This is dependent on the borehole direction, dogleg severity, running procedures, time required to perform the survey, temperature, gyro construction, gimbal balance, and the earth's rotation. This will cause the gyro to drift during the survey. If this drift is constant, it can be accounted for easily, and the results corrected. However, the drift is observed to be nonlinear, and this might cause errors in the survey results (Wolff & de Wardt, 1981).

A gyro survey is not affected by magnetic disturbance and is often used if steel is present, or if a particularly accurate survey is needed. This can be before a kick off is planned, before entering the reservoir, when other wells are close or inside the casing. Recently gyroscopic surveys have been integrated into the BHA as well, however high quality surveys often has to be performed on separate wireline runs.

Development of ranging tools

Up until the 1970s the majority of relief wells were drilled according to the same principle. The relief well was directionally drilled to intersect the flowing reservoir, as close to the blowout well as possible, utilizing conventional borehole positioning surveys. At this point fluid was pumped into the relief well to obtain hydraulic communication between the two wells. Because of the large uncertainty with regards to bottom hole position of the wells, two or more relief wells often had to be drilled to achieve control. This strategy worked particularly poorly on deep wells, low permeability reservoirs or high rate blowouts (Wright and Flak, 2006).

During 1970 a Shell operated well in Mississippi blew out spewing toxic hydrogen sulfide and lighting the rig site on fire. The surface conditions made any top kill efforts to bring the blowout to a halt impossible. This spurred the development of new technology. A wireline tool was developed to measure the local magnetic field around the relief well. Since this would be distorted by the remanent magnetization found in steel casing located in the blowing well, these measurements were used to calculate distance and direction to the target. The relief well was drilled close to the casing of the blowing well, and after several sidetracks perforating guns were used to obtain hydraulic communication at around half of total depth (Grace, 1994). This method resulted in a patent but was never commercialized.

During a blowout in Texas in 1975, a wireline tool was developed. This tool also measured the remanent magnetization in steel casing located in the blowing well. However, the approach differed from the previous method in that the magnetic gradient was measured along the wellbore of the relief well. Since the gradient from the earth's magnetic field would be small and uniform over the distance of the relief well, and the gradient from the relief well casing would be larger, the two signals could be differentiated and the distance and direction to the target could be calculated. The detection range of this tool was approximately 10 meters (Grace, 1994). This tool represented the state of the art for some years following this event. The tool is stil commercially available through a proprietary hardware, software and interpretation tool package.

In 1980 a 5700-meter deep blowout in Louisiana prompted the development of another tool. Arthur F. Kuckes, applied and engineering physics professor at Cornell University, was contacted. He proposed that active electromagnetic ranging could be used to locate steel in the blowing well. This was done by placing an injector electrode near the wellhead, together with remote return electrodes located on either sides of the wellhead, 1400 meters apart. A current was injected into the ground and the low resistance of the steel casing provided an excellent flow path for the flowing current, subsequently creating a magnetic field circumfering the casing of the blowing well. An extended lateral range electrical conductivity (ELREC) wireline tool was used to measure the magnetic field strength and direction, and made it possible to calculate the relative distance between the targets. The blowing well was directly intersected at 2900 meters TVD and successfully killed (Kuckes et al. 1984).

The intersection depth utilizing surface injection was limited by the resistivity of the downhole formations. In 1982 active electromagnetic ranging were developed further by integrating the injector electrode into the survey string. The string consists of magnetic sensors at the bottom of the string, and an alternating current injector located 100 meters further up the string. The sensor and injector was connected by an insulated bridge cable and attached to a standard logging wireline. The downhole electrode injected a uniform alternating current radially into the surrounding formation. If the current reached the steel casing of the blowing well, the current would choose the path of least resistance, short circuit and create an electromagnetic field around the target tubular. The sensors in the bottom of the relief well could measure the imposed magnetic field, and calculate the relative distance between the wells (West et al. 1983).

State of the art of ranging techniques

Today, both passive and active ranging tools are used to locate the relative position of one borehole compared to another, and are used both for well avoidance and well intersection. All methods rely on magnetic measurements.

Active ranging techniques can be divided into two categories, depending on whether or not access is possible in both wells. If both wells can be accessed, a source tool can be lowered into the target well to produce a magnetic field that can be picked up by a receiver magnetometers in the intersecting well. The source can be an AC solenoid, DC electromagnet, electric wireline or strong permanent magnets. This method offers the highest range and accuracy of all ranging methods (de Wardt et al. 2013).

During a blowout access to the blowing well will probably not be possible. To intersect a blowing well using active electromagnetic ranging an electric current is applied to steel tubular in the blowing well to create a magnetic field around the target. If surface conditions allow, and the target casing can be accessed at the wellhead, the current can be applied topside. However, depending on formation resistivity this method is only applicable for targets down to a certain depth.

Over the last 25 years, active electromagnetic ranging with a downhole injector electrode has been the preferred method to facilitate direct intersection of a blowing wellbore (de Wardt et al. 2013). As of today this technology is only available through a proprietary tool. This tool has a maximum ranging distance of between 40 to 60 meters, depending on the resistivity of the formation. The uncertainty has been reported to be 20-30% for the first ranging surveys (Grace, 1994). By performing a triangulation bypass, drilling past the blowing wellbore before dropping down to parallel, the uncertainty is reduced to 10%. Once the distance between the relief well and target has been reduced to 3 to 4 meters, the direct relative distance can be calculated by measuring the magnetic field gradient difference between two magnetometer sensor probes in the tool (de Wardt et al. 2013).

A variation of this tool exists, which enables the active electromagnetic ranging tool to be integrated into the BHA. This tool contains a battery powered probe in a bit sub and can be used to perform ranging surveys without the need to pull the drill string out of the hole. The range and accuracy is reduced compared to the wireline tool, depending on incident angle and formation resistivity the range is between 20 and 40 meters (de Wardt et al. 2013).

Today passive magnetostatic ranging tools have been integrated into the MWD-package, eliminating the need to use wireline. This can decrease the time used to home in on the blowing wellbore, since less tripping must be performed. In addition, circulation is maintained on bottom reducing potential openhole issues. MWD integrated passive magnetic ranging is offered through several different service companies.

Steel is naturally ferromagnetic, however the magnetism is randomly distributed along the material giving no net magnetic signal. Because of this passive magnetostatic ranging surveys rely on the remanent magnetization originating from the manufacturing process or magnetic inspection procedures (de Lange & Darling, 1990). Under ideal conditions passive magnetostatic ranging can have a detection range of above 20 meters and is not dependent on formation resistivity (van Noort et al. 2012). However, the strength and distribution of the magnetization is highly unpredictable and the condition of the target casing often unknown. This makes interpretation of the measurements highly complex (de Lange & Darling, 1990). This has caused several passive magnetostatic MWD guided relief wells to miss their target, requiring several sidetracks or alternative methods to secure intersection (Grace, 1994).

