High-Resolution 3D Site Characterization

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Summary

We present the results of a novel method for high-resolution 3D site characterization. The strategy is based on using 3D seismic data as the framework for integrating geochemical, geophysical and geotechnical data. The end-results are 3D volumes with various attributes relevant for improved site characterization and ultimately geohazard assessment (i.e. identification of shallow gas, boulders, faults and fractures, leakage, spatial variability, soil strength…). We further show that geochemical data integrated with current high-resolution 3D seismic data can be used to constrain fluid migration pathways to the seafloor. In addition, re-processing focusing on the higher frequencies of 3D seismic data increases the resolution, resulting in a data volume displaying more details on the geology and geomorphology of the sub-surface when compared to data processed for deeper imaging. Finally, we configured an optimized 3D seismic acquisition system, which is fine-tuned for imaging the top 150 m of overburden with a meter-scale lateral and vertical resolution. Such a high-resolution 3D seismic system would provide data volumes that allow well-constrained integration of various type of data.

Introduction

The integration of in situ measurements with seismic data is important for base line site characterization and geohazard assessments before drilling or before placing installations on the seabed. However, site survey investigations often require extrapolation of in-situ geotechnical measurements using widely spaced 2D seismic profiles as a guide, whereas geochemical data documenting active natural hydrocarbon leakage are not generally acquired.

Here, we present the results of a novel method aimed at high-resolution 3D characterization of the sub-surface properties and of the shallow stratigraphy. The approach is based on the integration of high-resolution 3D (HR3D) seismic data with in situ geochemical and geotechnical measurements, but also on the superior resolution of the P-Cable 3D seismic data when compared to conventional 3D (**Figures 1 and 2**).

Methods

The P-Cable system (Planke and Berndt, 2003; **Figure 1**) has short streamers to collect HR3D seismic data mostly before the first seafloor multiple. As such, the current system is superior for imaging the shallow stratigraphy with native 6.25x6.25 m bin-size and retained frequencies of 270 Hz at depths of 500 m below the seafloor compared to conventional 3D systems (**Figure 2**).

The first step was to integrate seep data from 160 gravity cores with P-Cable 3D seismic data, all acquired in the Hoop area of the Barents Sea. This step aimed at constraining the hydrocarbon migration from deep structures to the seabed using these two complementary datasets.

The second step was to re-process P-Cable 3D data from the Vestnesa Ridge off the West-Svalbard continental margin (e.g., Bünz et al., 2012). This area is known for active seepage that appears as acoustic flares in the water column and circular pockmarks on the seabed. P-Cable 3D seismic data were acquired by the Arctic University of Norway for investigation of gas hydrates and associated fluid dynamics. The data were re-processed with focus on the top 200 ms below the seafloor. The processing workflow included re-binning to a natural bin size of 6.25x3.125 m with a median fold of 4 and pre- and post-migration re-processing for seismic signal of up to 700 Hz. The aim of this exercise was to improve the resolution of the data and further constrain fluid migration, fault patterns and the details of the glacial history.

The third step was to identify and quantify the parameters controlling the resolution in the data in order to propose an optimized configuration for acquiring 3D seismic data able to resolve meter-scale objects. The approach was to analyze the propagation of seismic waves in water and sediments by varying acquisition parameters, offset range and source spectra signature in different water depths (Lebedeva-Ivanova et al., submitted).

