Subsidence measurement and improved statics solutions through accurate node depth determination during time-lapse deep-water OBN surveys

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Summary

Principles from gravity-subsidence surveys have been integrated in OBN operations to accurately measure relative node depths using a technology called DepthWatch. In our deep-water fields, the accuracy obtained is < 5 cm, much better than that from OBN-reported depths or acoustic bathymetry data. We present a novel workflow to produce a measurement of seabed subsidence with an accuracy of 3 cm, by comparing node depths measured at successive OBN surveys in the same field. Accurate subsidence measurements are important for geomechanical model calibration and for understanding field-scale compressibility. This information can be useful for early identification of challenges to the stability of field infrastructure. We also demonstrate that accurate node depths contribute to improved OBN water statics solutions and reduce noise in high-fidelity 4D seismic data, improving our understanding of the field in production.

Operational method

Improved accuracy of relative node depths is achieved by thermal and mechanical stabilization of pressure sensors, calibration in relevant pressure and temperature ranges, measuring on top of the node, accurate determination of water density and local gravity, and use of reference measurement locations for sensor drift corrections (Eiken et al., 2008; Vatshelle et al., 2017; Agersborg et al., 2017; Hatchell et al., 2019).

Dedicated sensor packages are incorporated into the ROV body and the manipulator arm, and the data they produce are monitored in real time during the operation. The actual node depth measurements are performed when the ROV arm is in contact with the node at its deployment position, either during node deployment or recovery (Figure 1). Small modifications in the node handling procedure for the ROV are introduced to provide the most repeatable measurement conditions.

Reference measurement locations are visited at least twice during the operations. They are either a few seismic nodes or existing seabed infrastructure. Measurements at reference locations are performed during idle time for the node vessel, or by means of minor modifications of its trajectory during the deployment or recovery operation. By closely co-ordinating with planned OBN operations, the node relative depth measurements can be acquired at a fraction of the time and cost of an OBN survey. The final product is a map of relative node depths with respect to a reference node (Figure 2).

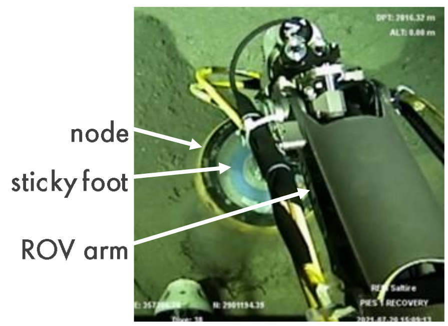

Figure 1: Node depth measurement on an OBN using a sticky foot on an ROV arm

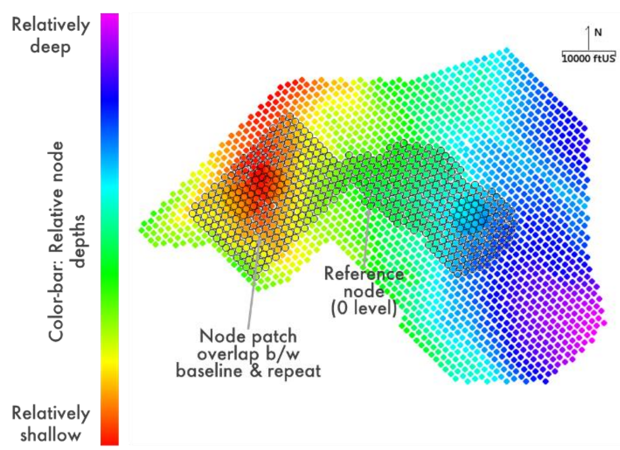

Figure 2: Node relative depths with respect to a reference node. The shaded area represents the overlap between the baseline and repeat surveys where subsidence is computed.

Subsidence measurement workflow

To measure seabed subsidence, we utilize accurate node-depth measurements from successive OBN campaigns in the same field. Even if the nominal target node positions are the same in both campaigns, operational efficiency constraints result in the actual lateral positions differing by up to a few