The range and accuracy of passive magnetostatic ranging tools can be increased if the target casing is magnetized to saturation. This is done using an electric coil before the casing string is lowered into the hole. Recent investigations showed that this would increase the maximum ranging distance of passive ranging tools to beyond 40 meters (van Noort et al. 2012).

Homing in on a blowing well

The first ranging point is usually located at least 300 meters above the final intersection point. This is to allow the relief well to be dropped to parallel with the blowing wellbore, and to allow course correction before intersection is made (JWCO, 2009). Depending on uncertainty regarding the initial position of the blowing well and the uncertainty related to the ranging tool, the first ranging survey is performed at a horizontal distance of between 20 and 60 meters to the target.

To accomplish a direct intersection using active ranging techniques, 10 to 15 ranging runs are normally required. The drill string must be pulled out of the hole, the ranging string run into the hole and the measurements taken, and the drill string must be lowered down again to continue drilling. Depending on the depth of intersection, a ranging run can take from 6 hours and up to three days.

Intersection facilitated by passive magnetostatic ranging requires a different relief well drilling strategy. Often the uncertainty regarding the position of the target wellbore is larger than the maximum range of the magnetostatic tools. Because of this, the ellipse of uncertainty must be investigated in a systematic way. This involves tracing across the ellipse of uncertainty, starting at the boundary of the ellipse and carefully move in on the calculated target position (Abel & Towle, 2003).

Hydraulic communication and killing operation

The blowing well is killed by circulated kill fluid into the blowing wellbore to increase the bottom hole pressure and regain overbalance. This can be accomplished by injecting a kill fluid with the required density to balance the pressure at static conditions, or by circulate a lighter fluid into the blowing well at high rates to create a frictional backpressure to supplement the hydrostatic pressure. The latter is referred to as a dynamic kill (Adams & Kuhlman, 1994).

Once intersection has been made the relief well will experience total losses into the blowing wellbore. Hence the drilling mud used to drill the last section is used as the initial kill fluid. The mud window and required drilling fluid properties will dictate what fluid should be used at this stage. Fluids can be changed during the operation, and this is referred to as a staged kill operation.

It is important that the bottom hole pressure in the relief well is higher than the pressure in the blowing well to prevent influx from the blowing well into the relief well. Because of the pressure differential between the wells kill fluid will flow from the relief well and into the wellbore of the blowing well. As this takes place kill fluid is pumped into the relief well to prevent the fluid level, and hence the hydrostatic pressure, in the relief well to drop. Depending on the required kill operation parameters surface pumps can be used to increase the volumetric flow rate. To minimize pressure loss in the relief well, fluid is pumped through both kill and choke lines, and potentially through the drill pipe as well.

Depending on the surface pressure required to obtain the necessary flow rate, the mud pump circulation system and/or high-pressure cement pumps can be used. The friction pressure loss in the relief well is important because this pressure does not contribute to increase the bottom hole pressure, but must be delivered by the rig pumps. If the pump pressure required becomes too large, conventional surface equipment might not be strong enough. If this is the case several relief wells might have to be drilled to limit the flow rate in each well and still deliver the required kill fluid rate to stop the blowout.

Usually water based kill fluid is used, however if the well is blowing from a HPHT reservoir oil based mud might be required to prevent the kill fluid from starting to boil. The density that can be used depends on the specific mud window and is limited to around 2.2 SG to secure suspension of weighting material. As a heavier liquid is injected into the blowing well the hydrostatic pressure exerted on the flowing formation from the fluid column is increased. As the bottom hole pressure rises, the pressure differential between the flowing formation and the blowing well is reduced, causing a decrease in the inflow from the reservoir. Frictional forces acting between the fluids and the borehole wall, and between different phases in the well, create a pressure loss throughout the well. By injecting kill fluid at a high rate, the frictional pressure can supplement the hydrostatic pressure in the blowing well, reducing the required kill fluid density.

If the blowout fluid has high gas content and large flow potential, the killing operation becomes more complex. It can become difficult to increase the wellbore pressure because the injected kill fluid is diluted to a large extent and blown out of the well by the large volumetric flow from the reservoir. These blowouts can require a higher injection rate to kill successfully.

It is important to monitor the bottom hole pressure during the dynamic killing stage to ensure that the pressure in the wellbore does not exceed the formation strength and a fracture is created. This can lead to lost circulation and further complicate the killing process. The bottom hole pressure can be monitored through the drill string by circulating at a low rate to open the flapper valve and measure the surface pressure. It is important that the rate is low enough to minimize frictional pressure loss through the drill string. If frictional pressure loss in the relief well is a concern, kill fluid can be circulated at a high rate through the drill string as well. If this is the case, the bottom hole pressure can be recorded by pressure while drilling (PWD) tools integrated into the BHA. Once the well is killed dynamically, a fluid with the sufficient density to balance the reservoir pressure is injected into the well. During displacement to static kill fluid the bottom hole pressure must be monitored and the injection rate reduced as the well is being filled with heavy fluid as not to fracture the formation.

Once all reservoir fluids are circulated out of the well above the injection point, reservoir fluid exists below the injection point. This rat hole must be displaced to kill fluid before the well is statically dead. This is done simply by letting the lighter fluid in the bottom of the well rise to the surface or by bullheading heavy fluid down into the well and the reservoir fluid back into the reservoir. This can be a time-consuming process, and can subject the openhole section to high stresses.

SSWD in relief well drilling

In relief well drilling, SSWD can be used in combination with conventional technology to guide the relief well close enough to steel tubular in the blowing well to apply magnetic ranging tools. This can potentially reduce the time associated with MWD- and gyro surveys and reduce the overall number of ranging runs required. In addition, SSWD can be used to continuously perform check shots to obtain time-depth information, increasing the accuracy of the seismic data. Further, data obtained from SSWD can be compared to data from MWD, logging while drilling and rate of penetration. This can be used to update original seismic data with accurate formation properties. This will further increase the accuracy of the method and allow for accurate geosteering-, anti collision or well placement purposes. SSWD may also potentially be used as a look ahead of the bit tool to identify potential dangerous zones before drilling into them. This will increase the safety and effectiveness of the relief well drilling process.

If the SSWD method functions as anticipated and offers the high degree of accuracy needed, it can be used as a standalone method to facilitate direct intersection of a blowing well independent of the presence of steel in the target wellbore. If an extended openhole section exists below the last set casing shoe, SSWD may be used to intersect the blowing well at a deeper point. This will offer a several advantages to the killing operation.

By intersecting the blowing wellbore at a deeper vertical depth a higher column of kill mud can be obtained, reducing the required static kill mud weight and wellbore pressure in the unprotected openhole section. Further, the increased flow length will give a higher frictional backpressure for a given injection rate, reducing the dynamic kill rate. In addition, the pressure at

the injection point will be higher. If the reservoir fluid consists of gas or an oil containing gas, the volumetric flow rate can be significantly lower at this point. This will lead to a lower degree of kill fluid dilution, and a quicker pressure build up in the blowing well (Adams & Kuhlman, 1994).

