Advanced Imaging Solution Using Existing Data Set for Geohazard Analysis

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Introduction

Once the drilling decision is made, following a full prospect evaluation, the well planning and design phase starts. A key component of planning is to assess and mitigate any hazards associated with drilling, for which the operator is responsible. The traditional approach is to acquire a dedicated site survey, which can be time-consuming and expensive. The objective of a site survey is to identify hazards which may affect the operational or environmental integrity of a proposed drilling operation. These hazards maybe geological or man-made. This is usually achieved by acquiring dedicated high-resolution (HR) 2D or 3D seismic site surveys. For cost and time reasons, the site surveys are often acquired as a grid of 2D lines around the planned surface locations of the well, and typically cover a small area. This implies that the approximate location of the well is decided before conducting the site survey, which in turn will help to further refine the location based on a hazard analysis of the data. A new site survey might be necessary if the hazard assessment indicates the planned well has to be moved. Although rare, such risks do exist and may have cost and time implications for a project. Site surveys are designed to image the shallowest overburden, and are normally acquired with shallow towed sources and receivers, making the weather conditions a key factor for their success. To control the cost, typical site surveys are acquired with short offsets, which means they may rely on earlier exploration seismic surveys to obtain an accurate near-surface velocity model.

The International Association of Oil and Gas Producers (IOGP) produces guidelines for the conduct of offshore drilling hazard site surveys (IOGP report number 373-18-1, 2017). The report suggests as long as the data fulfills these guidelines, it should have sufficient quality and resolution to enable an effective geohazard analysis. In deep water, the use of large-scale 3D seismic volumes will provide data fit for purpose assuming the acquisition geometry provides the appropriate spatial sampling. In shallow water (<250 m), the acquisition geometry may not be suitable for near-surface imaging with conventional algorithms. The interplay between shallow water data and conventional 3D seismic acquisition near offsets, can mean only high reflection angles are recorded. This can cause imaging gaps in seismic data that are visible as an illumination footprint. In shallow water a separate site survey data set might be needed.

What if we could produce a product needed for hazard analysis without acquiring new data? What if we could cover an area 10 to 20 times larger than the one of 2D HR seismic surveys, and with a full 3D perspective? What if we can perform this at any time we needed it? Having such a solution can have several advantages: there will be more time available for well trajectory design; the same geohazard products can be used for more than one well over the licence area; no dependency on weather condition; a more environment friendly solution as no new data set needs to be acquired. In this paper one such solution is proposed, explained in detail and illustrated with case studies.

Our proposal is based on an advanced imaging (migration) solution which can produce a high-resolution image using existing multisensor streamer data instead of acquiring an expensive site survey. Separated Wavefield IMaging (SWIM) is an innovative technology that takes advantage of the extended illumination provided by sea-surface reflections. The concept of SWIM is to use each receiver as a "virtual" source, expanding the surface coverage of the seismic experiment and enhancing the subsurface illumination, particularly for shallow reflectors. As a result, the equivalent survey provides an image with greater sampling both in terms of spatial extent and angular diversity. The multisensor nature of Ocean Bottom Surveys (OBS) acquisition means SWIM is also a powerful tool for OBS surveys. Using reciprocity, SWIM benefits from extended illumination, beyond that of the receiver array.

Method

Wave-equation migration consists of numerically extrapolating source and receiver wavefields into the subsurface. An image of the reflector is formed where these two wavefields coincide. When imaging primary reflections, the source wavefield is initiated by a point source and propagated into the earth. The wavefield recorded at the surface is used as receiver wavefield. These surface recordings contain not only primary reflections but also multiple-scattered energy. When imaging primary reflections, the multiple-scattered waves are treated as noise that are typically attenuated in the preprocessing (e.g., surface-related multiple removal). In recent years, we have seen the use of multiple reflections for imaging, rather than removing them as noise (Berkhout and Verschuur, 1994; Whitmore et al., 2010; Lu et al., 2015). Free-surface energy may sample the subsurface differently to primary energy as they travel through subsurface more than once. Therefore, using multiple energy in the imaging step can increase information about the subsurface.

