Novel seismic forward modelling of the seal bypass structure: an example from the Loyal field of the North Sea (Scotland, UK)

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Summary

Fluid escape pipes and blow out structures represent important seal bypass system (SBS) affecting the overburden. Most of those structures have been proven major fluid conduits that may reveal important hints on the fluid migration and fine-tuning our understanding on the main process controlling their genesis can be crucial in elucidating subsea hazard aspects during exploration stage. However, due to the lack of direct geological evidence and clear geophysical imaging, there are still uncertainties concerning they main architecture (root, conduit and seal). In order to contribute to the seismic interpretation of those subsurface structures, we propose a forward seismic modeling aiming at exploring the nature of certain seismic structure responses and architectures observed across the Loyal field (Shetland basin) and using different petrophysics properties. We first build a geological model with essential rock profiles and well logging data constrained. Then, we employ three approaches, i.e., forward modeling, ray-tracing analysis and time-to-depth conversion, to unravel and explore some of the main internal structures observed within the interpreted fluid pipe seal by-pass structures present in the Loyal field. The results allow us to put some constrains on the origin and nature of some specific seismic features observed in the seal bypass structures: (i) the absorption effects in the conduit result in the lacking resolution in the internal-pipe and root structures, (ii) the upward deflections are almost formed by the real upward dragging intrusive material and (iii) the internal pipes are affected by low velocities related to fluid-rich solid material.

Introduction

SBS are structures that cut the sealing seal sequences vertically and allow fluid migrating horizontally into the overburden porous grid (Cartwright et al., 2007). The fluid escape pipe (Figure 1) is one kind of SBS that shapes vertical or sub-vertical structures cutting through the seal overburden reaching already or closely to the top layers forming termination. Fluid escape pipes are important subsurface structures which can act as secondary hydrocarbon migration and vertical fluid flows, as well as forming the porous networks for the fluid through the overburden sealing sequences (Berndt, 2005; Cartwright et al. 2007; Cartwright and Santamarina, 2015; Huuse et al., 2010).

Details of them are still poorly understood, while the intrusive over-pressured mechanisms that have been proposed seem very complex and not single-factor influenced (Cartwright et al., 2007; Cartwright and Santamarina, 2015). Moreover, the lack of direct analogue outcrop information (e.g., analogue rock and well logging) makes seismic data the main subsurface source of dataset.

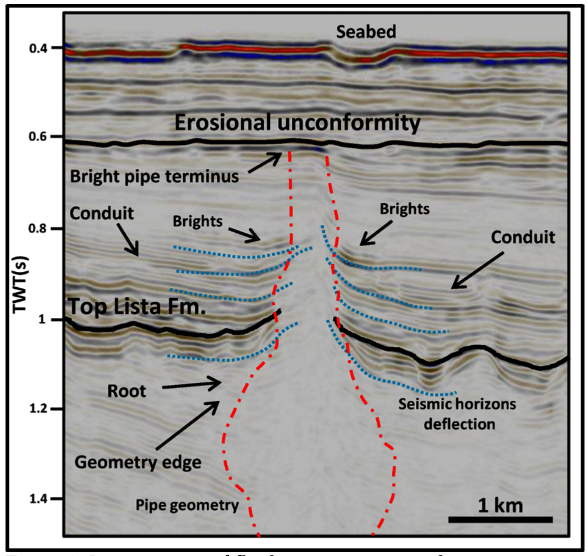

Figure 1: Interpretation of fluid escape pipe on real seismic images

Here, we aim to explore the geometrical and petrophysical situation of the fluid escape structures described in the Loyal field from previous seismic interpretation (Maestrelli et al., 2017), and through the utilization of ray-tracing test towards the conduits and time-to-depth conversion experiments, we explore the potential time pitfall when interpreting those structures.