Generally, a relief well will take a longer time to drill than the blowing well because of an aggressive well trajectory and because of the time associated with the homing in process. The time used on ranging runs vary greatly depending on the techniques used and the depth of investigation. The drilling time will increase when intersecting at a lower point because a longer relief well is needed to reach the target. However, since SSWD-surveys can be performed independently of downhole operations, the non-drilling time is greatly reduced. Graph 1 illustrates an idealized time vs. depth curve for both conventional relief well drilling and a relief well utilizing SSWD and intersecting the bottom of the well.

Simulation

A simulation model was prepared to investigate the benefits of a deeper intersection point utilizing the SSWD method. An idealized well profile was used together with typical well properties. The blowing well is located offshore with a water depth of 150 meters. The well consists of 2000 meter intermediate casing and an openhole section of 1000 meters. The source of inflow is located at 3150 meters TVD. The reservoir fluid consists of black oil with a composition as suggested by Pedersen et al. (1989). This mixture has a gas oil ratio of $162.2 \text{ Sm}^3/\text{Sm}^3$, oil density of 742 kg/m^3 and oil viscosity of 1.360 cP at standard conditions. The bubble point pressure is 290 bar. The reservoir pressure and temperature is 400 bar and 100°C . Figure 4 shows the relief wells intersecting the blowing well at the casing shoe and the the bottom.

A commercial process modeling software were used together with regression analysis to find temperature and pressure dependent properties for the oil mixture. The compressibility factor of the associated gas is calculated using Standing's correlation for pseudo-reduced properties (Whitson & Brulé, 2000) together with Hall & Yarborough's equation of state (1973). The equation is solved using the Newton-Raphson method. The gas phase viscosity is calculated using a correlation suggested by Ohirhian and Abu (2008).

The blowout rate was calculated by progressively increasing the in-situ inflow rate until the hydrostatic- and frictional pressure loss in the well was high enough to balance the pressure at the wellhead, as suggested by Hasan et al. (2000). This was done by dividing the blowing well into 3000 segments, each spanning one meter. The input pressure of the deepest segment was set equal to the bottomhole flowing pressure. During the first simulation the in-situ inflow rate was set low. All fluid properties were calculated for the given pressure, temperature and flow rate. The pressure drop over the 1-meter segment was calculated using the Beggs and Brill method (1973) to account for liquid holdup, flow regime and interfacial tension between the oil and gas phase. The input pressure of the next segment was set equal to the output pressure of the previous section. This process was repeated until calculations had been performed for the entire well. If the pressure at the wellhead was not balanced, the in-situ inflow rate was increased and the process was repeated.

To simulate a dynamic killing operation a given rate of water with a given amount of weighting material is injected into the blowing well at a certain depth. The effective liquid mixture viscosity between two immiscible fluids is calculated using the Brinkman equation (1952), and the average properties are updated to account for the added fluid. The new blowout rate is calculated, and the relief well injection rate is increased until the in-situ inflow rate from the reservoir is zero.

Assumptions in simulation model

It is assumed that the reservoir can deliver the required flow rate to balance the wellhead pressure. This is dependent on the area of exposed productive sandface, effective permeability, pressure differential and viscosity of pore fluid among others. A reservoir productivity index term can be included into the simulation model, however it was deemed more sensible to use a reservoir that could support the calculated blowout rate, as the production capabilities of a reservoir is dependent on many factors and outside the scope of this paper. The dynamic kill rate and fluid density required to retain overbalance will theoretically not be affected by the production capabilities of the reservoir (Leraand et al, 1992).

Further only stabilized injection- and blowout rates are included in the simulation model. As kill fluid is introduced into the blowout wellbore a kill fluid front will propagate upwards in the well progressively increasing the hydrostatic pressure and the frictional pressure loss. Even though the required density and flow rate to balance the reservoir pressure is injected into the blowing wellbore the inflow from the reservoir will not seize because the kill fluid front must reach the surface, and because the kill fluid is diluted by a lighter reservoir fluid. However, as kill fluid is distributed in the system the overall density of the fluid column increases. This will cause the bottom hole pressure to increase, and the pressure differential between the blowing well and the reservoir will decrease. This reduces the inflow as described by Darcy's equation. Since the inflow from the reservoir is reduced, the kill fluid is diluted to a lesser degree, further increasing the density of the fluid column. This transient behavior will continue until equilibrium is reached. Since only stabilized rates are simulated this transient phase is not considered. Because of this, the time required to kill the well is not evaluated, nor whether it is more beneficial to flush the blowing well with a higher density or volumetric flow rate in order to bring the blowout to a stop as soon as possible.

As a base case, the simulation was performed without any obstructions in the blowing well. In a blowout situation tubular, plugs and equipment used in the drilling, completion or workover process might be present. Debris from the blowing reservoir or collapsed formations might also be present and choke the flow. This will lead to a lower blowout rate, and subsequently a lower dynamic kill rate. This can easily be included in the simulation by changing the hydraulic diameter of certain parts of the wellbore.

It is assumed that the injected fluid is immiscible, and will not form a homogeneous mixture with the hydrocarbons from the reservoir. Instead a continuous phase will form, and the other phase will be dispersed as tiny bubbles or slugs in the continuous phase. Because of this, interfacial tension will create additional frictional forces. Initially hydrocarbon will form the continuous phase, but as the water fraction increases inversion will take place and water will form the continuous phase.

Further, it is also assumed that the gas phase never reaches sonic velocities along the flow path. Since this is the maximum velocity the gas can reach, it will naturally be choked if sonic velocities are reached. Simulations showed that the gas mixture never reached sonic velocities for an offshore blowout because of the added hydrostatic pressure. However, this should be taken into account for onshore blowouts.

In addition, the well shape and casing program were assumed equal for both wells. This was done to purely evaluate the benefits of a deeper intersection point and ignore the changes well trajectory or dimensions would make on the killing operation. When utilizing SSWD to intersect the blowing wellbore it might not be necessary or beneficial to drill past and parallel to the blowing well. This can simplify the relief well trajectory. Further, depending on the pressure regime in the overburden a deeper intersection point may require an additional casing string to be run. This will cause the flow area in the relief well to be smaller and therefor increasing the surface pressure.

Simulation result

Figure 5 shows the simulated wellbore pressure and pressure loss when no kill fluid is injected into the blowing well. Figure 6 and 7 show the difference in hydrostatic- and frictional pressure loss for bottom hole- and casing shoe intersection for different relief well injection rates. Figures 8 and 9 show the wellbore pressure for casing shoe- and bottom hole intersection, respectively.