Imaging using primary and multiples, referred to as Separated Wavefield IMaging (SWIM) is an innovative migration technology, which takes advantage of the extended illumination provided by sea-surface reflections. Multisensor acquisition enables an accurate separation of upgoing and downgoing wavefields (Carlson et al., 2007). The downgoing wavefield recorded at each receiver is used as a "virtual" source (top image of Figure 1 – 'VS') wavefield for the forward propagation. This helps in expanding the surface coverage of the seismic experiment and extending the subsurface illumination (top image of Figure 1- 'EI'), and compares favorably to conventional imaging using a wavelet for the source wavefield located at the field source locations. The upgoing wavefield, as an extension to the recorded downgoing wavefield is used as the receiver wavefield.

As outlined above, and shown in Figure 1, SWIM utilizes the multiple energy for imaging which has travelled through subsurface more than once. This also allows a subsurface location to be illuminated more times than conventional imaging providing greater angular diversity (bottom left image of Figure 1- 'DS'). In shallow water environments, imaging using primary reflections can produce illumination gaps (bottom right image of Figure 1 – 'AF'). This is due to sparse source sampling in the crossline direction which is dependent on the acquisition geometry. To fully understand potential drilling risks, complete near-surface illumination is critical for geohazard analysis. By using each receiver as a virtual "source" (Figure 1 – 'VS'), SWIM not only fills the illumination gap but also extends the illumination to a larger area.

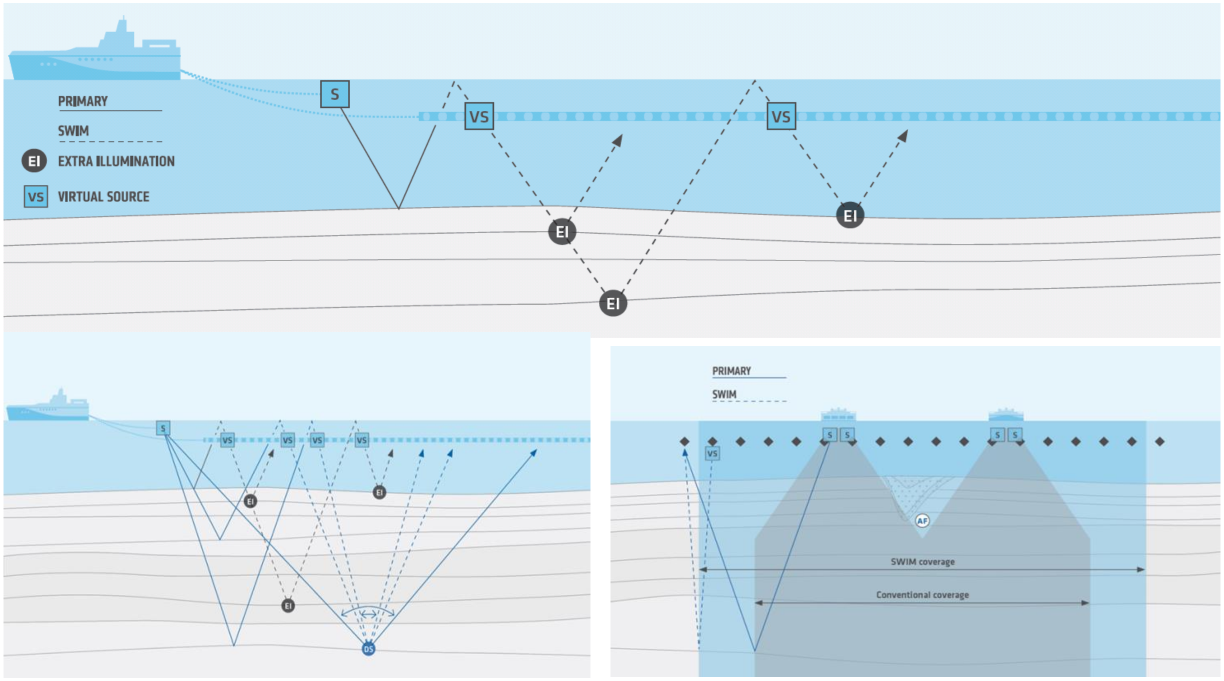

Figure 1. Illustration of SWIM imaging principle: Note the extended illumination ('EI') (top) and angular diversity ('DS') (bottom left) provided by SWIM imaging by using the receiver array as virtual sources along the sail line direction. Illustration of difference in illumination area provided by SWIM and conventional imaging (bottom right)

Seismic data quality requirements for geohazard assessment

The International Association of Oil and Gas Producers (IOGP) produce reports for the conduct of offshore drilling hazard site surveys. The IOGP report 373-18-1-1 (October 2017) provides guidance for the conduct of offshore drilling hazard site surveys, and states that "The quality of any data set selected for use in a site survey should be directly related to the types of conditions expected to exist within the area of interest". Section 5 of the report details the seismic data requirement. The report outlines a decision tree as shown in Figure 2, which presents a simple process for assessing the data needs of a project. The section states that there are four general areas of practice that are common within the industry:

- use of pre-existing site survey data
- use of an exploration 3D seismic data set
- use of an exploration 3D seismic data set combined with limited site survey data acquisition
- use of a newly acquired site survey.

