Surface Seismic Monitoring While Drilling using Diffractions - Concept and Field Data Example

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SUMMARY

Diffractions from boreholes can be made visible using surface seismic data, subject to certain favorable conditions. This makes diffraction processing and imaging a more natural complement to the Surface Seismic monitoring While Drilling (SSWD) method than traditional reflection processing, which suffers from limitations in illumination and resolution. We discuss the SSWD method in combination with diffraction imaging and demonstrate its potential on a field data set.

INTRODUCTION

Surface Seismic monitoring While Drilling (SSWD, Evensen et al. 2014) is a new technique to monitor the drilling of a borehole using surface seismic acquisition only. It has prospective applications in the monitoring of regular drilling operations, geosteering, as well as relief well drilling. Advantages of SSWD compared to conventional Seismic monitoring While Drilling (SWD, which uses receivers located in the borehole, see, e.g., Mathiszik et al. 2011) are that the monitoring does not require interruption of the drilling operation and that it does not depend on the presence of steel in the wells. SSWD therefore potentially allows more efficient and accurate wellbore positioning.

Boreholes, and vertically aligned subsurface objects in general, are traditionally seen as difficult to detect and image using surface seismic data. Two main challenges are lack of illumination and resolution, which both prevent a clear reflection signal. Borehole diameters are typically much smaller than the dominant seismic wavelength: less than 1 m versus about 40 m for a frequency of 50 Hz and medium velocity of 2000 m/s. The detection of boreholes on surface seismic data is therefore a question of ultra-high resolution detection and imaging. Løseth et al. (2011) demonstrate that some vertically aligned objects can be made observable as pipe-shaped anomalies on surface seismic data. Raknes and Arntsen (2014) show that under certain conditions objects much smaller than the seismic wavelength can also be detected on surface data.

Diffractions appear to be a natural choice for the detection of vertically aligned objects, and boreholes in particular. By their very nature, diffractions have much more favorable illumination properties, which allow them to detect vertical boreholes even on a regular limited surface acquisition. In addition, diffractions have, at least in theory and under idealized circumstances, the ability of super-resolution imaging, that is, the recovery of structural details much smaller than the seismic wavelength. In Moser et al. (2016) the detection of boreholes by diffractions on surface data is discussed in detail and a number of conceptual examples are presented.

The purpose of this paper is to further develop the concept of SSWD using diffractions and demonstrate the detectability of boreholes by diffractions on a field data example.

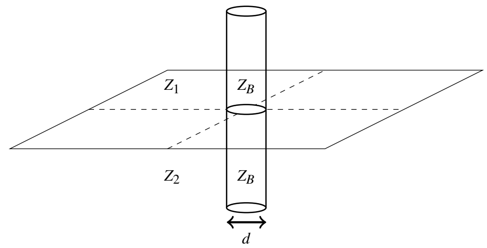

Figure 1: Parameters defining diffraction response from borehole: diameter d and impedance contrast of borehole (Z_B) with host rock (Z_1, Z_2).

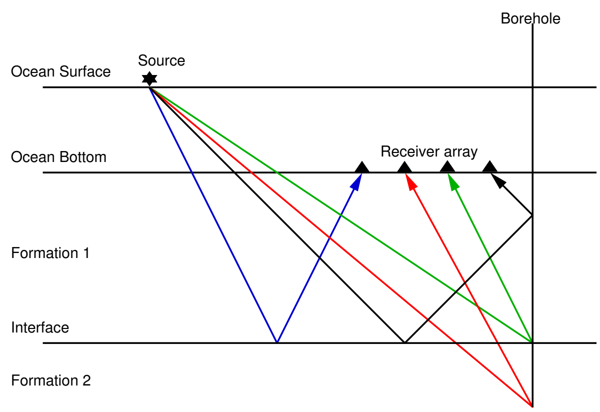

Figure 2: Responses in borehole model: reflection (blue), diffraction on borehole head (red), diffraction on borehole-interface intersection (green), prismatic reflection (black).