Using seawater as the injection fluid, the simulation shows that a deeper intersection point would reduce all critical values during the killing operation. For casing shoe intersection the dynamic kill rate was simulated to be 290 l/s, the static kill mud density was 1728 kg/m³ and the maximum casing shoe pressure was 354 bar. For a bottom hole intersection the dynamic kill rate was 151 l/s, the static kill mud density was 1308 kg/m³ and the maximum casing shoe pressure was 278 bar.

Further, the relief well surface pressure and kill rig pump requirements were calculated for both cases. Depending on injection strategy the surface pressure ranged from 508 to 1494 bars for casing shoe intersection and 244 to 617 bar for bottom hole intersection. The minimum required pump power were calculated to be 19759 hp for casing shoe intersection and 4942 hp for bottom hole intersection. Hence the deeper intersection point reduced the dynamic kill rate with 48%, the surface pressure with between 52 and 59% and the minimum pump power requirement with 75%. The casing shoe pressure was reduced by 21% during dynamic killing and 23% when the well was statically killed.

Offshore drilling rigs typically have a mud circulating system capable of delivering between 4800 and 8800 hhp, and have an output pressure rating of 345 or 517 bar. This depends on what kind of mud pumps the rigs are configured with, and the number of pumps available. Based on an analysis of 82 active drilling rigs operating in the North Sea it was found that the average available pump power was 6000 hp, and 48% of the rigs had a pressure rating of 517 bar (offshore.no, 2013).

If the surface pressure during the killing operation surpasses the maximum output pressure of the mud circulation system, it cannot be used during the dynamic killing operation. If this is the case, cement pumps must be used to deliver the required dynamic kill rate. Typical offshore cement pumps have a maximum output pressure of between 1035 and 1379 bar. The number of cement pumps needed is dependent on pump type, discharge pressure and flow rate.

As described earlier a bottom intersection reduces the required dynamic kill rate and the high surface pressure experienced during dynamic killing. This can enable a standard offshore drilling rig to drill the relief well and perform the kill operation, and consequently reduce the time associated with mobilization of equipment and lead to a faster termination. It can also reduce the cost of the operation since less equipment is needed. Off bottom intersection increases the dynamic kill rate, and subsequently the surface pressure and pump power requirement. This can potentially mean that the mud circulation system is not rated for the discharge pressure needed, and a large number of cement pumps must be used. Depending on available deck space this might require additional pumping vessels or even a second kill rig.

In extreme cases the surface pressure might become too large for surface equipment to handle, in that case an additional relief well must be drilled. Local legislations might prohibit such a well to be drilled in the first place, or the casing program for the planned well must be altered. A method that enables the bottom of the well to be intersected at all times might aid in a safer construction of these wells.

In addition, a bottom hole intersection reduced the wellbore pressure during both dynamic and static killing. This can be crucial if the open hole section consists of weak formations. During dynamic killing from the casing shoe, the wellbore pressure in the open hole section will increase as the injection rate is increased. This might cause the formations to fracture during killing, potentially leading to losses and further well integrity issues. The opposite is true for injection at the bottom of the well. As the injection rate is increased, the pressure in the open hole section is decreased. So, there is no danger of fracturing the formations during the dynamic killing operation.

Conclusions

- If the SSWD method works in practice as indicated on the simulated seismic, it will allow for direct and continuous positioning of the well path on the seismic section or in the seismic cube.
- A field test is needed to verify the concept and the accuracy. If the accuracy proves to be sufficient, this method opens for a wider use of surface seismic in drilling operations.
- SSWD may be used in combination with conventional ranging tools to increase the safety and potentially reduce non-drilling times during a relief well operation. If the accuracy is high enough it can also be used as a standalone method to intersect a blowing wellbore.
- SSWD is not dependent on any steel present in the blowing wellbore to facilitate direct intersection between the blowing well and the relief well. This makes it possible to intersect a blowing well in the bottom of the openhole section.
- A deeper intersection point is favorable during a killing operation because the dynamic kill rate and static kill mud density is reduced, the pump pressure required can be reduced, the casing shoe pressure is reduced, a faster pressure buildup can be achieved and a smaller rat hole needs to be displaced after the well is dead.
- Government regulations might prohibit the drilling of wells that will be difficult to kill with only one relief well. A method that offers the advantage of intersecting at the bottom of a blowing well independent of the presence of steel will be valuable because it can give greater flexibility with regards to casing depths and wellbore dimensions.

