We LHR5 03

Seismic Diffraction Response from Boreholes

T.J. Moser* (Moser Geophysical Services), B. Arntsen (Norwegian University of Science and Technology), S. Johansen (Norwegian University of Science and Technology), E.B. Raknes (Norwegian University of Science and Technology) & S. Sangesland (Norwegian University of Science and Technology)

SUMMARY

Borehole diameters are typically much smaller than the dominant seismic wavelength and near-vertical borehole geometries do not favor reflection response at a surface acquisition. For these reasons - resolution and illumination - we study the diffraction response from boreholes on surface seismic data. Diffractions from boreholes are observable on surface seismic data under certain relatively mild conditions (sufficient frequency content, signal-to-noise and impedance contrast between the borehole and surrounding rock), and can be used to trace its trajectory. This is the objective of Surface Seismic monitoring While Drilling. In particular, we show that organizing the diffraction imaging in a time-lapse and target-oriented fashion can result in a very efficient and accurate way of monitoring the borehole during drilling.

Introduction

It has been recognized that vertically aligned objects in the subsurface, such as naturally occurring vertical blow-out pipes and certain fracture systems, can be observed on conventional surface seismic data (Løseth et al. 2011). For objects or scatterers with dimensions of the order of the seismic wavelength or larger and subject to favorable illumination relative to acquisition, this is to be expected. However, it appears that under certain conditions much smaller objects can also be detected on surface data (Raknes and Arntsen, 2014). This has led to the conjecture that surface seismic data may be used in the imaging and monitoring of boreholes (Evensen et al. 2014). 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. This is the objective of Surface Seismic monitoring While Drilling (SSWD, Evensen at el. 2014). The purpose of this paper is to explore the potential of diffractions and diffraction imaging in the detection of boreholes. We discuss concepts of diffraction imaging with application on borehole monitoring and offer a number of conceptual and field examples.

Diffraction Imaging

Diffractions appear to be the natural choice for seismic events to be used in high-resolution detection problems of vertically aligned objects. Many publications point out that reflection seismic processing is geared towards the major seismic events and mapping of the main geological boundaries. 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 (Moser, 2011). The reason is that, by definition, reflections follow Snell's reflection law and are therefore detectable only for reflecting interfaces with an orientation which is favorable to the acquisition geometry. By contrast, diffractions do not follow Snell's law, are scattered in all directions and therefore in principle always observable for a given acquisition.
Diffraction imaging is based on these principles and designed to suppress the reflective component of the recorded seismic wave field, either in data (Khaidukov et al. 2004) or image domain (Moser and Howard 2008). This suppression typically occurs by measuring the agreement with Snell's law for a certain data sample (defined as specularity) and tapering it accordingly (Sturzu et al. 2013). 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 (Sturzu et al. 2015, where further references are found).

Diffractions from boreholes

Borehole geometries are characterized by ultra-small diameters compared to the seismic wavelength, but extension in depth range of up to thousands of meters. They are typically vertically oriented near the surface and deviated up to horizontal slopes at deeper ranges. Therefore, they act as kinematically as *curved line diffractors* (Pelissier et al. 2012). Line diffractions obey Snell's law in the direction along the line, but not perpendicular to it, and are therefore confined to a cone with its axis tangent to the line (Moser, 2011). For curved lines, the cone changes direction along the line and generates caustics at a distance from the curve depending on its curvature. For torquing lines, as in the case of a relief well spiralling around a blow out well, the diffraction patterns and associated caustics are even more complicated.

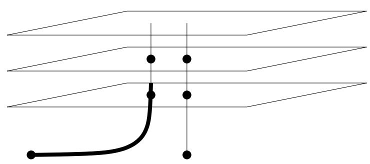

Figure 1 *Diffraction response from a borehole observable on surface seismic data: tip diffractions from the borehole head and intersection with reflecting interfaces (bold dots), curved line diffractions from deviated borehole sections (bold curve).*

In dynamical sense, portions of a borehole will generate a seismic signal when the borehole material constitutes an impedance contrast with the surrounding rocks. Most significant impedance contrasts typically occur at the *borehole head* and at the *borehole intersection with reflecting interfaces*. The borehole head generates a single tip diffraction, normally visible on regular migration images (depending on the migration algorithm). At the intersection of the borehole with a reflecting interface, there is an interplay of three impedances: above and below the interface and inside the borehole. This leads to a composite of tip diffractions, usually better visible on diffraction images than regular migration images. In addition, curved line diffractions from a deviated borehole can be observed on surface seismic data, depending on acquisition (Figure 1).