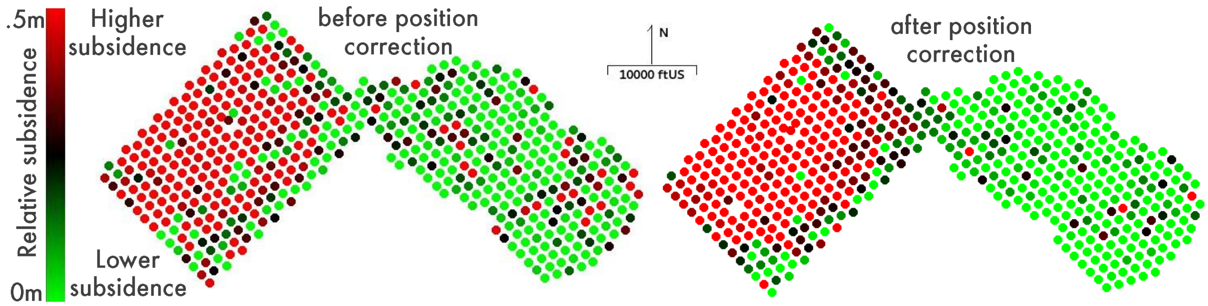

Figure 3: Measured relative subsidence before (left) and after (right) correction for node position non-repeatability between baseline and repeat surveys. After correction the subsidence bowl in the field in the west is more continuous with smoother gradation from high to intermediate to low subsidence, and the subsidence in the field in the east is less noisy.

meters. This can introduce differences in the deployment depth on a tilted seabed, and in turn noise in the subsidence data. We use acoustic bathymetry data to reduce this noise, by subtracting from time-lapse depth differences the contribution arising from different lateral node positions in the baseline and repeat surveys. While acoustic bathymetry maps suffer from sizeable inconsistencies in absolute depth at large lateral ranges, they accurately describe relative depths at short lateral ranges.

The overall workflow we apply is as follows:
1) We compute the difference in relative depths between nodes placed at the same target location at the baseline and repeat surveys.
2) We correct for differences in deployment position by subtracting the height difference between the node locations in the two surveys, according to the bathymetric map.
3) We calibrate the resulting subsidence values via a common bulk shift to a reference zero-levelling area with negligible expected subsidence.

Subsidence results and uncertainty

We apply the subsidence workflow to two adjacent deep-water producing fields. We use the overlapping node patch (Figure 2) between two OBN campaigns (400 m × 400 m node grid) separated by a few years.

Figure 3 shows the resulting relative subsidence before and after the node position non-repeatability correction described in the previous section. Even before correction, the overall computed subsidence in the field in the west is larger than the field in the east, with relative magnitudes in line with a-priori information. After correction the subsidence bowl in the west is more continuous with smoother gradation from high to intermediate to low subsidence, and the measurements in the east area are less noisy.

Figure 4 shows a smoothed and interpolated version of the node-wise subsidence corrected for node position non-repeatability. Note that the relative subsidence differs by about 0.5 m between the two adjacent producing fields in the time between the successive OBN surveys.

This new calibrated result provides an independent measurement of the distribution of seafloor subsidence across the region, important for geomechanical model calibration and understanding field-scale compressibility, with implications for the stability of wells and seafloor infrastructure.

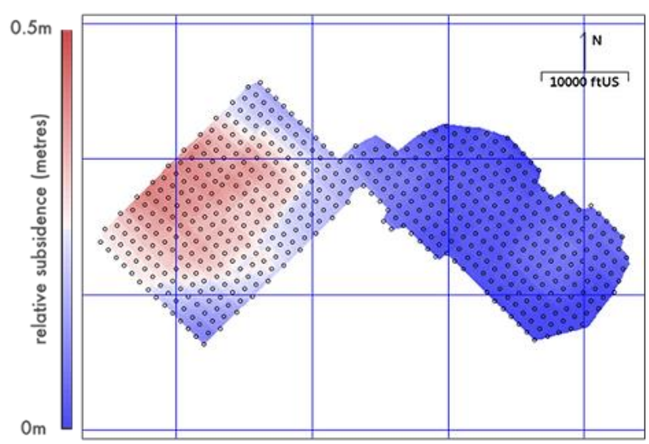

Figure 4: Smoothed subsidence map post node-position non-repeatability correction with an overlay of the node positions. Shows ~.5m difference in subsidence between the adjacent producing fields over a few years, with an overall uncertainty of ~3cm.

