Enhancing subsalt imaging of DAS-VSP data using a structurally adaptive aperture

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Summary

3D DAS-VSP surveys have the ability to complement surface seismic data to provide a holistic subsalt image and illumination. However, the DAS-VSP geometry intrinsically has limited angular coverage which leads to strong swing artifacts that contaminate and degrade the seismic image. To enhance the image quality of DAS-VSP data, we propose to use a structurally adaptive aperture in reverse time migration to confine the image only to those within a predefined angular range. Application of the algorithm to one field DAS-VSP data collected in a complex salt environment clearly shows significant uplift in the subsalt image.

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Introduction

Vertical seismic profiling (VSP) can provide critical information for subsurface structures with high fidelity and accuracy because of the short distance from receivers to subsurface targets [Balch and Lee, 1984; Xiao and Leaney, 2010; Zhan et al., 2019]. Especially, the recently developed distributed acoustic sensing (DAS) array could be permanently deployed in a well as VSP sensors for time-lapse monitoring due to its cost-efficiency and endurability of high pressure and high temperature [Li et al., 2022; Mateeva et al., 2012; Zhan et al., 2020]. For imaging subsalt areas with potential reservoirs, VSP can make a unique contribution to compensate for the subsalt illumination which is rarely fully covered by surface seismic reflection surveys [van Gestel et al., 2019]. However, there is an intrinsic limitation of the DAS-VSP geometry in angular coverage. The limited in-situ illumination will cause strong migration artifacts that contaminate and degrade the seismic image. To enhance the image quality of DAS-VSP data, we propose to use a structurally adaptive aperture in reverse time migration to mitigate the migration artifacts.

Reverse time migration (RTM) is a preferred algorithm for imaging geological complexity using arrivals that propagte in any direction, and it has been often used to image VSP data [Baysal et al., 1983; Chang and McMechan, 1986]. To mitigate the migration artifacts in VSP RTM, many efforts have been committed, such as up-down wavefield separation in the data domain [Foster and Mosher, 1988], wavefield separation in the image domain [Liu et al., 2011], and angular filtering during imaging [Hu et al., 2021; Zhang, 2014]. The data pre-processing (including denoising and up-down separation) can enhance the image by removing noise in data and suppressing the unmatched crosstalks during migration, but it cannot mitigate the artifacts caused by the limited stack of image smearings due to insufficient illumination. Angular filtering during imaging can adaptively control the effective imaging aperture along the well trajectory to mitigate the swing artifacts. This can be adopted in VSP RTM by limiting the opening angle of reflections which can be efficiently computed directly from the propagating wavefields using its energy flux direction (i.e., Poynting vector) [Yoon and Marfurt, 2006; Yoon et al., 2011; Zhang, 2014].

In this extended abstract, we introduce the idea of a structurally adaptive aperture in RTM and investigate its impact to the imaging of DAS-VSP data. An application of the algorithm to one field data collected in a geologically complex environment with challenging salt bodies demonstrates its effectiveness in attenuating the swing noise commonly seen in a VSP image.

Method

Conventional RTM commonly contains three parts: forward-propagating the source wavefield (e.g., acoustic wavefield $\boldsymbol{P}_{src}(\mathbf{x},\boldsymbol{t})$), backward-propagating the receiver wavefield ($\boldsymbol{P}_{rcv}(\mathbf{x},\boldsymbol{t})$), and applying an imaging condition (e.g., zero-time-lag crosscorrelation), where $\mathbf{x} = (\mathbf{x},\mathbf{y},\mathbf{z})$ is the spatial coordinate at an imaging location and $\boldsymbol{t}$ is time. Here, we introduce a weighting factor $\boldsymbol{\Phi}(\boldsymbol{x},\boldsymbol{t},\boldsymbol{\theta_s})$ as a function of $\mathbf{x}$, $\boldsymbol{t}$, and the reflection angle of incident source wavefield($\boldsymbol{\theta_s}$), as given in equation (1),