SURFACE SEISMIC MONITORING WHILE DRILLING

The SSWD method (Evensen et al., 2014) is based on a surface seismic source generator and a receiver array located on the seabed, and is particularly designed for application on relief well drilling and blow-out well killing. One advantage is that SSWD does not rely on magnetic survey methods. 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. SSWD is not dependent of any casing or steel tubular present in the well to identify the relative wellbore positions. Another advantage of SSWD is that it allows real-time seismic monitoring of the well paths without

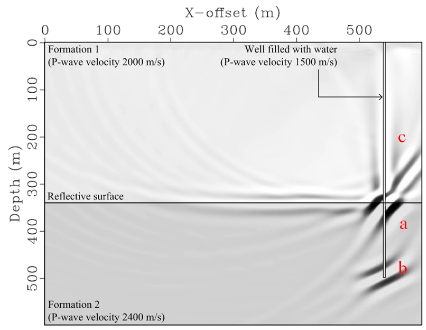

Figure 3: Seismic wave interaction with vertical well (after Lødemel, 2013).

interfering with the drilling operation. This has the potential of a more precise relative wellbore positioning.

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 diffractive 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.

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 (Measurement While Drilling) 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 potentially dangerous zones before drilling into them. This will increase the safety and effectivity 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 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. 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.

DIFFRACTIONS FROM BOREHOLES

The interaction of seismic wave propagation with a borehole is intricate and not fully explored in the literature to this date. Complicating factors are its vertically oriented geometry, the ultra-thin diameter compared to the seismic wavelength and the scattering contrast of its contents with respect to the host rock. The vertical orientation of boreholes typically implies that parts of the borehole do not generate a reflection response on surface acquisition. The ultra-thin diameter (typically less than 1 m versus a seismic wavelength of more than tens of meters) implies that even for deviating or horizontal sections of the borehole trajectory, the seismic response will not be reflective. The detectability of a borehole further depends on the contrast of its contents with the surrounding material, or more precisely, the discontinuous changes of that contrast along the borehole. Impedance contrasts (reflecting boundaries) in the surrounding material are a cause of borehole diffractions and their amplitude is proportional on the modulus of the contrast (Figure 1).

Based on these considerations, diffractions appear to be the natural choice for seismic monitoring of boreholes. First, discontinuities along the borehole trajectory will act as composite point diffractors and scatter energy in all directions, independent of the borehole orientation. Diffraction polarity reversals may be associated with these discontinuities. Second, depending on the contrast with the host rock, the borehole head will generate strong tip diffractions in all directions. Third, portions of the borehole that are deviated or even horizontally oriented may generate edge diffractions observable at the surface acquisition. Curvature and torsion of the borehole trajectory further enrich its seismic diffraction response. Figure 2 offers an illustration for a simple case of a vertical borehole in 2D. Here, the diffractions at boreholes discontinuities and the borehole head are displayed. Prismatic reflections may have additional benefits in borehole detection, which are not yet fully explored. Figure 3 shows the simulated interaction of seismic waves (diffractions) with the borehole (depth migra-

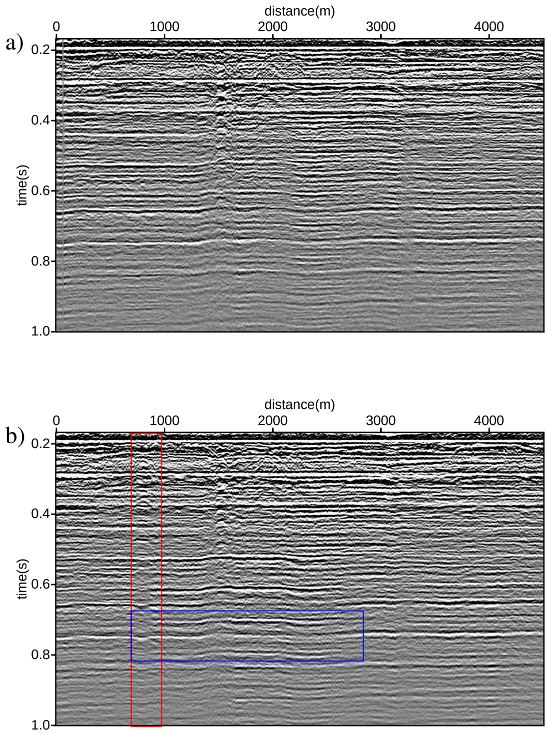

Figure 4: LOSEM data raw stack. a) 1988, b) 1990. Red box: seismic response from relief well; blue box: anomaly due to gas blow out.

tion image with layer reflection muted out).