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Figures

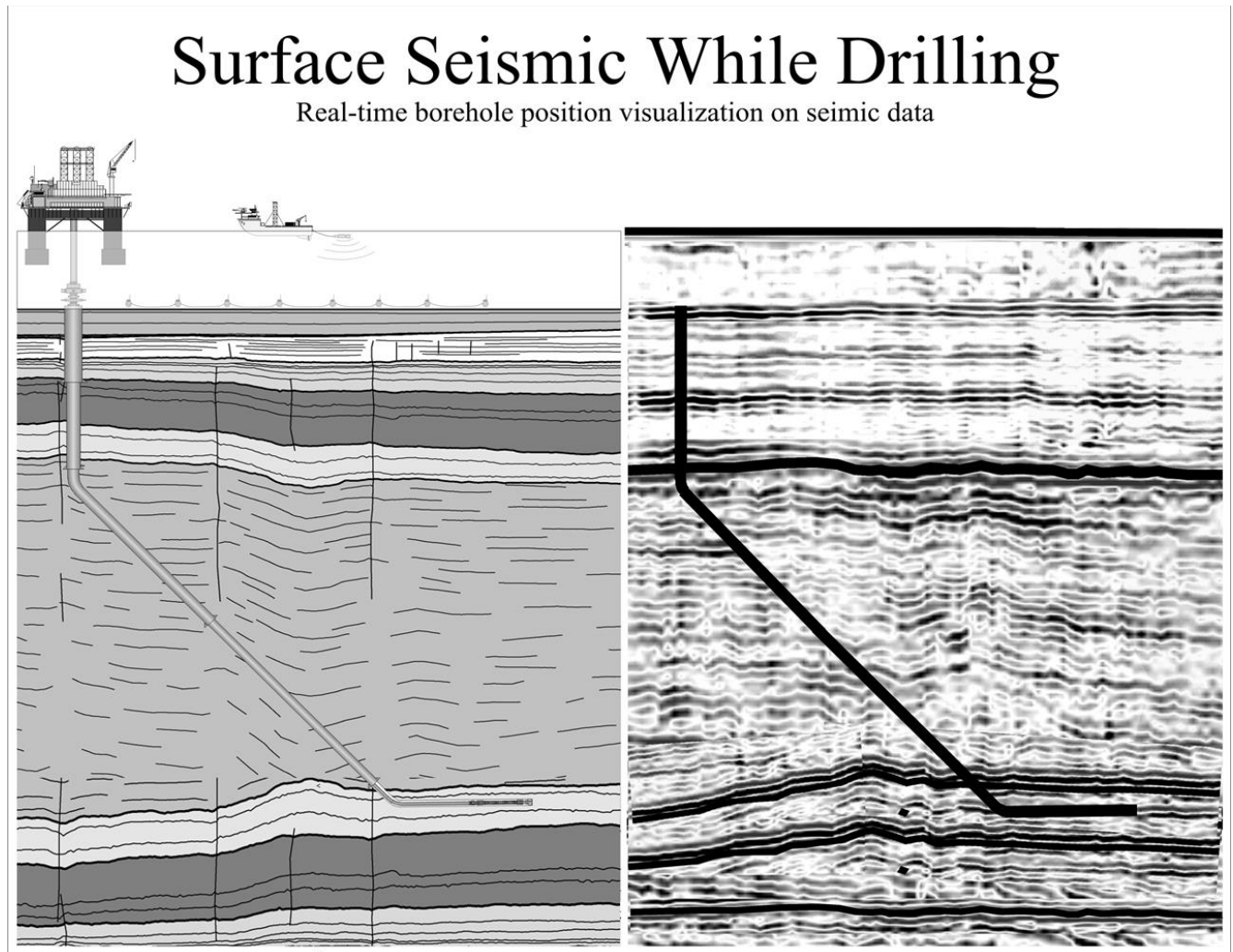


Figure 1 - Direct monitoring of the drilling operation using surface seismic has the potential to increase safety and drilling accuracy.

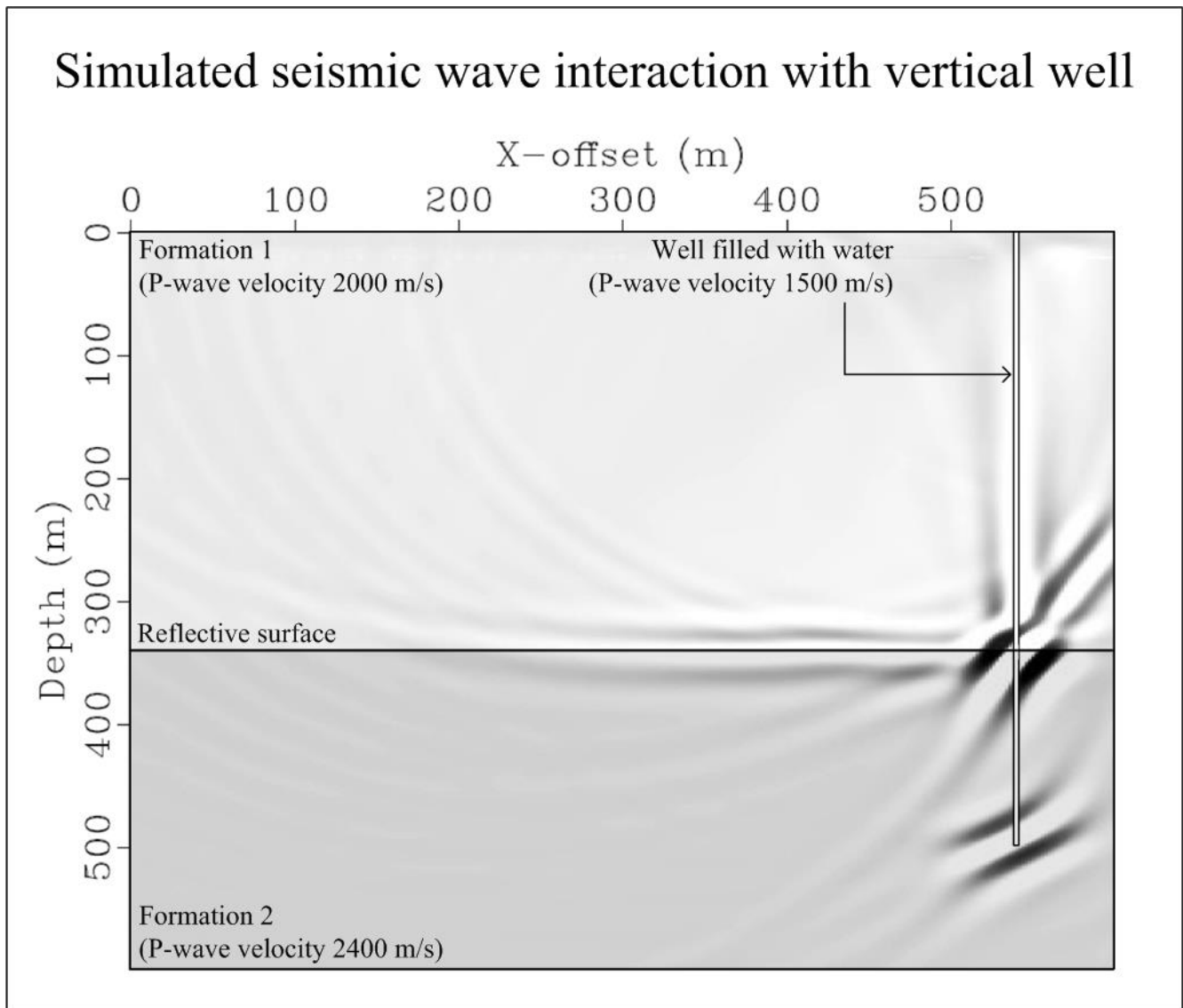


Figure 2 - Although normally below resolution for standard surface seismic a borehole can be visible on a carefully processed seismic section. It is the diffractions from the bottom of the well and where the well crosses the formation boundary that have the clearest responses. But, the indirect reflection from the vertical borehole itself is also visible.