Figure 2, taken from the report, outlines a simple flow chart to decide which area of practice will be best based on the analysis of existing data sets.

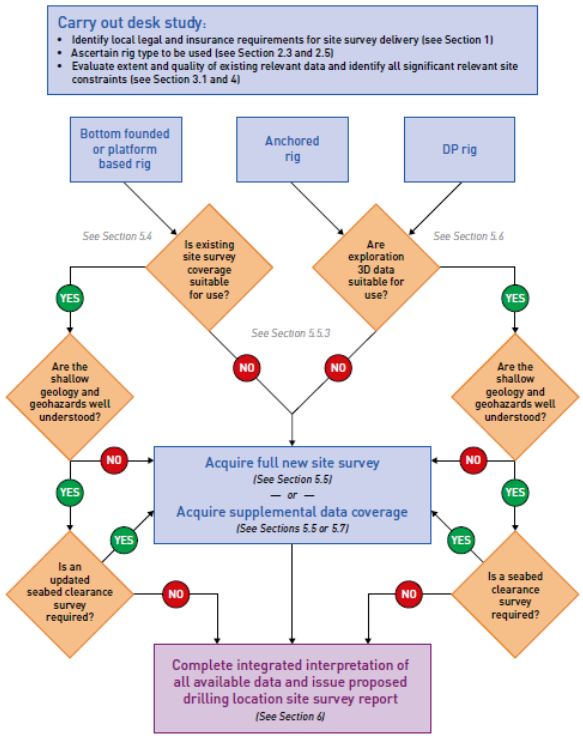

Figure 2. Site survey decision tree (IOGP report 373-18-1-1, 2017)

In the case of use of an existing exploration 3D seismic data set, section 5 further outlines minimum data acceptability criteria as listed below

- **Frequency content**: the data set should possess a useable frequency content up to, and preferably beyond, 60 Hz to the full depth of interest below seabed.
- **Seafloor reflection**: should be free of gaps and defined by a wavelet of stable shape and phase to allow auto-tracking of the seabed event with minimum user intervention and guidance.
- **Acquisition artefacts**: such as cross-line statics and/or amplitude striping, though possibly identifiable in the shallow section, should not detract from the overall interpretation of a picked event when mapped in time or amplitude. Similarly time slices, or windowed attribute extractions should be devoid of, or show minimal, acquisition artefacts to the detriment of their interpretation.
- **Merge points**: between data sets of differing origin or vintage that cross a study area should be marked by minimal − and preferably no − time or phase shifts and amplitude changes across the joins that might otherwise be to the detriment of the interpretation.
- **Bin sizes**: preferably less than 25 × 25 m in both directions.
- **Sample interval**: processed output sample interval should preferably be 2 milliseconds and certainly be no more than 4 milliseconds
- **Imaging**: attention to definition of an accurate velocity model in the shallow section in processing should have allowed optimum structural and stratigraphic resolution to have been achieved in the migrated volume. The shallow section should show no indication of under, or over, migration artefacts.
- **Multiple energy**: should either be unidentifiable or at a level that does not interfere with the analysis of the shallow section.

- **Data coverage**: the available exploration seismic data coverage should fully meet the guidelines for data coverage set out in section 5.2 above.

Similar guidelines exist in Bulat and Long's (2006) report 'Use of 3D Seismic data as a substitute for high-resolution seismic surveys for site investigations'. Prepared by **British Geological Survey** for the Health and Safety Executive 2006. Research report 459.