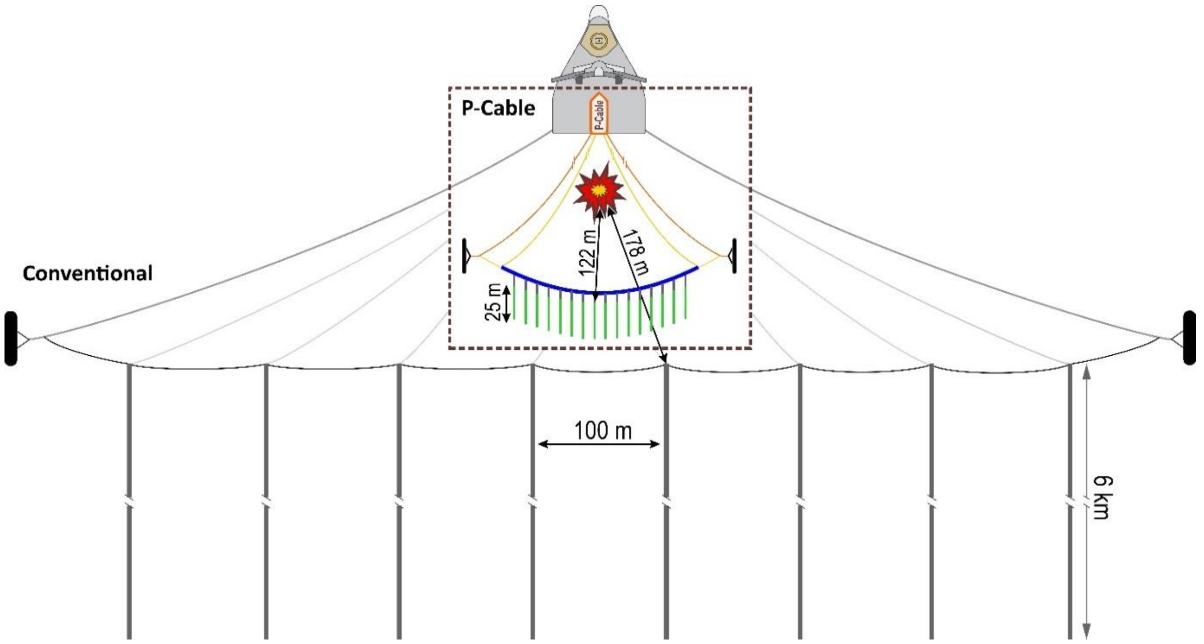

__Figure 1__ Conventional and P-Cable 3D seismic acquisition setups at a similar scale. Arrows mark the streamer lengths and minimum offsets. Blue line represents the P-Cable cross-cable.

Results

The integration of P-Cable 3D seismic data and seep results involves the detailed interpretation of a ca. 40 m thick glacial package between the seafloor and a distinct unconformity, URU (Upper Regional Unconformity). We have mapped a shear margin moraine with associated shear planes, mass transport deposits, and a well-defined soft reflection at the base of the moraine (**Figure 2**, Bellwald and Planke, 2018). This soft reflection is interpreted as a gas-charged layer above URU. Potential gas accumulations are imaged as high-amplitude reflections in sedimentary sequences below URU.

