REVEALING 4D SUBSIDENCE WITH 3D WATER-BOTTOM TRAVELTIME INVERSION

S. Dega[1], T. Allemand[1], Z. Yu[1], N. Salaun[1], A. Lafram[2], A. Grandi[2], E. Jungo[2]

[1] CGG; [2] TOTAL E&P

Summary

The quality of time-lapse analysis depends highly on the repeatability of the acquisition. However, in practice, it is almost impossible to perfectly mimic a base survey due to environmental conditions and inaccurate measurements. Lack of repeatability often results in 4D noise, which may compromise the 4D signal. In the presence of subsidence, caused by the depletion of the reservoir, 4D signal exists outside of the reservoir area, and its extraction from noisy 4D data can be challenging without a priori information. Water layer tomography has already been proposed to recover uncertain parameters from the acquisition in order to address the non-repeatability effects in the data but not with as many parameters as presented in this paper: water velocity, source position, top of the water layer and start of data time. Unlike most water layer tomography, our method not only relies on the inversion of the water-bottom primary but also of the first-order multiple travel times picked in the data. An application to a 3D deep-water survey offshore Angola is presented. The flow is applied independently to all vintages of a 4D project resulting in significant reduction of the 4D noise and a clear visibility of the subsidence.

Revealing 4D subsidence with 3D water-bottom traveltime inversion.

Introduction

One ground rule in time lapse or 4D seismic is to maximize the repeatability between acquisitions of the different surveys, as it will generate less 4D noise. Among all survey parameters, source and receiver positioning, sea surface variations and water velocity play a crucial role in seismic repeatability and their accurate knowledge is the key to achieve a good 4D result. MacKay et al. (2003) showed that water velocity in a given area, due to changes in temperature and salinity, could vary as much as 30 m/s and then induce dynamic time shifts in recorded data, while Lacombe (2006) explained that tidal variations can also add to the effects of water velocity variations. Johnston (2013) described how an error in offset measurement significantly increases the normalized root mean square (NRMS). Unfortunately, reliable measurement of these parameters is not always available, and inaccuracies result in time shifts in seismic traces, i.e. residual statics.
To deal with residual statics in 3D surveys, 4D projects usually resort to pure matching techniques (Rickett et al, 1998). These methods rely on a priori information regarding the location of the 4D signal, but, in the presence of subsidence, reliability of such a priori information can be questionable. To avoid this problem, another strategy entails estimating the residual statics based on a physical model of wave propagation in the water layer and then correcting statics on each vintage independently. For this purpose, water-bottom traveltime inversion has been used for many years. Ritter (2010) proposes to estimate the variation of the propagation velocity in water and a constant vertical shift of the water-bottom depth with a 3D tomographic method, which minimizes the L2 norm of primary water bottom travel time residual, using a picked water-bottom reflection. Udengaard and Craft (2012) applied a similar tomographic approach on OBN direct arrivals to determine position and timing corrections and to update the depth dependent water column velocity, but this does not correct for residual tidal statics. In the following section, we describe an enhanced 3D water bottom traveltime inversion for towed streamer: the water layer inversion (WLI). While it estimates the errors in water velocity and sea level for each shot as in existing methods for streamers, it also includes errors in source position and start of data time. Our method, particularly suited for deep-water acquisitions, not only inverts for more parameters than existing technologies, but it also relies on precise modeling using both water-bottom primary and first order multiple travel times for a better conditioning of the inverse problem. We apply the method on real streamer data, and we show how the application of the residual statics corresponding to this inverted water layer model leads to less jitter in 3D data, a better 4D difference, and finally, a much better visibility of the subsidence, without resorting to any 4D matching technique.

Estimation of the acquisition parameters from water-bottom travel times

We propose a 3D tomographic method that directly estimates the water layer parameters having the most impact on the repeatability, independently for each shot: a constant water velocity variation, shot point position, sea level and start of data recording time (Figure 1). The inversion aims to recover the corresponding corrections *dv*, *dhx*, *dhy*, *dz* and *dt* to be added to the initial parameters, based on the information extracted from water-bottom primary and first-order reflection travel times. For most deep-water acquisitions, these two events can be easily picked on the data since they have stronger amplitude than noise. We assume the source and receiver depths to be constant, as well as the receiver positions and the water-bottom topography.