Modern, high-resolution acquisition and processing flows for 3D exploration, can fulfill the requirement for "frequency content", "bin size", "sampling interval" and "Multiple energy", in deep water data. However, in a shallow water environment, conventional imaging using only primary reflections can struggle to fulfill the requirements pertaining to "seafloor reflection", "acquisition artefacts" and "imaging" as outlined above. As described in the previous section SWIM on the other hand can provide high-resolution images of the seabed and shallow reflectivity, free of acquisition related artefacts. SWIM can be combined with velocity model building technologies such as Full Waveform Inversion (FWI) to provide very accurate velocity models of the shallow section. SWIM angle gathers can provide much improved image domain Quality Control (QC) of the velocity model obtained by FWI. Additionally, a very accurate near-surface velocity model, obtained by FWI, benefits the accuracy of the SWIM imaging step.

Geohazard processing flows, using the innovative imaging method presented in this paper, can solve the shortcomings of conventional primary imaging, and therefore avoid the acquisition of a new site survey for detailed geohazard analysis.

Geohazard processing description

The seismic processing for geohazard analysis was performed at 2 ms temporal sampling, starting from the wavefield separation process based on pressure and particle velocity sensor measurements (Carlson et al., 2007) to obtain upgoing and downgoing wavefields.

Figure 3 summarizes the complete workflow for the geohazard processing (Oukili et al., 2019). In one flow the upgoing wavefield data are processed alone through a high-resolution processing sequence where a Kirchhoff Prestack Depth Migration (KPSDM) was used. The imaging was performed using a velocity model with Tilted Transverse Isotropy (TTI) and included 3D Q compensation. The signal bandwidth was optimized by prior preconditioning steps that include source-side deghosting, designature and shallow water demultiple steps. In the second flow both the upgoing and downgoing wavefield data are input to Separated Wavefield IMaging (SWIM) exploiting the benefits of additional subsurface illumination from surface related multiples (Whitemore et al., 2010). The final SWIM migration is performed with a maximum frequency of 190 Hz.

The two workflows described are merged after migration in the prestack domain; SWIM data are used to fill in the missing near angle information in the shallow part of the KPSDM angle gathers. The SWIM information provides the shallow image, beyond which the high-resolution KPSDM contributes to the final image. A common velocity model was used for both migrations, which was built with an advanced workflow combining Full Waveform Inversion (FWI) and reflection tomography. This cannot be applied to typical site survey data set due to the short offsets used in site survey acquisitions.