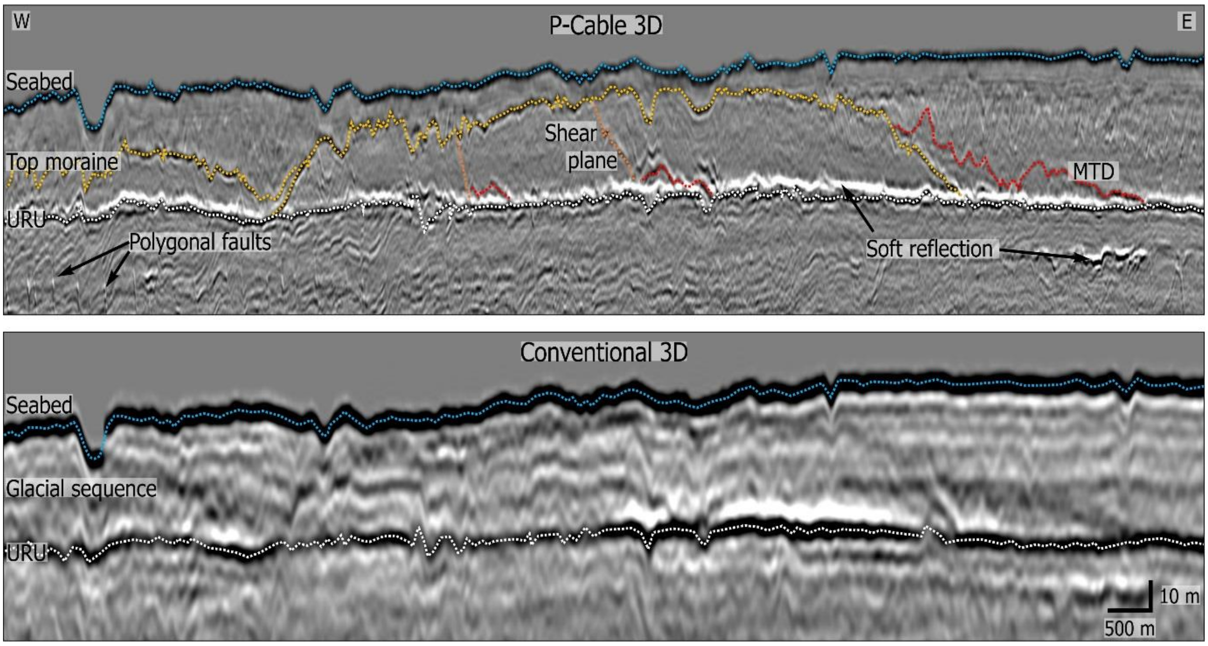

__Figure 2__ Comparison of the first 100 m below the seafloor between P-Cable 3D (top) and conventional 3D (bottom) seismic data collected at the same location in the Barents Sea (seismic data courtesy of TGS). The figure (after Bellwald and Planke, 2018) shows that P-Cable data can image the internal structure of the glacial sequence, shallow stratigraphy, polygonal faults and soft reflections. Upper Regional Unconformity, MTD: Mass Transport Deposit.

The integration of the seep and P-Cable data suggests that hydrocarbon compounds do not always migrate vertically to the surface, but instead follow discontinuities between the glacial units and internal structures imaged in the HR3D seismic data. Therefore, the distribution of the geochemical and microbial seep anomalies appears to be controlled by the changing geology of the glacial package. For example, the moraine seems to filter the hydrocarbons where the most mobile compounds primarily migrate upward to the surface, whereas the heavier compounds either follow porous beds laterally towards fractures or remain trapped at the base of the moraine.

The re-processed data show a sub-meter vertical resolution within the upper 50 m below the seafloor, and meter-scale resolution between 50 to 200 m below the seafloor. In addition, the re-binning provides a horizontal resolution of 3 m along in-lines and 6 m along cross-lines. This increase in resolution resulted in more detailed imaging of the sedimentary layering, and chimney structures below the pockmarks, and display an increased fault definition (**Figure 3.A**) when compared to data optimized for interpreting deeper levels (**Figure 3.B**). In addition, the reprocessed data show that the widths of the interpreted chimneys can decrease suddenly towards the seafloor, but also indicate if a seep structure reached the seafloor or not.