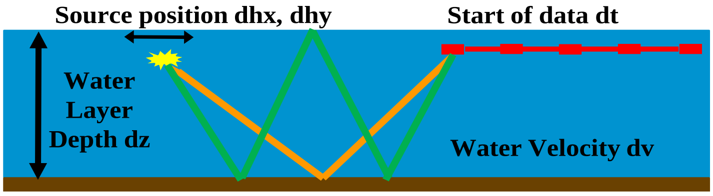

Figure 1 *Schematic representation of the five parameters inverted by the WLI, and the data used for the inversion (water-bottom primary and first order multiple).*

All these parameters influence the computation of travel times by ray tracing. It is then possible to form a non-linear minimization problem with an objective function C based on the difference between observed and computed water-bottom primary (p) and first order multiple (m) travel times.

$$C(dhx,dhy,dz,dv,dt) = \lambda_1^2 \sum_{rcv} \left|\left|T_p(rcv,dhx,dhy,dz,dv) - \left(t_{p,OBS}(rcv) - dt\right)\right|\right|^2 + \lambda_2^2 \sum_{rcv} \left|\left|T_m(rcv,dhx,dhy,dz,dv) - \left(t_{m,OBS}(rcv) - dt\right)\right|\right|^2 \quad (1)$$

The modelled travel times are computed for each source-receiver pair by ray tracing in a given initial variable 3D velocity field, $v(x,y,z)$, with a known water bottom.

We iteratively solve the non-linear problem described by equation (1) with a local optimization method. At each iteration, we first perform ray tracing in the water layer and compute the Fréchet derivatives; we then solve the linearized problem jointly for all parameters with an algorithm based on SVD decomposition. We added damping terms to the cost function for more stability. The inversion is performed independently on each shot and outputs a constant value for the perturbations of the parameters we want to recover. The model estimated by the WLI is used to compute statics to be applied to the traces.

Application on 3D survey

The flow is applied to a 3D survey over the Dalia field located in Angola deep offshore Block17. As a deep-water survey, water-bottom primary and multiple events are well visible and distinct.

We invert for the survey parameters at an early stage of the processing, after tidal and receiver motion corrections. Several runs of the inversion are carried out. After the first run of WLI inverting all parameters, a global median value of the gun delay (start of time *dt*) is kept for the whole survey, as the gun delay is constant over the survey, and the data is shifted accordingly. After the second run, keeping fixed the gun delay, median values of *dv* are computed for each sequence, as water temperature varies during the survey, and the corresponding static time-shifts are computed and applied to the data. This process is repeated for *dz* and finally *dhx* and *dhy*. Salaun and al. (2021) describe the detailed workflow and show the necessity of the *dhx* correction for the inversion stability for undershoot sequences with a push-reversed configuration, due to an erroneous location of the tail boil. The application of the workflow on the data (Figure 2) results in a strong attenuation of the jittering. After application of the WLI, the water-bottom is less broken, much smoother and continuous.

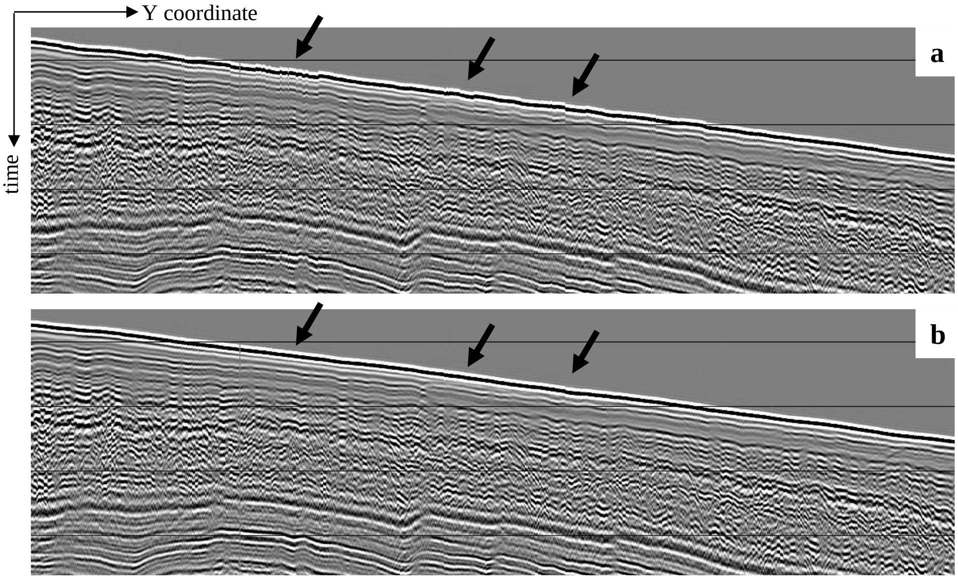

Figure 2 *Crossline sections from pre-migration stack before application of statics derived from WLI (a) and after (b).*