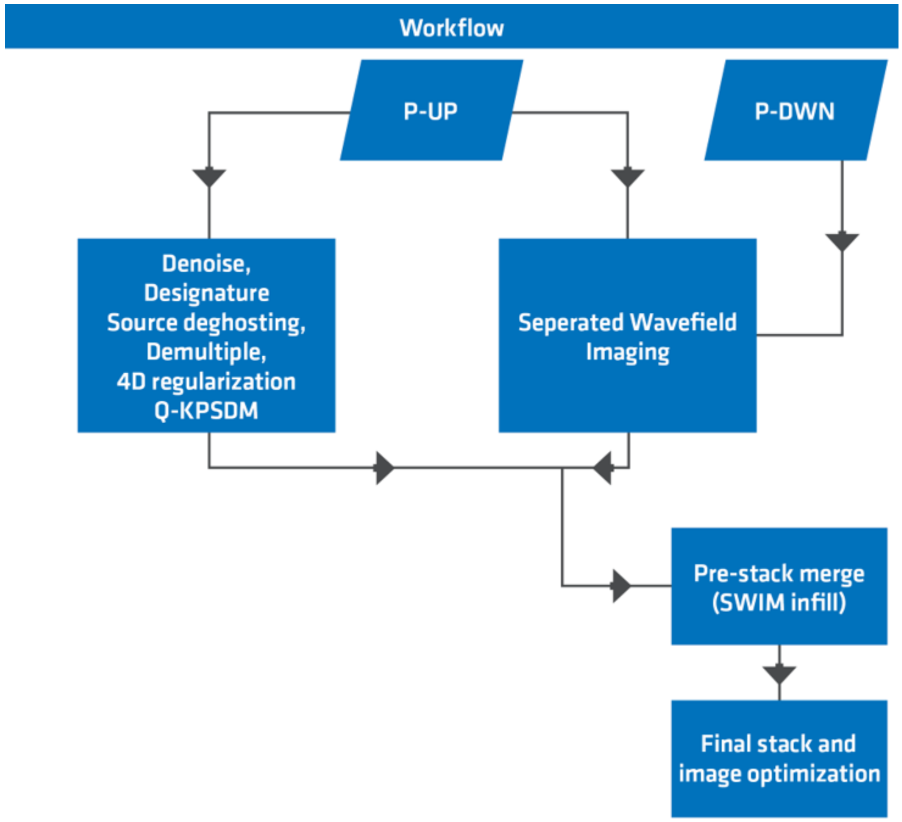

Figure 3. Geohazard processing flow implemented to produce the final result

Results

The results of SWIM processing for geohazard data are presented for two different data sets. The first data set is from Central Graben area in the Norwegian North Sea. The seafloor lies between 30 m and 130 m. The field data were acquired in 2015 using 12 multisensor streamers each separated by 75 m. The second data set is from Barents Sea. The seafloor here lies between 150 m and 300 m. The field data were acquired using 10 multisensor streamers each 75 m apart.

Data set 1 – Central Graben

Figure 4 compares the 4 ms sampled 3D stack from the modern regional broadband processing (termed conventional imaging) to 2 ms sampled 3D geohazard processing using SWIM. The conventional image was obtained with a KPSDM using the same velocity model as that used for the SWIM geohazard product.

It can be seen in Figure 4 that using SWIM produces a high-resolution shallow image that is not present in the conventional imaging. One can observe much better shallow reflectivity in the SWIM image, which are hard to track in the conventional image, as the field seismic data has not recorded the shallow events; the acquisition geometry inhibits the recording of near angle reflectivity. The comparison between the two images converges with depth.

Time slice displays show that shallow interpretation is challenging in the conventional imaging as it contains a strong footprint associated with illumination gaps from imaging with only primary reflections. SWIM however, produces a much higher-resolution and footprint free image, critical for shallow geohazard analysis. Reflections are easy to interpret and track in the SWIM image, whereas in the conventional image they are not. In this instance the SWIM result achieves the requirements of the IOGP guidelines for continuous and trackable seafloor and near-surface reflectivity.