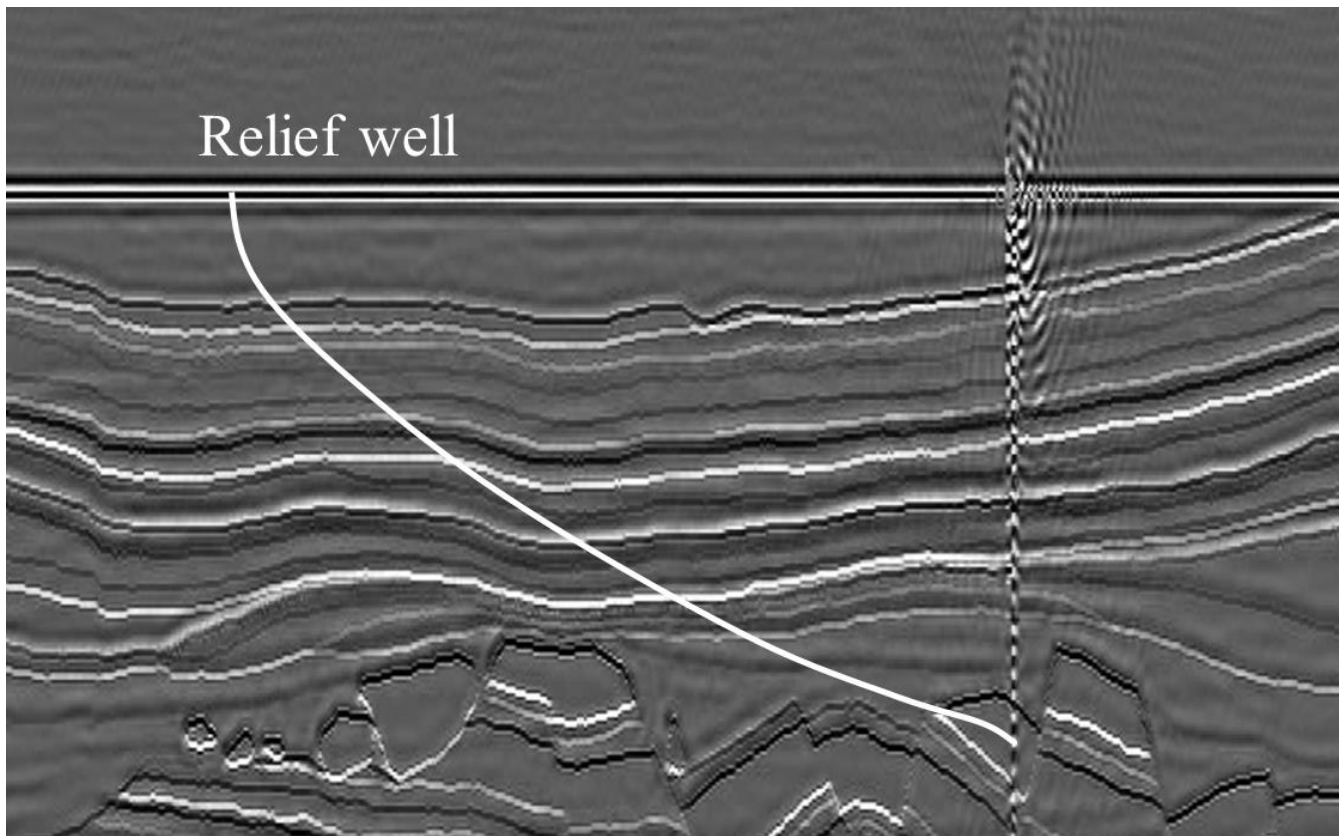


Figure 3 - The target for a well is defined on seismic data, and the well prognosis is made from the interpreted seismic section. Depth conversion is done to convert from two-way seismic travel time to a normal depth scale in meters used in the well prognosis. This modeling result shows how the vertical borehole can be displayed on the seismic section itself. We also show how a conceptual relief well could be monitored on the same seismic section.

Casing shoe-versus-bottom-hole intersection

Evaluating critical aspects of relief well killing operation

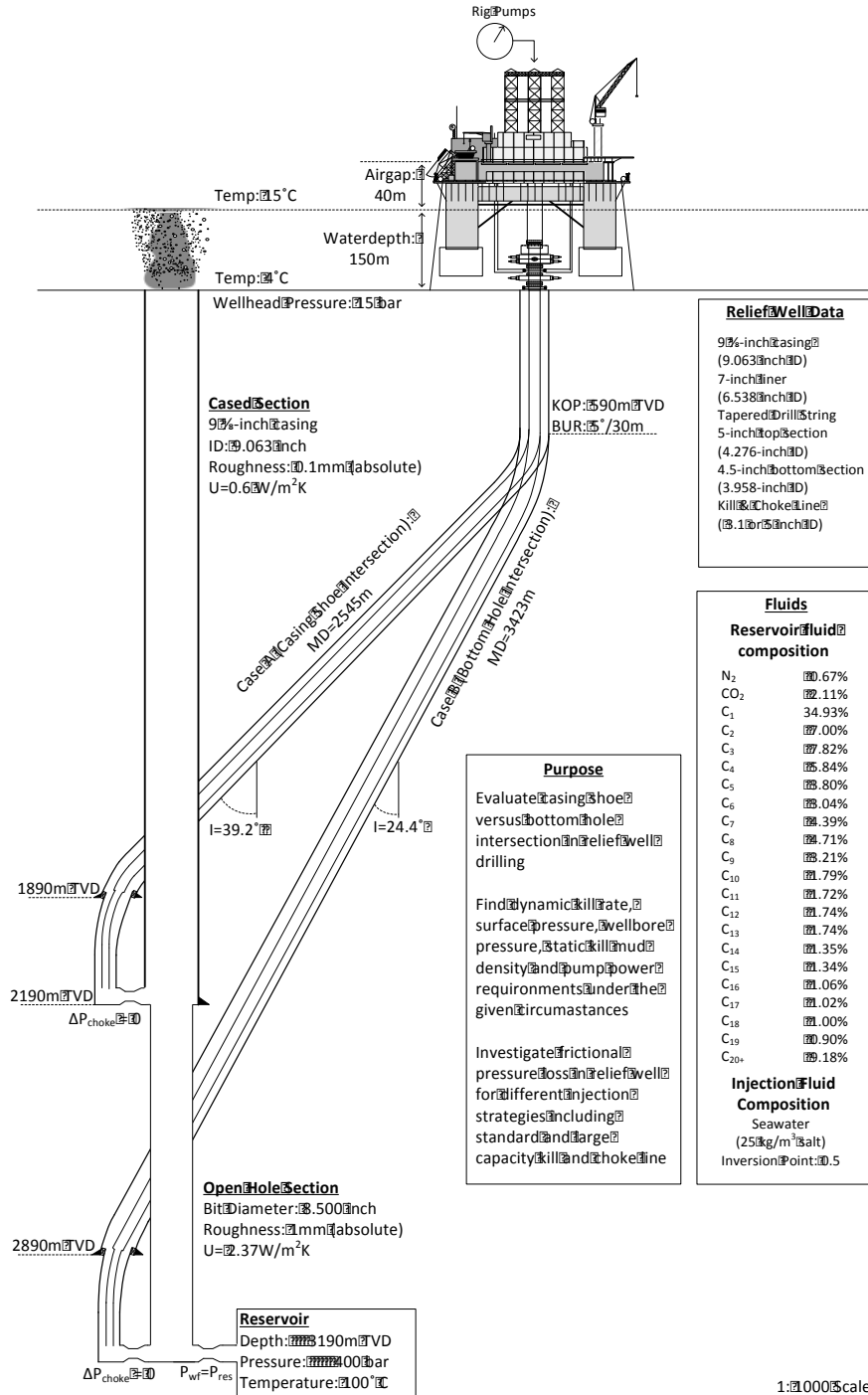


Figure 4 – Schematic of simulated well

Depth versus Time

(Illustrative case)