Application on 4D survey

The application of the 3D WLI on all vintages of a 4D project allows us to evaluate the impact of the method on 4D data. The Dalia field is known to have strong subsidence with arching effects making difficult the application of 4D matching techniques as geological 4D time shifts are located in the overburden, which is where matching filters are computed. The base and monitor surveys were acquired in 2012 and 2014 respectively, and both used flat streamers with 2.5km maximum offset.
Figure 3 shows the 4D difference computed on pre-migration stacks between 2012 and 2014 before (a) and after (b) WLI on an inline where black arrows indicate the location of the two reservoirs. WLI helped to reduce the 4D noise and highlight the 4D signal on both reservoirs. QC on the NRMS maps (lower NRMS means more repeatable data) computed around the water-bottom confirms the effectiveness of the method, reducing the NRMS median value by almost 9% from 14% (c) to 5.5 % (d), which is very good at such an early stage of the processing.

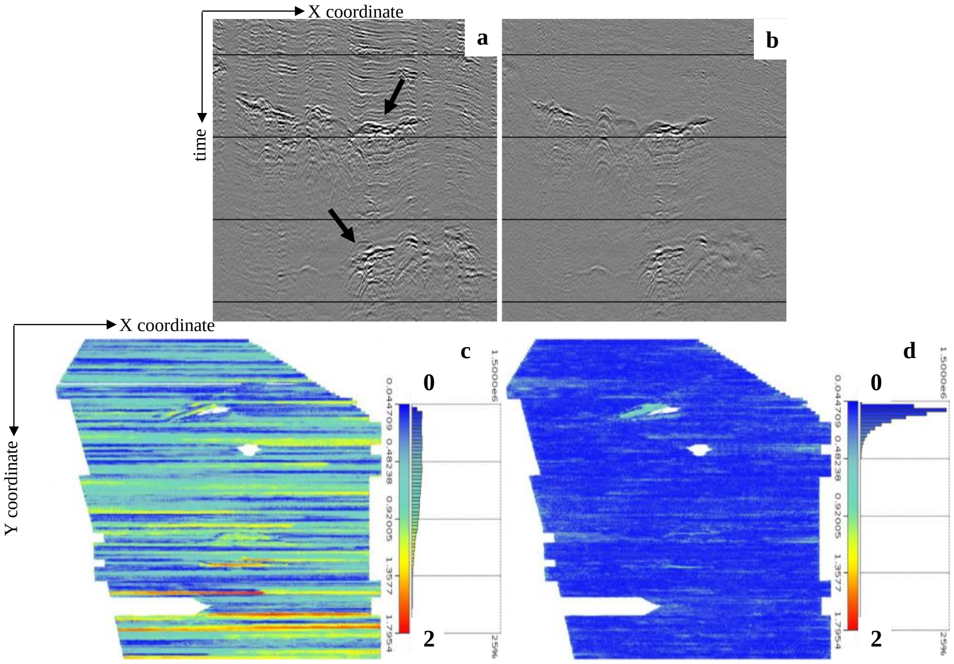

Figure 3 *4D difference between 2012/2014 at the reservoir location before WLI (a) and after (b). The reduction of the 4D noise on the whole survey is shown by NRMS maps around the water-bottom before (c) and after WLI (d).*

A comparison with the legacy 4D project, for which a different de-signature (Salaun et al., 2021) and conventional matching techniques were applied, of the 4D time shifts between 2012 and 2014 after pre-stack time migration is shown in Figure 4. Looking at a depth slice at reservoir level, legacy 4D signal (a) is blurred and less clearly delimited whereas the new processing (b) is less noisy with stronger 4D signal. On an inline section, the legacy time shifts (c) in the overburden are strong up to the water-bottom, which is geologically doubtful and probably related to 4D noise, as a dimming of amplitude is expected in the shallow. The new processing (d) has time shifts more coherent with the phenomenon of subsidence (Rodriguez-Herrera et al, 2015).