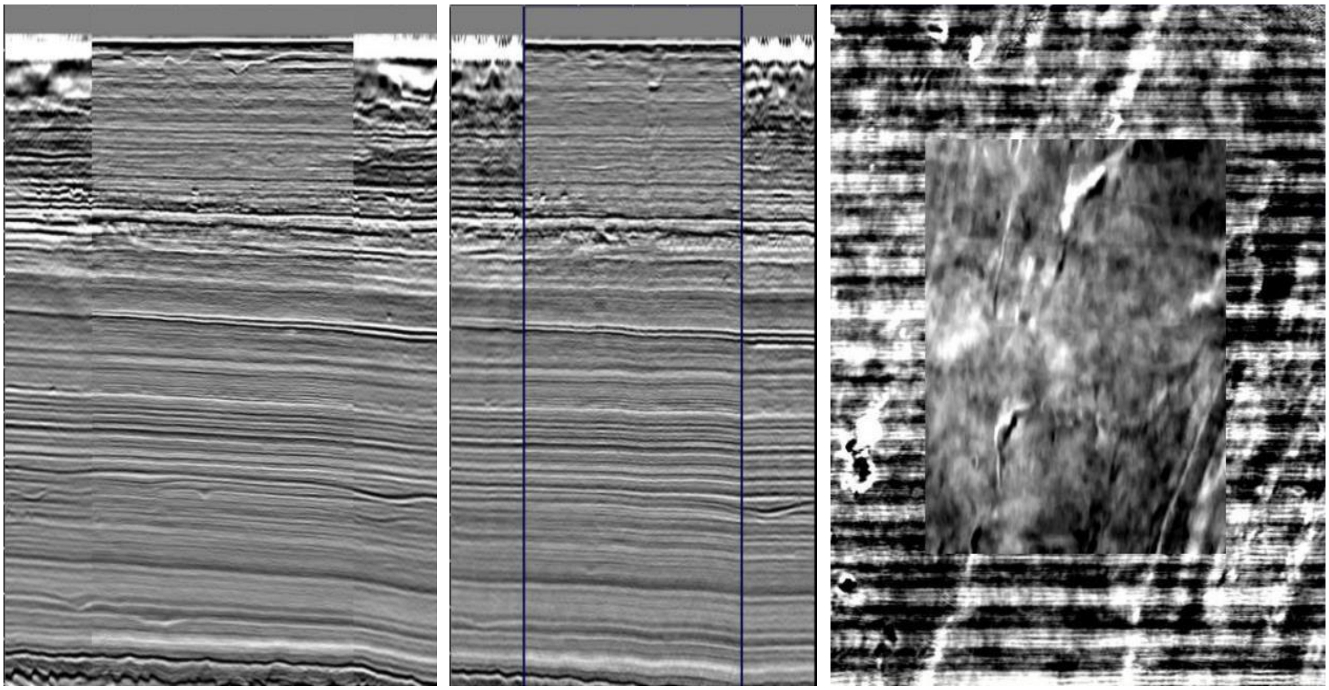

Figure 4: Image obtained by Separated Wavefield IMaging (inset) and conventional imaging (background) for an inline (left), crossline (middle) and shallow time slice (right).

Data set 2 – Barent Sea

Conventional imaging and SWIM are compared in Figure 5. The conventional imaging was obtained by high-resolution processing at 2 ms and with a spatial sampling of 6.25 m x 6.25 m, followed by Q Kirchhoff Prestack Depth Migration (QKPSDM) using the same velocity model as used for the SWIM imaging.

Figure 5 shows that imaging using conventional high-resolution processing does not give a completely artefact free image of the near-surface; a strong footprint is present, and the near-surface is contaminated by strong post-critical energy that masks amplitude analysis for identifying geohazards. By accessing the information in the free-surface reverberations, SWIM produces a high-resolution shallow image where near-surface reflectivity anomalies are easily identifiable (Figure 5 right - orange arrow). Poor near-surface imaging with primaries is caused by the interplay between the shallow subsurface reflectivity and the acquisition geometry, leading to a lack of illumination of the water bottom and shallow overburden. Additional subsurface information contained in the free-surface energy used in SWIM creates a clearer image of the near-surface, making the data suitable for geohazard analysis.

The two case studies illustrate the benefits of using free-surface energy with an advanced imaging algorithm. When compared to conventional imaging in shallow water environments, separated wavefield imaging enables a high-resolution, artefact free near-surface reflectivity data set, meeting all the seismic data requirements outlined in the IOGP report (373-18-1-1, October 2017) for geohazard analysis.

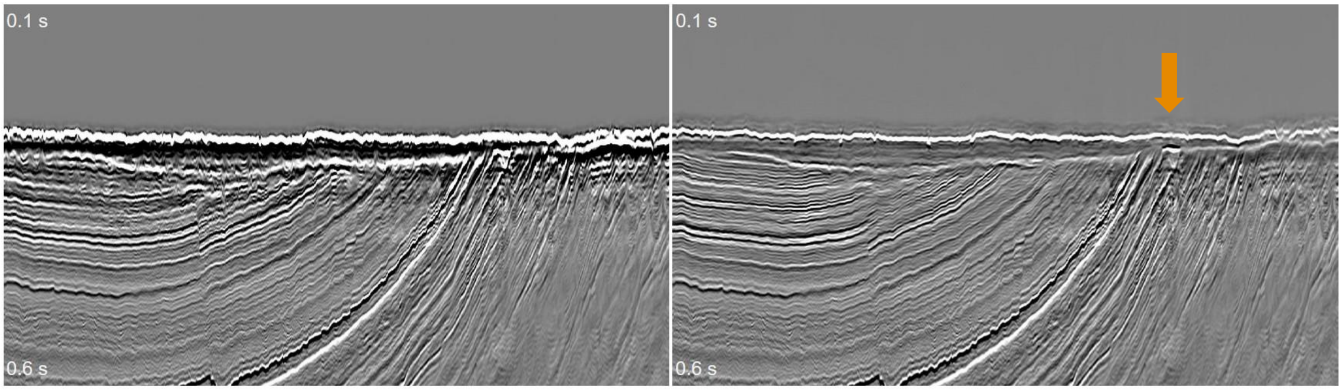

Figure 5: Image obtained by primary imaging (left) and Separated Wavefield IMaging (right) for a crossline. Note the presence of a strong acquisition footprint on near-surface reflectivity that is present on the conventional imaging but not on the SWIM image.

Conclusion

It is the operator's responsibility to collect all the necessary information to act in a safe manner when planning and actioning a drilling campaign. As detailed and demonstrated in this paper, an innovative imaging algorithm can provide high-resolution images of sufficient quality to perform effective geohazard analysis from existing exploration seismic data sets. This may remove the need to acquiring an additional costly and time-consuming site survey.

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