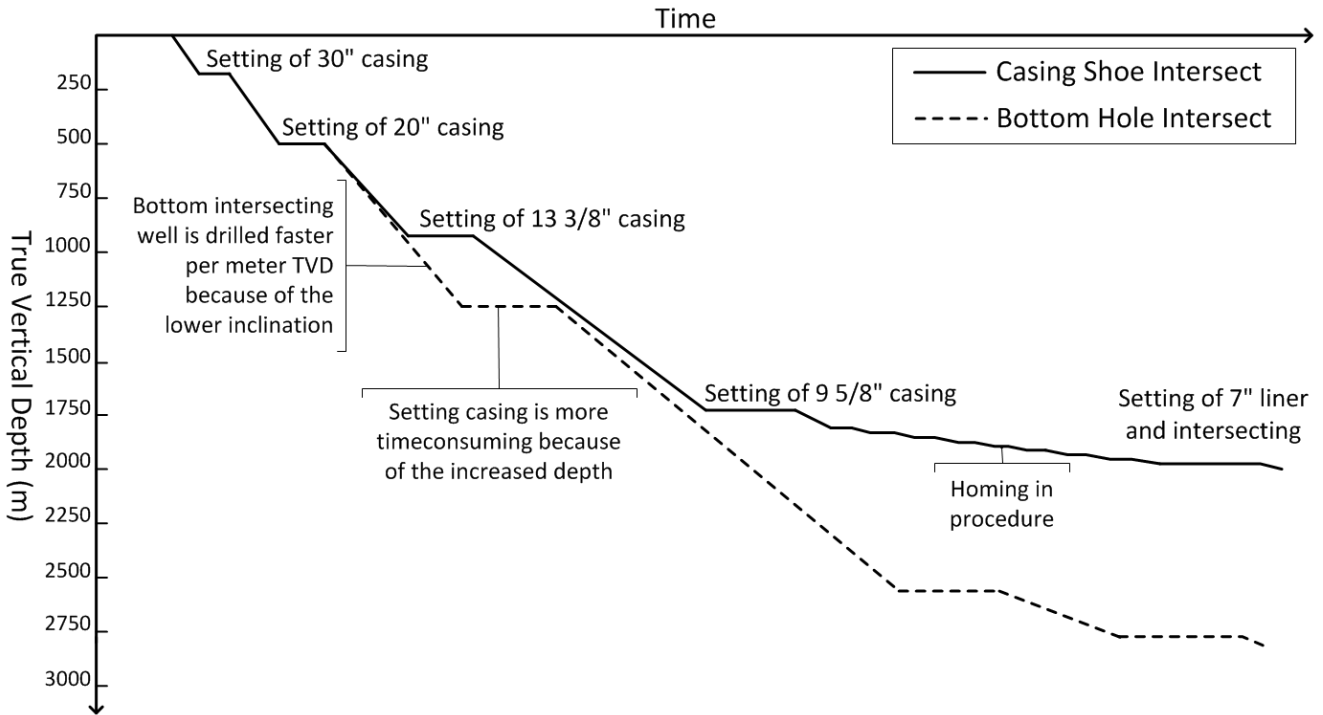


Figure 5 – Illustration of time vs. depth curve for casing shoe- and bottom hole intersection

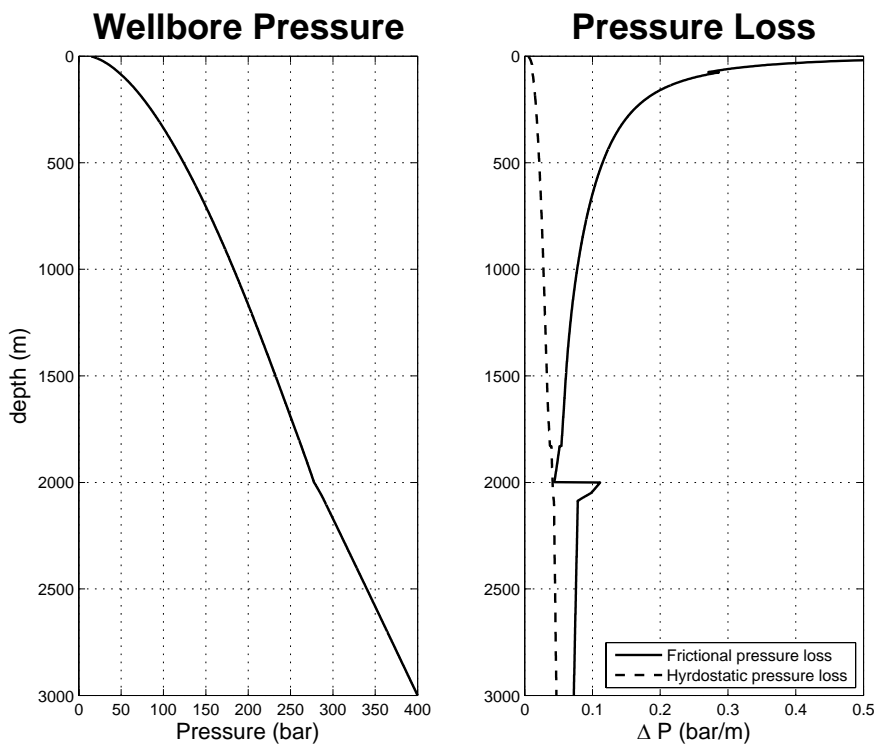


Figure 6 – Wellbore pressure and pressure loss in blowing well without kill fluid injection