Diffraction imaging is proposed as a tool to image the borehole trajectory during drilling, based on surface seismic acquisition. Diffraction imaging has a potential to achieve high-, or even superresolution, is achievable under certain conditions by isolating diffractions, either in the stage of processing pre-stack and pre-migration data or during the migration. In addition to its high-resolution capability, diffraction processing has the benefit of an illumination of the target which is in many cases superior to standard reflection processing. Diffraction imaging is an emerging technology for high-resolution imaging of small-scale subsurface structural details, and has found many applications, e.g. in reservoir imaging and fracture detection (Moser et al. 2016, where further references are found).

Time lapse offers an additional perspective to SSWD using diffractions. The seismic monitoring of the drilling of a well acts as a sequence of time-lapse surveys. The time-lapse response will primarily consist of diffractions, since the changes in medium during the drilling are mainly caused by the moving borehole. The diffraction imaging of the moving borehole can therefore make use of the same background and reflector models. Organizing the diffraction imaging in a target-oriented fashion, with an image area concentrated around the borehole head, allows therefore for a very fast and continuous update of

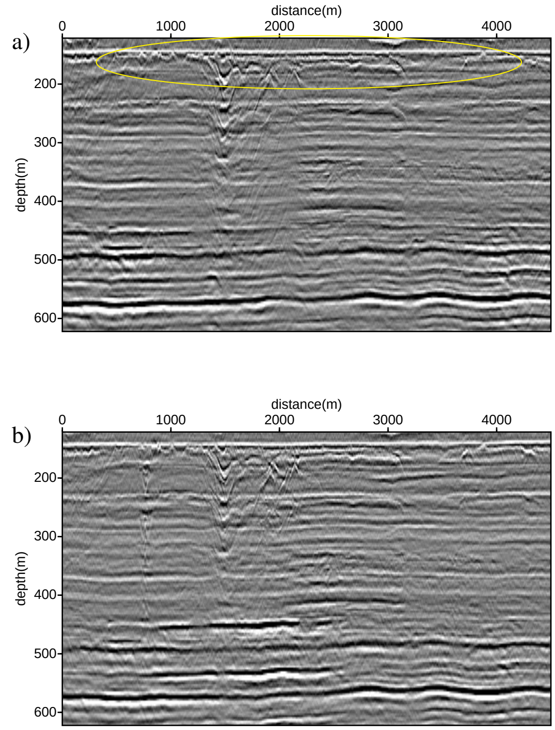

Figure 5: Regular migration. a) 1988, b) 1990.

the borehole diffraction image, and hence efficient monitoring of its trajectory.

EXAMPLE

We demonstrate the diffraction imaging of a borehole on the LOSEM (Long-term Seismic Monitoring) time-lapse data set from a field in the southern part of the Norwegian North Sea. Here, a base data set was acquired in 1988. In 1989, one of the exploration wells was exposed to underground leakage, as a result of which gas migrated from the deep reservoir into

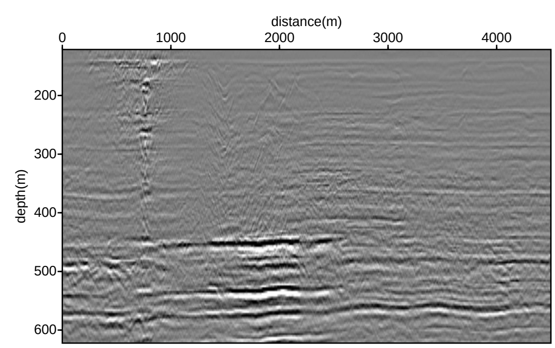

Figure 6: Time lapse regular migration.