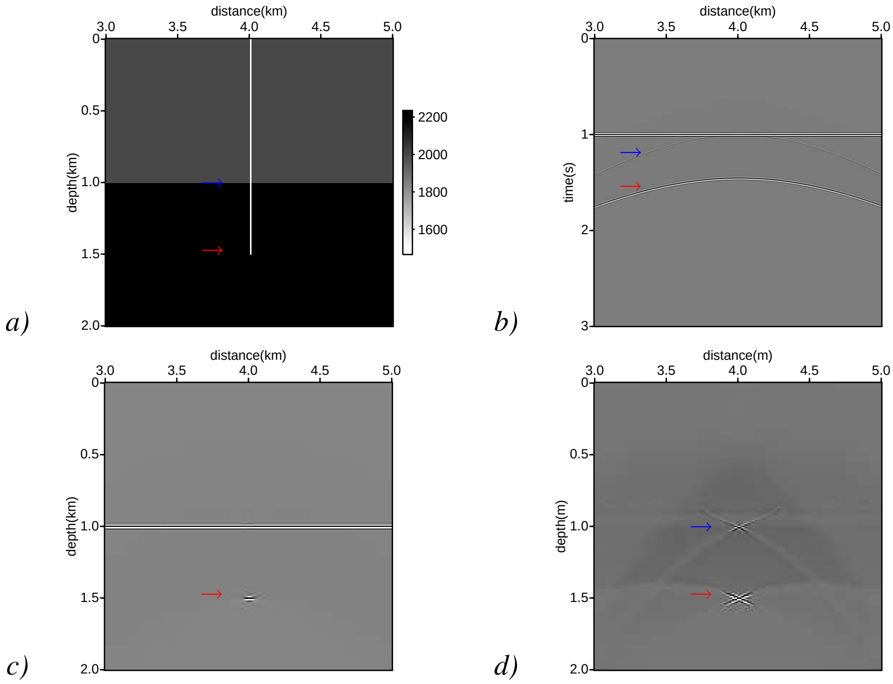

Figure 2 *Diffraction imaging of vertical borehole, a) model, b) data, c) regular migration and d) diffraction image. Note that while the borehole head is clearly visible on the regular migration (red arrow), the borehole intersection with the interface is visible only on the diffraction image (blue arrow).*

Time Lapse

The principle of Surface Seismic monitoring While Drilling (SSWD) is based on real-time monitoring of the drilling of a well by a fixed and permanent surface seismic survey. Simulations indicate that it is possible to locate the wellpaths of wells on seismic data. This method allows real-time seismic monitoring of the well paths without interfering with the drilling operation and for more precise relative wellbore positioning (Evensen at al. 2014). The seismic monitoring at subsequent time intervals acts as a sequence of time-lapse surveys. Since the changes in the medium during the drilling are induced principally by the moving borehole, their seismic time-lapse response will be mainly diffractive. For the diffraction imaging of the borehole this has the benefit that the same background model can be used and the same reflector model (dip field used in specularity analysis, see Sturzu et al. 2013). Organizing the diffraction imaging in a target-oriented fashion, with an image area concentrated around the borehole head, allows for a very fast and continuous update of the borehole diffraction image, and hence efficient monitoring of its trajectory.

Examples

We illustrate the seismic diffraction response from boreholes on a number of examples. The first example concerns a vertical borehole in a simple two-layered medium sampled on a 10 m × 10 m spacing grid (Figure 2). The borehole is represented by one horizontal grid point and has a constant velocity of 1500 m/s, the upper and lower layer velocities are 2000 m/s and 2200 m/s. A zero-offset data set generated at 50 Hz frequency by ray-Born modeling (Moser, 2012) is displayed in Figure 2b). Here, a strong tip diffraction is seen from the borehole head and much weaker diffraction from the interface intersection (red and blue arrows). Note that both diffractions have uniform polarity - no polarity reversal occurs at