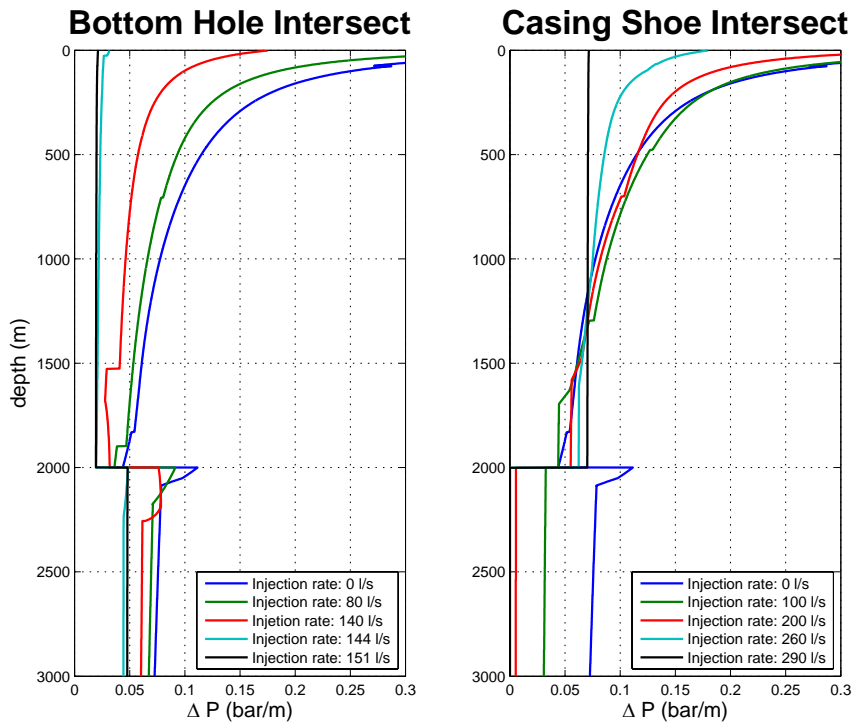


Figure 7 – Frictional pressure loss during kill fluid injection

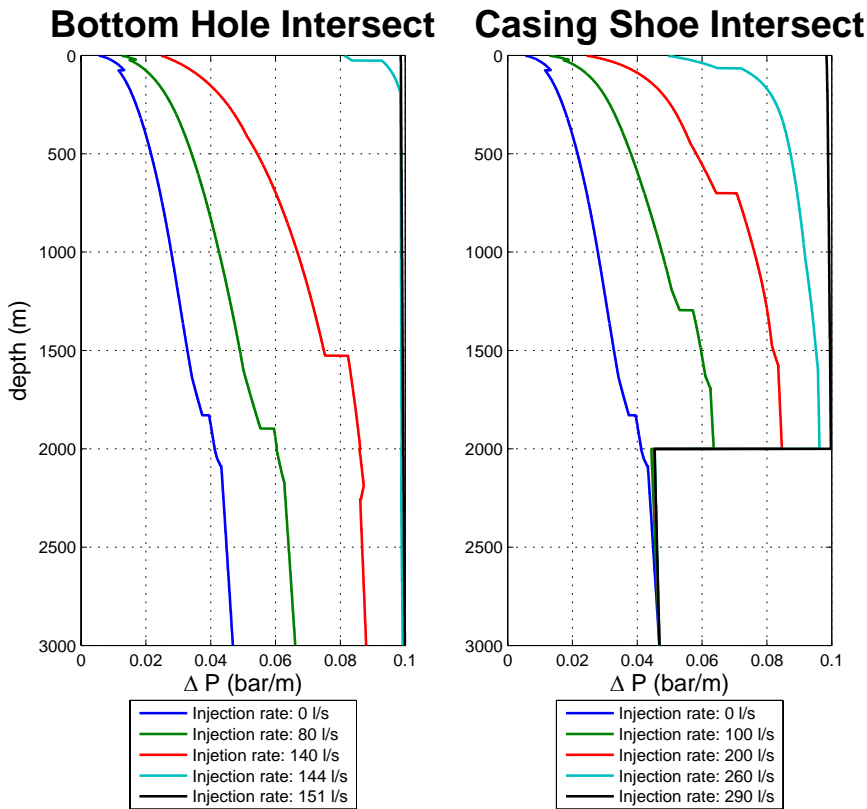


Figure 8 – Hydrostatic pressure loss during kill fluid injection

Wellbore Pressure – Casing Shoe Intersect

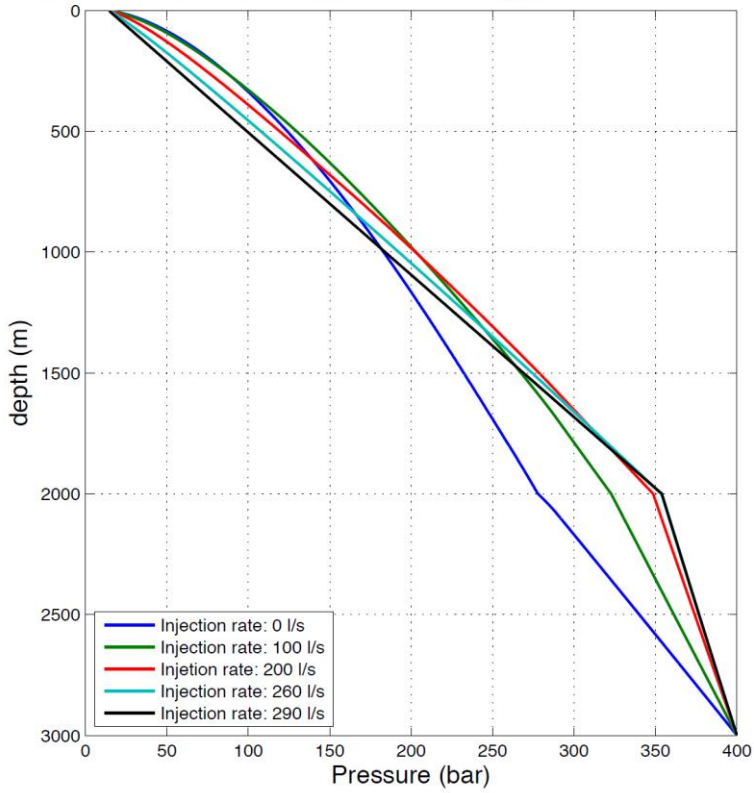
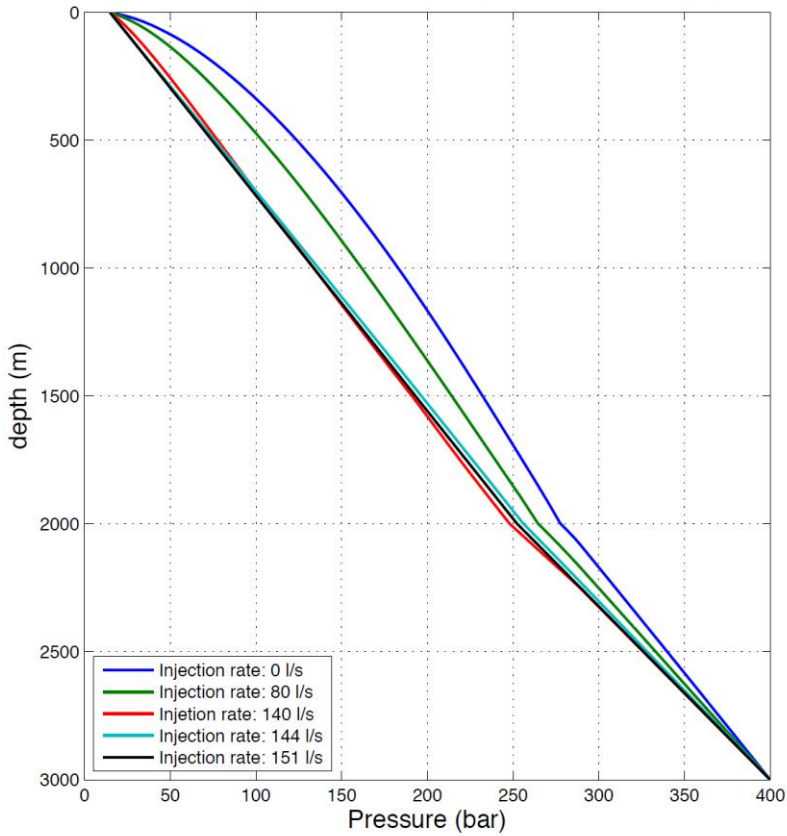


Figure 9 – Wellbore pressure during kill fluid injection at casing shoe

Wellbore Pressure – Bottom Hole Intersect



Graph 6 – Wellbore pressure during kill fluid injection from bottom of well