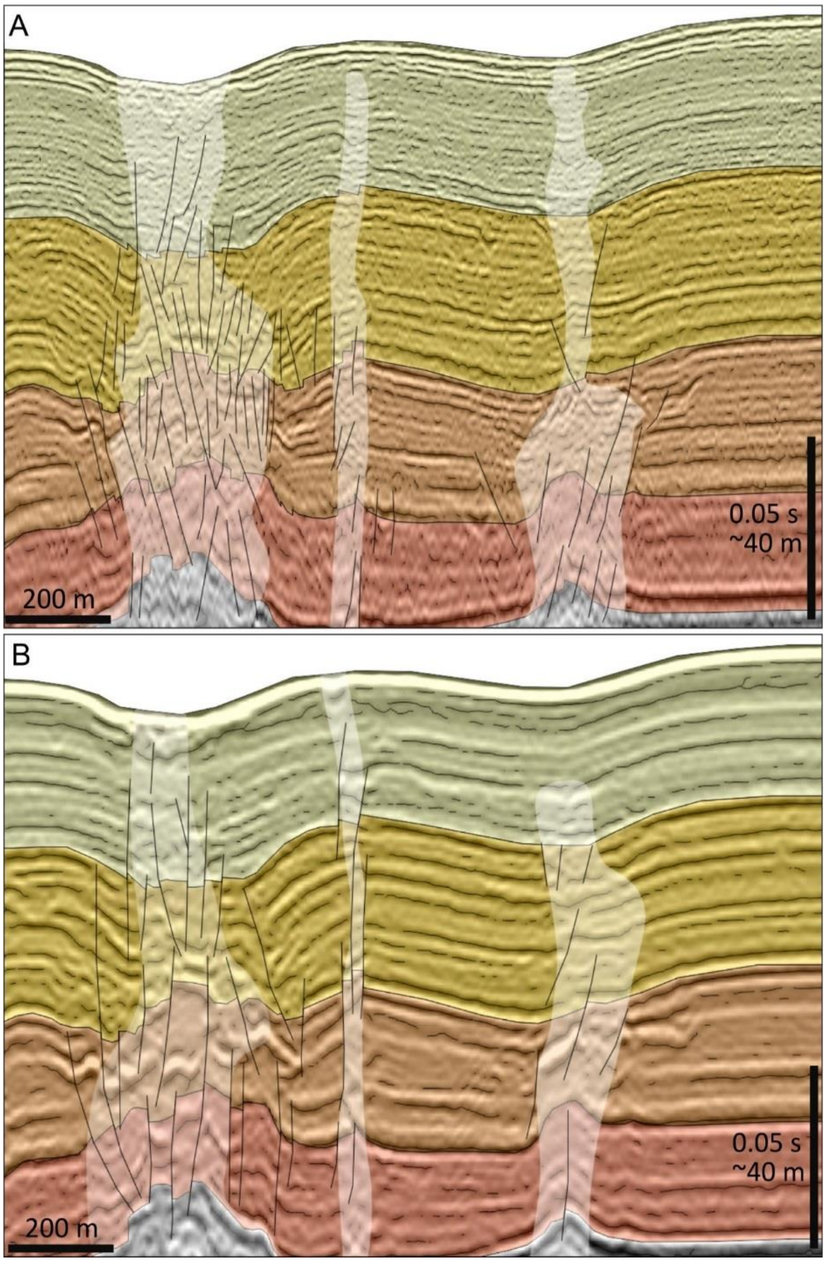

***Figure 3** Comparison between **A**) high frequency processing (bin size of 3.125x6.25m) and **B**) standard processing (bin size of 6.25x6.25m) along the same line within the P-Cable 3D cube acquired on the Vestnesa Ridge. Seismic data (courtesy of the Arctic University of Norway) imaged vertical chimney structures located below pockmarks associated with acoustic flares in the water column (Bünz et al., 2012).*

The results from the theoretical calculations on the propagation of acoustic waves show that resolution of 3D seismic data is increased when using a reproducible seismic source with high frequencies up to at least 600 Hz. In addition, the trace density should be uniform and more than four million traces per square kilometer. Furthermore, the acquisition system should have an offset range shorter than c. 200 m. The resulting 3D seismic data volume will reach the one-meter scale for water and target depths less than 600 m. However, such leap in resolution would require better navigation accuracy and updated processing techniques to deal and assist with the increased level of detail.

Conclusions

High-resolution 3D site characterization can deliver reliable quantitative property volumes of the sub-surface when based on seismic data able to image meter-sized objects. This leap in resolution can be achieved today by acquiring 3D seismic data using currently available sources and receivers arranged in a configuration similar to the P-Cable system with tight streamer spacing, short offsets and fast shot rates.

The resulting 3D seismic volumes will represent the framework for data interpretation, integration and inversion where in situ measurements can be propagated with minimal data interpolation. These results will have direct implication for geohazards assessment and overburden management by generating the best possible 3D ground model. In addition, a better understanding of fluid migration in the shallow sub-surface will probably lead to the development of new techniques relevant for oil and gas exploration.

Acknowledgements

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