Field Description

<u>Geologic Setting</u>

The Loyal field is located 60-km northeast of the Faeroe-Shetland Trough (North Sea), which has experienced a complex evolutionary history in geology (Dore et al., 1997; Dore et al., 1999; Dean et al., 1999; Roberts et al., 1999). The main structural element from the seismic volume is the Mesozoic/Paleozoic Judd High in the southwest of the portion. The Cenozoic stratigraphy is characterized by the Ekofisk and Maureen Formations (The T10-T20 BP sequence). The hydrocarbon reservoirs are hosted in the T30-T50 sequence represented by Lista, Sele and Balder Formations (Leach et al., 1999). The T38-T40 succession represents the lateral continuation of the top of the basalt here corresponding to the Top of Paleocene sediments

(Sorensen, 2003; Watson et al., 2017). The major seal for the reservoir underlying is the Top of the Lista Formation. The youngest overburden units observed are Mio-Pliocene turbiditic channelized sediments and contouritic deposits (Maestrelli et al., 2017). The Loyal field has no evident findings on basalt, but only clues of gas and sand intrusions based on the information from the BP industry report, which can also be supported by the stratigraphic chart (Figure 2).

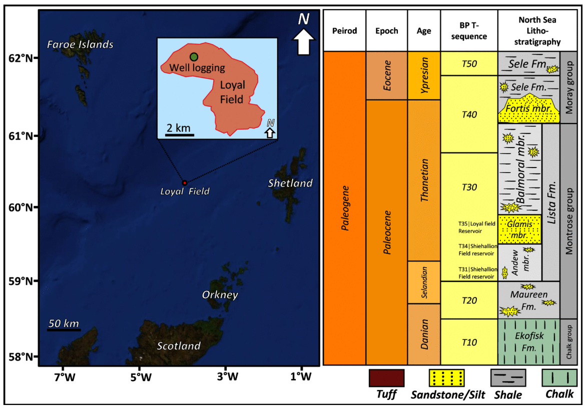

Figure 2: Location and stratigraphic chart

Seismic Data

The area containing our simulation target within the seismic dataset is the Loyal field (North Sea, UK) and located in the southernmost part of the Faeroe-Shetland Trough, which is on the edge of the channel, to the north of Schiehallion, west Shetland (Figure 1). The data area covers about 15 x 17 km^2. The seismic volume is characterized by zero-phase American polarity with red for the positive peak, with frequencies in a range between 20 to 80 Hz.

Analogue Outcrop and Well Logging Dataset

Only one well and well log dataset (204/20) could be used as well tie for the seismic dataset. This well logging provides us a reference property range and the Lista Top Formation reference layer. The nearby VSP dataset proves that the velocity in our area of interest is between 1700 m/s to 2200 m/s and the tuning thickness is between 5- to 27-m.

Methodology

Seismic forward modeling has been performed following a method using ray-generated Point Spread Function (PSF) for convolution with an input reflectivity model, which directly and efficiently simulates PSDM-like images (Lecomte et al., 2003; Lecomte et al., 2008; Lecomte et al., 2016; Figure 3). The workflow as shown in Figure 4 performs standard ray-tracing and time-to-depth conversion experiments to explore the illumination responses to obtain the best imaging of highlighted features

and to test the significance of some apparent pull-up pitfalls, respectively.

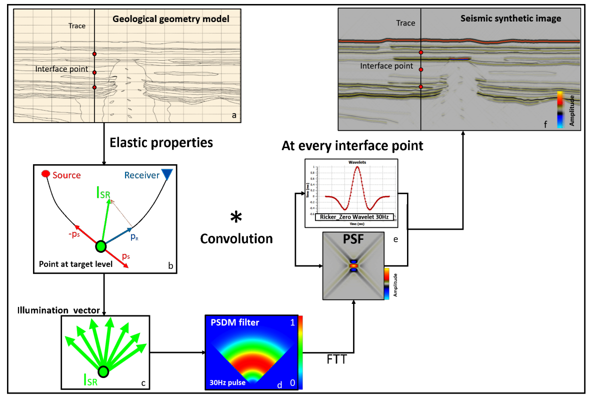

Figure 3: Methodology: ray-generated Point Spread Function (PSF) for convolution, a) Input geometry model, b) illumination of interface point dependent on source/receiver positions, c) illumination vector, d) PSDM filter in frequency domain, e) PSF and wavelet for convolution and f) seismic synthetic image