A thorough analysis is performed to quantify the accuracy of the resulting subsidence measurements. The uncertainty sources considered include uncertainties in the parameters used for pressure-to-depth conversion (local gravity and density); the measurement of relative pressure with sensors that have undergone a dedicated calibration at the relevant

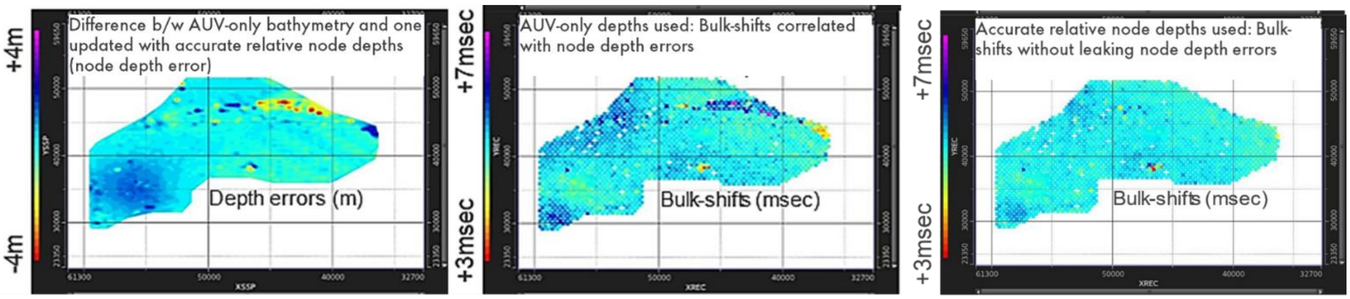

Figure 5: Difference between AUV bathymetry map and the updated map including accurate relative node depths (left). Node-dependent bulk timing errors obtained from first arrival data while using AUV only (centre) and along with accurate relative node depth constraints (right).

pressure and temperature conditions (different for the baseline and repeat surveys); limited repeatability of the operational procedure for relating the depths measured by the instrumentation with the actual deployment depths of the nodes. The analysis yields an accuracy in relative subsidence of 6 cm at each node, of which only 2.4 cm is correlated between nodes and the rest is operational.

To evaluate the effect arising from the uncertainty in the measured lateral positions of the nodes, we perform a dedicated test. We vary node positions by 0.5m, which represents the positioning accuracy according to seismic travel time inversions with careful statics corrections applied. Then, based on acoustic bathymetry information, we convert that error into an error in the vertical position. The standard deviation in subsidence is found to be < 5 cm.

To cross-check the accuracy estimate, we compute the discrepancy between the subsidence measurement at each node and a smooth interpolation into that location of subsidence measured at the rest of the nodes. The distribution of the discrepancies is approximately Gaussian with a standard deviation of 7 cm after removing outliers, compatible with the accuracy estimate. Note that the accuracy is improved to better than 3 cm when several nodes are included in the evaluation over an extended area, as done in the final smoothed subsidence map. This is due to the reduction of the uncorrelated uncertainty components.

In summary, this is a new, independent measure of subsidence in the field with high accuracy (~3cm uncertainty over a few years, better than other offshore monitoring technologies deployed in the region) and having relatively large spatial coverage (OBN node patch) on a 400mX400m node grid. It effectively complements other subsidence monitoring technologies in the field: spatially sparse PMTs with high temporal resolution (Hatchell et al., 2017), 4D seismic depth-shifts with more extensive spatial coverage but poorer vertical accuracy and resolution (Kiyashchenko et al, 2020), and the more localized TLP tendon tension data.

Improvements in seismic processing

Node depth constraints are crucial for the accuracy of OBN statics. Significant improvements in 4D OBN statics are achieved by the joint use of time-lapse direct arrival and first-order multiple information, while accounting for spatio-temporal water velocity changes (Kiyashchenko et al., 2020). For a subsiding seafloor, constraining depth change becomes important for the 4D OBN statics correction.

In seismic processing, inaccuracy in node depths leads to incorrect node-dependent bulk shift timing updates, thus affecting the quality of the OBN statics solution. With accurate node depths, timing error corrections are fully decoupled from the bathymetry errors. This is demonstrated in Figure 5. Note that the difference between AUV seafloor depth and the accurate relative node depth-driven updated bathymetry shows the subsidence bowl and few localized errors (left).

The workflow for OBN statics derivation includes determination of multiple factors including node-dependent bulk timing error (bulk shifts) corrections (Kiyashchenko et al., 2020). The node depths are typically constrained using available information from sources besides seismic wave travel times. The bulk shifts derived before, using inaccurate AUV-driven relative node depths, show strong imprints of bathymetry error (centre). After using accurate relative node depths, these imprints are greatly reduced (right).