Conclusion

We presented an innovative method to estimate the main non-repeatable acquisition parameters through inversion not only of the water-bottom primary but also of first order multiple travel times. For the application on real 4D data, the process was applied independently on each vintage to correct for residual statics. The diversity of the parameters recovered by the inversion, greater than in existing water layer tomography, allowed these residual statics to be obtained with high precision. This results in reduced jitter on 3D data but also in better 4D repeatability as well as reduced 4D noise. The reduction of 4D noise, significantly improved compared to conventional matching methods, allowed clearly revealing the subsidence in the overburden area to further help the interpretation of the production-induced changes in the reservoir.

Acknowledgements
The authors would like to thank Total & partners, ANPG, and CGG for permission to publish this paper.

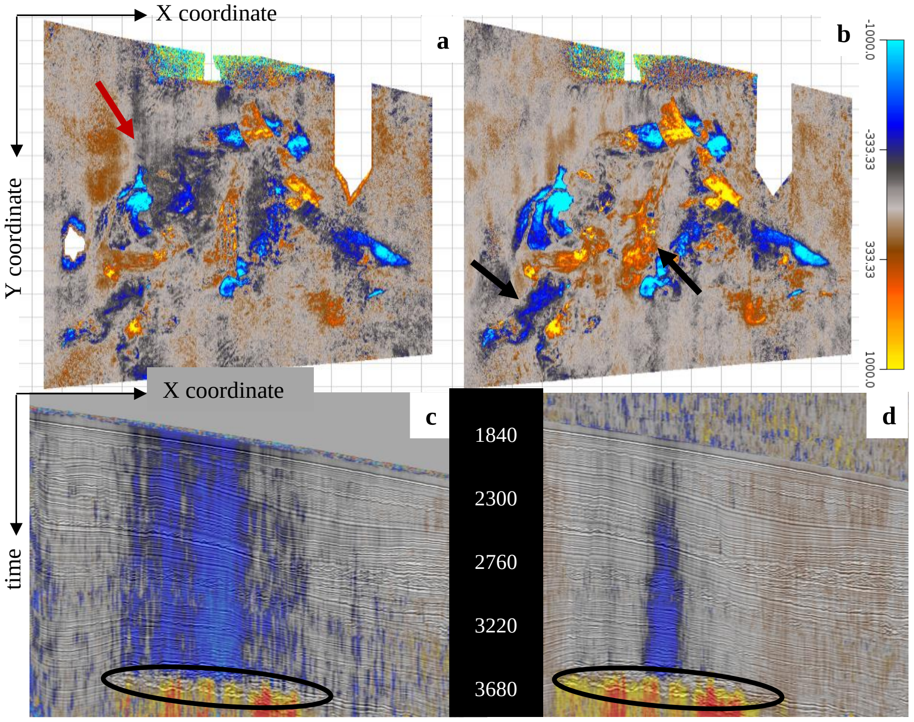

Figure 4 *2012/2014 4D time-shift depth slices at the reservoir depth after PSTM from the legacy project (a) and the current re-processing (b). (c) and (d) are the same 4D time shifts viewed on an inline section where the reservoir is circled in black. The new processing results in a more coherent subsidence with a diming of magnitude in the shallow.*

References

Johnston, D. [2013] Practical Application of Time-lapse Seismic Data. *SEG Distinguished instructor series*, no. 16.

Lacombe, C., Schultzen, J., Butt S., and Lecerf, D. [2006] Corrections for water velocity variations and tidal statics. *68th EAGE Conference & Exhibition*, Extended Abstracts, P098.

MacKay, S., Fried, J., Carvill, C. [2003] The impact of water-velocity variations on deep water seismic data. *The Leading Edge*, **22**, 344–350.

Rickett, J., Lumley, D. [1998] A cross-equalization processing flow for off-the-shelf 4D seismic data. SEG Technical Program Expanded Abstracts, 16-19.

Ritter, G. L. D. S. [2010] Water velocity estimation using inversion methods. *Geophysics*, **75**, no. 1, U1-U8.

Rodriguez-Herrera, A., Koutsabeloulis, N., Onaisi, A., Fiore, J. and Selva F. [2015] Stress-induced signatures in 4D seismic data: Evidence of overburden stress arching. SEG Technical Program Expanded Abstracts, 5368-5372.

Salaun, N., Pouget, M., Yu, Z., Beigbeder, C., Rivet, A., Peiro, M., Dega, S. [2021] Beyond cross-equalization, a novel 4D processing flow over Dalia and Rosa fields. *82th EAGE Conference and Exhibition*, Extended Abstracts (submitted).

Udengaard, C.R., Craft, K. [2012] Analysis of water column complexity in OBN data. *74th EAGE Conference & Exhibition*, Extended Abstracts, B046.