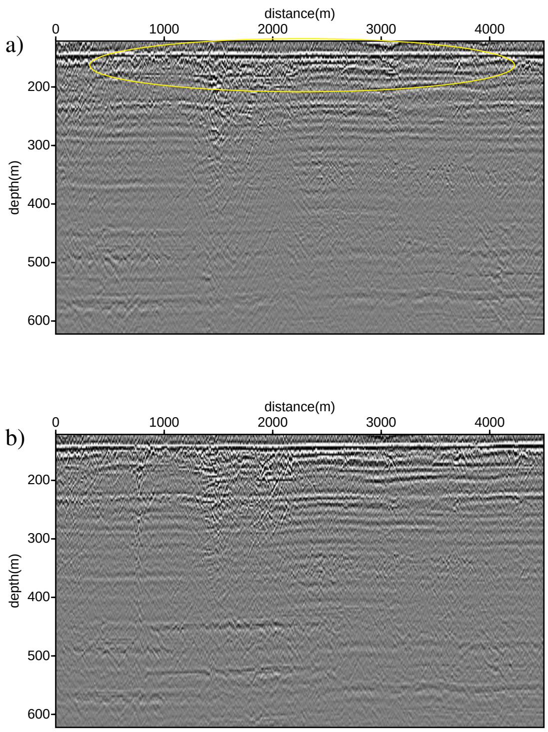

Figure 7: Diffraction images. a) 1988, b) 1990.

shallow formations. A relief well was drilled and after 326 days the underground leakage was stopped. Several surface surveys were acquired during the period; here we use a survey from 1990 as a monitor survey. For a detailed description of the data set and drilling history we refer to Landrø (2011).

Raw stacks of the base and monitor data sets are displayed in Figure 4a and Figure 4b. The original well was a vertical well drilled at the horizontal location 1470 m, the relief well was also vertical and drilled at 770 m. By comparing the base and monitor, one can see that the blow-out has generated a strong reflection in the monitor data set (indicated by the blue box). The same anomaly has been demonstrated in raw stacks by Landrø (2011). The relief well is vaguely visible in Figure 4b by disturbances of the original reflections (red box). The frequency range of the data is 20-100 Hz; with the main velocity at 1900 m/s this implies a seismic wavelength in the range of 19-95 m, i.e. significantly exceeding the borehole diameters (less than 1 m).

Regular pre-stack depth migrated images are shown in Figure 5a and Figure 5b. Here, a low frequency version of a P-velocity model obtained from wave-equation migration (Raknes and Arntsen, 2014) has been used for both the 1988 and 1990 data sets, allowing good focusing of both images. On the 1990 migrated image, the underground blow-out is clearly visible, as well as traces of the relief well. The time-lapse effects are highlighted in the time-lapse regular migration image (Figure 6), obtained by adaptive subtraction of the 1990 and 1988 images.

For the diffraction imaging, the respective 1988 and 1990 regular images have been used in the extraction of reflector dip fields (not shown here because of the largely laterally homogeneous character of the model). The diffraction imaging is carried out using the same input data sets and velocity model, sorting migration output in specularity gathers, tapering reflecting energy above specularity 99 %, and finally stacking the tapered gathers into diffraction images (see Sturzu et al., 2013 for a detailed work flow).

The diffraction images for 1988 and 1990 are displayed in Figure 7a and Figure 7b. Here, the main reflectivity is removed and small structural detail enhanced - for instance the shallow details indicated by the yellow ellipse in Figure 5a/Figure 7a which are believed to be the traces of tunnel valleys and valleys in general. The 1990 diffraction image (Figure 7b) shows that the gas blow-out and relief well are imaged with much higher resolution, although much weaker in amplitude, than on the regular migration (Figure 5b). The time-lapse diffraction image (Figure 8) isolates the gas blow-out and relief well and allows an accurate tracing of its trajectory.

CONCLUSIONS AND OUTLOOK

The concepts and field data example presented here show that diffraction processing and imaging is a natural complement to the SSWD method. Diffractions from boreholes can be made observable using surface seismic data, subject to relatively mild conditions. Because of their high-resolution imaging capacity, diffractions allow more accurate tracing of the borehole trajectory, possibly in a time-lapse context. On the other hand, because of their weak amplitudes, diffraction- and time-lapse-friendly processing is critical for its success.

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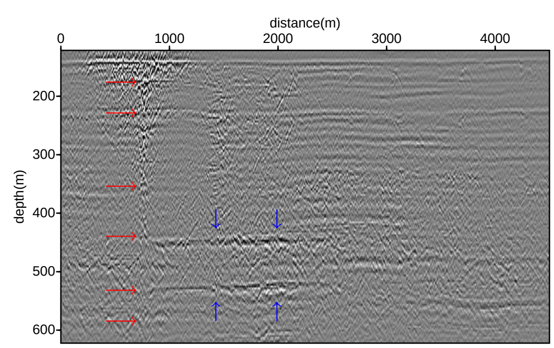

Figure 8: Time lapse diffraction image. Red arrows: relief well; blue arrows: anomaly due to gas blow out.

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