the interface, since the geometry is symmetrical with respect to the borehole. This points to the composite character of the diffractions arising from the borehole-interface intersection. The regular (Kirchhoff) migration is able to image the borehole head (Figure 2c, red arrow) but the interface intersection is too weak to discern (only by a very faint amplitude drop). By contrast, the diffraction image sharply locates both the borehole head and interface intersection (Figure 2d).
The second example is a three-dimensional borehole deviating up to a horizontal slope (Figure 3). This example illustrates the occurrence of curved line diffractions discussed above.
The third example concerns a time-lapse field data example (Figure 4). Here, diffraction energy from the interface intersections is visible on the monitor data set (Figure 4b) and even stronger on the difference data set (Figure 4c). We consider this example as a crucial one, since it demonstrates that the diffraction response from the borehole is actually a real and observable phenomenon.
The final example comes from the Kvalhovden area of east-Spitsbergen, Norway (Johansen et al. 2007). Based on outcrop data, we derived two velocity models: one with two vertical wells and one without (Figure 5a). In these models we generated pre-stack data sets using ray-Born modeling (at 100 Hz), and subsequently migrated them and derived diffraction images with a conservative specularity taper of 98% (Sturzu et al. 2013). The diffraction images without and with wells are displayed in Figure 5b/c. The diffraction response from the boreholes is difficult to separate visually from other diffractive response on these images, due to the highly complicated structural geology. The time-lapse image, on the other hand, allows to clearly separate them (Figure 5d). Here, the borehole trajectories are imaged at high resolution, and traceable by their intersections with interfaces and the borehole heads.

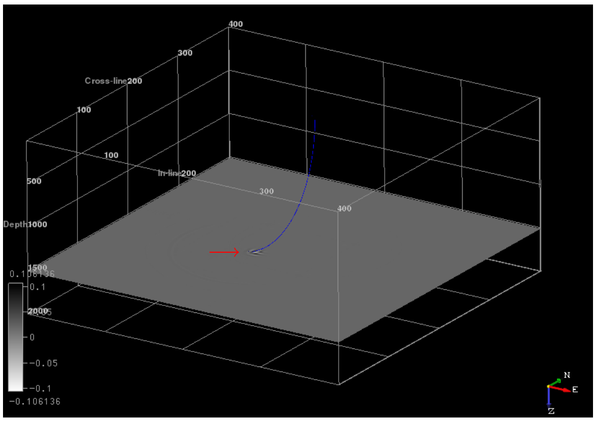

Figure 3 *Diffraction image of 3D deviated borehole - slice through borehole head.*

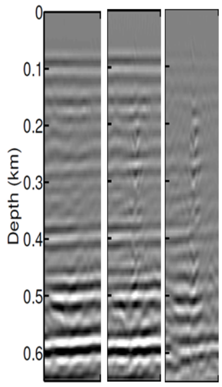

Figure 4 *Time-lapse seismic response from borehole. Left to right: Before/after drilling, difference.*

Conclusions

Conceptual and field data examples demonstrate that boreholes can be detected using diffractions from surface seismic data under certain conditions: sufficiently high signal frequency, signal-to-noise ratio and impedance contrast between the well and its surroundings. Diffractions from the borehole head are often strong enough to be seen on a regular migration image, from intersections of with geological boundaries they are usually much weaker. Diffraction imaging reveals these by removing the reflective component in regular migration. As a result, on diffraction images both the borehole head and discontinuities such as intersections with reflectors are typically visible. The capability of diffraction imaging to reveal borehole discontinuities implies, in principle, that the borehole trajectory can be detected and imaged from surface seismic data, in particular when this is designed in a time-lapse and target-oriented fashion.

References

Evensen K., Sangesland S., Johansen S.E., Raknes E.B. and Arntsen B. 2014. Relief Well Drilling Using Surface Seismic While Drilling (SSWD), *SPE Drilling Conference and Exhibition*, SPE 167994-MS.
Johansen S.E., Granberg E., Mellere D., Arntsen B. and Olsen T. 2007. Decoupling of seismic reflectors