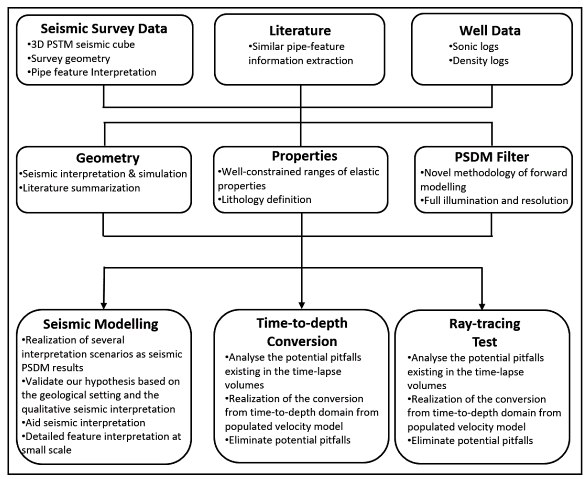

Figure 4: Workflow of the study

Examples

Figure 5 presents the ray-tracing experiment shows the ray-absorption situation in the two scenarios of source shooting from the pipe root and center. The strong bright anomalies in the conduit layers absorb a big portion of rays reaching the root zone, which can explain why the root and internal zone of the pipe remains very chaotic and lacking resolution.

Figure 6 presents the time-to-depth conversion test which gives an opportunity to quantitatively investigate whether the real cause of the upward deflection of the pipes i.e. the pull-up time pitfall effect or the rising of the sediment-fluid mix with hydrocarbon fluids. It was found that the velocity around 4450 m/s can trigger the pull-up deflection, which

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does totally mismatch with that observed at this depth. Then we performed the image-ray-tracing test with the triggering velocity i.e. 4450m/s. The results show that this velocity cannot entirely remove the velocity pitfall. It can further support that the unrealistic internal high velocity being the only factor is even higher than 4450 km/s. Therefore, we can conclude that the pull-up deflection can be only caused by the upward intrusion.

Figure 7 presents comparisons between the PSDM synthetic results and the real images. The original seismic images match the synthetic scenario with low-velocity internally rather than that with high-velocity. The results can be proven by the matching results of almost all big- and small- scale details. Therefore, we can conclude that the pipe structure has low-velocity nature, which can further support other similar pipe-like and SBS structures.

Conclusion

In this study, the overall 2D synthetic seismic modeling i.e. with standard ray-tracing, time-to-depth conversion tests and PSF-based convolution modelling, allowed us to better understand the seismic expressions observed and interpreted in the Loyal field:

- the ray-tracing test suggests that the seismic chaotic nature of the internal-pipe and root structures might result from the absorption effect in the conduit that prevent the rays to reach deeper part,

- by using time-to-depth conversion test, we rule out the possibility that some of the distinctive upward dragged reflector (apparent pull-up structures) may entirely be controlled by simple velocity push-up,

- the ray-tracing test suggests that the seismic chaotic nature of the internal-pipe and root structures might result from the absorption effect in the conduit that prevent the rays to reach deeper part.

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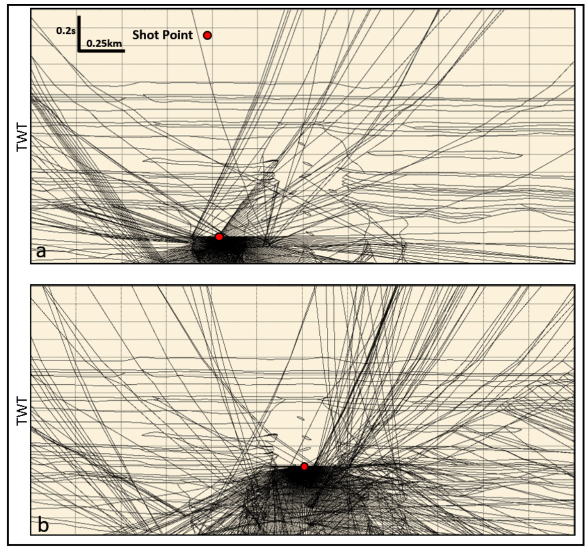

Figure 5: Ray-tracing experiment: a) shot from pipe root and b) from pipe center

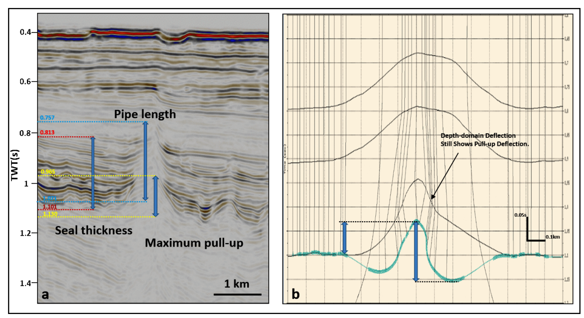

Figure 6: Pull-up time-to-depth conversion analysis: a) Maximum pipe pull-up in the Loyal field and b) time-to-depth conversion with the velocity calculated from the maximum pull-up deflection