In time-lapse mode, water velocity variations cause significant event timing changes for deep water and therefore lead to non-repeatability. Typically, time-lapse artifacts caused by day-to-day and spatial-dependent water velocity changes have the form of stripes in volumetric and map-based attributes. Therefore, accurate corrections for the water layer variability are essential to eliminate this type of noise. Precise node-based subsidence measurements ensure that the corrections related to water velocity are not influenced by node depth changes. With node depth change

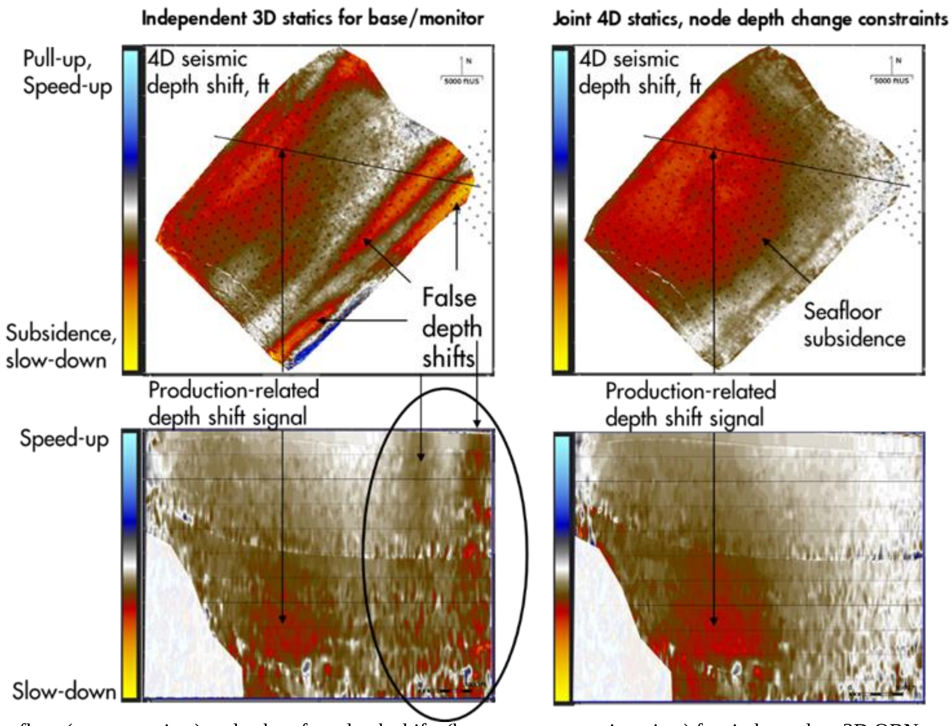

Figure 6: Seafloor (top, map view) and subsurface depth shifts (bottom, cross-section view) for: independent 3D OBN statics workflows used for baseline and monitor data (left), and joint 4D statics workflow using node depth change constraint (right). Improved statics workflow eliminates false depth shifts and shows subsidence not contaminated by water velocity changes. Areas with spurious depth shifts resulting from low seismic energy in a gate are faded.

constraints, the rest of the corrections (related to water velocity variations, tides, and timing) are easier to manage. As a part of comprehensive OBN statics correction workflow, this leads to improved estimates of seafloor and subsurface depth shifts related to subsidence and compaction-driven overburden velocity changes in a producing reservoir.

This is demonstrated in Figure 6. The left-hand plots show the seafloor depth shift map (top) and the volume traverse (bottom) views resulting from early (fast-track) OBN statics correction flow using AUV node depths and direct arrival travel time analysis. The real compaction-induced depth shift and the associated seafloor subsidence is seen, but it is obscured by water-velocity imprints (stripes of noise). The subsidence bowl shape is distorted ant its magnitude is underestimated. With the use of accurate relative node depth constrains and advanced OBN statics using both direct arrival and water bottom multiple, subsidence and subsurface changes are accurately recovered.

Conclusions

We have developed a novel workflow for computing a highly accurate (~3cm uncertainty), independent measurement of seafloor subsidence from time-lapse relative node depths measured in baseline and repeat OBN surveys. The accurate relative node depths and subsidence measurements are utilized for significantly improved OBN statics solutions, enhancing data repeatability and 4D signals. The resulting accurate seabed subsidence maps and depth shift volumes are useful for updating and calibrating geomechanical and reservoir models, improving our understanding of field-scale compressibility. These results also provide important information for ensuring offshore field integrity. Close collaboration and co-ordination with key stakeholders in the project ensured that the accurate relative node depth measurements were incorporated into the OBN campaign with high operational and cost efficiency.

Acknowledgements

The authors would like to acknowledge Shell International Exploration & Production Inc. and BP Exploration & Production Inc. for permission to publish this work. Thanks to Jan Stammeijer for providing valuable steer to the project, Matt Paloian for help with repeat measurement locations, & Ahmed AbdElAziz for useful comments and suggestions