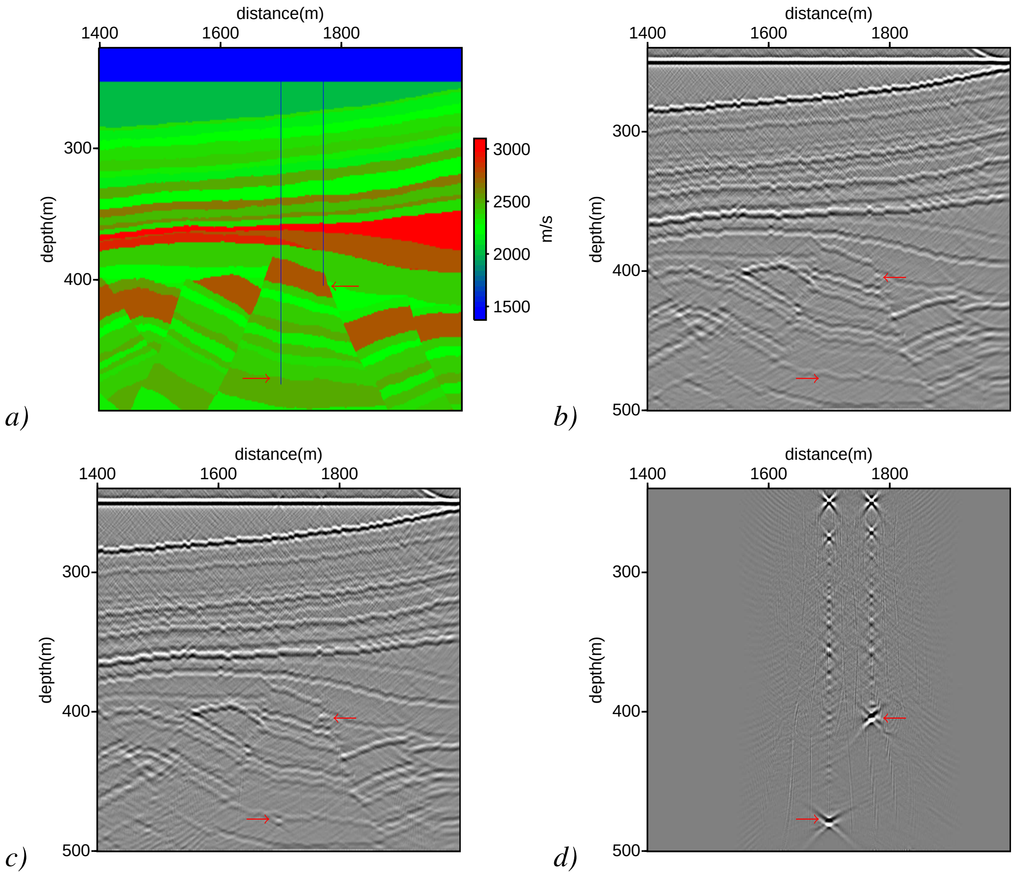

Figure 5 *Diffraction image from boreholes at Kvalhovden. a) velocity model with two wells, b/c) diffraction image without and with well, d) difference. Red arrows point to borehole head (absent in 5b).*

and stratigraphic timelines: A modeling study of Tertiary strata from Svalbard, *Geophysics*, **72**, 273-280.

Khaidukov V., Landa E. and Moser T.J. 2004. Diffraction imaging by focusing-defocusing: An outlook on seismic superresolution, *Geophysics*, **69**, 1478-1490.

Løseth H., Wensaas L., Arntsen B, Hanken N.M., Basire C. and Graue K. 2011. 1000 m long gas blow-out pipes, *Marine and Petroleum Geology*, **28**, 1047-1060.

Moser T.J. 2011. Edge and Tip Diffraction Imaging in Three Dimensions, *73rd EAGE Conference Vienna*.

Moser T.J 2012. Review of ray-Born forward modeling for migration and diffraction analysis, *Studia Geophys. Geod.*, **56**, 411-432.

Moser T.J. and Howard C.B. 2008. Diffraction imaging in depth, *Geophysical Prospecting*, **56**, 627-641.

Pelissier M.A, Moser T.J., Grasmueck M. and Pajchel J. 2012. Three-dimensional Diffraction Response of Salt Diapirs, *74th EAGE Conference Copenhagen*.

Raknes E.B. and Arntsen B. 2014. Time-lapse full-waveform inversion of limited-offset seismic data using a local migration regularization, *Geophysics*, **79**, WA117-WA128.

Sturzu I., Popovici A.M., Moser T.J. and Sudhakar S. 2015. Diffraction imaging in fractured carbonates and unconventional shales, *Interpretation*, **3**, SF69-SF79.

Sturzu I., Popovici A.M., Tanushev N., Musat I., Pelissier M.A. and Moser T.J. 2013. Specularity Gathers for Diffraction Imaging, *75th EAGE Conference London*.