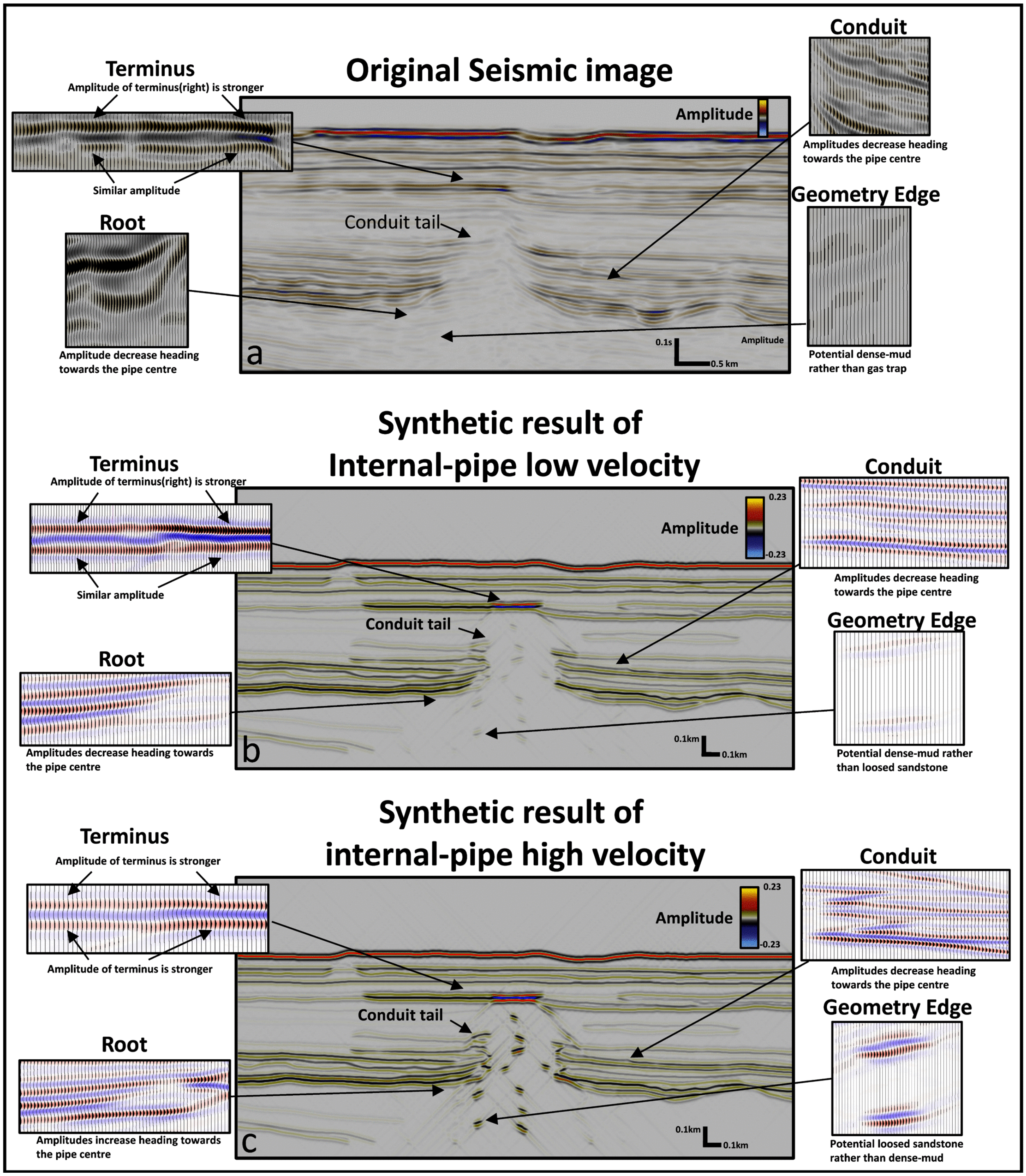

Figure 7: Comparison of the synthetic results with real seismic profile: a) original seismic image, synthetic images of b) internal-pipe low velocity and c) internal-pipe high velocity

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