$$\boldsymbol{R}(\mathbf{x}) = \sum_{\boldsymbol{t=0}}^{\boldsymbol{t_{max}}} \boldsymbol{P}_{src}(\mathbf{x},\boldsymbol{t}) \cdot \boldsymbol{P}_{rcv}(\mathbf{x},\boldsymbol{t})\boldsymbol{\Phi}(\mathbf{x},\boldsymbol{t},\boldsymbol{\theta_s}), \qquad (1)$$

where Φ controls the weight for the range ($[\theta_s^{min},\ \theta_s^{max}]$) of the opening angle at an imaging point:

$$\Phi(\mathbf{x},t,\theta_s) = \begin{cases} 1, & \theta_s^{min} < \theta < \theta_s^{max} \\ 0, & else \end{cases}. \qquad (2)$$

The opening angle θ_s **(Figure 1)** can be calculated in many different ways, one algorithm is to use the propagation dierection of the source or receiver wavefiled computed using Poynting vector [Yoon and

Marfurt, 2006] or optical flow [Zhang, 2014] and the structural dip information computed as a prior [Yoon et al., 2011].

Using equations (1) and (2), we can remove not only the low-wavenumber image artifacts along the wavepath associated with RTM, but also attenuate the swing artifacts that can not be stacked out due to insufficient illumination often seen in the image of a VSP data (Figure 1). Furthermore, the proposed structure adaptive aperture can be easily extended for elastic RTM for imaging of different wave modes.

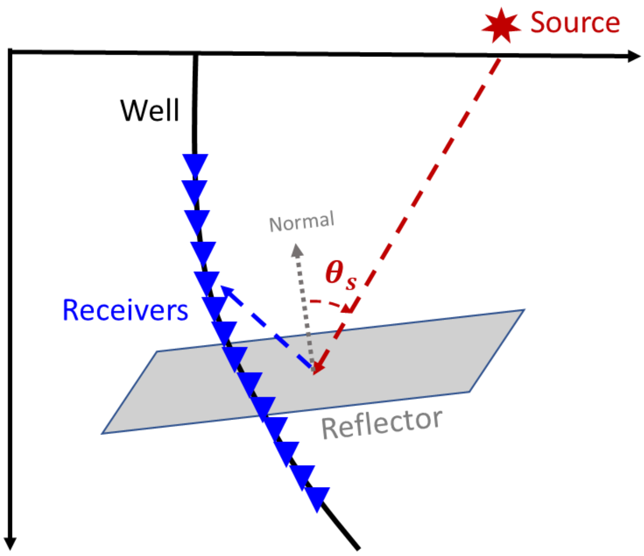

Figure 1 *Schematic illustration of the DAS-VSP geometry and the opening angle (θ_s) of waves reflected by the subsurface reflector from the surface source. The blue triangles delineate seismic sensors (traditional seismic sensors or DAS) along the well-bore. The gray dashed arrow points to the normal direction of the reflector that could be estimated from existing images.*

Field data example

We demonstrate the feasibility of this proposed method using one field DAS-VSP data. The data was collected in a geologically complex environment with multiple massive salt bodies. DAS channel depths vary from 1580 m to 6640 m at an interval of 10 m. Over 59,000 airgun shots were fired near the water surface covering a region of 7.5 km x 20 km. The well trajectory is shown as the black line in Figure 2 which also shows the conventional RTM result for the DAS-VSP data. Due to the limited illumination, strong swing artifacts present in the image, highlighted by the red circles, and the reflectors are severely contaminated, denoted by the red arrows. Figure 3 shows the result using the proposed method. Comparing Figure 2 with Figure 3, we can observe that strong artifacts have been suppressed (in red circles) and the reflectors become more coherent with higher imaging fidelity (red arrows). Especially we can observe more fine reflectors beneath the salt flank (black arrows).

The proposed method has high computational efficiency, it only requires an additional computation of the Poynting vector during the forward propagation of the source wavefield. Compared with the conventional RTM, the proposed method requires about 10% more computational cost. However, the adaptive aperture can bring the advantage of reduced disk usage and data I/O.

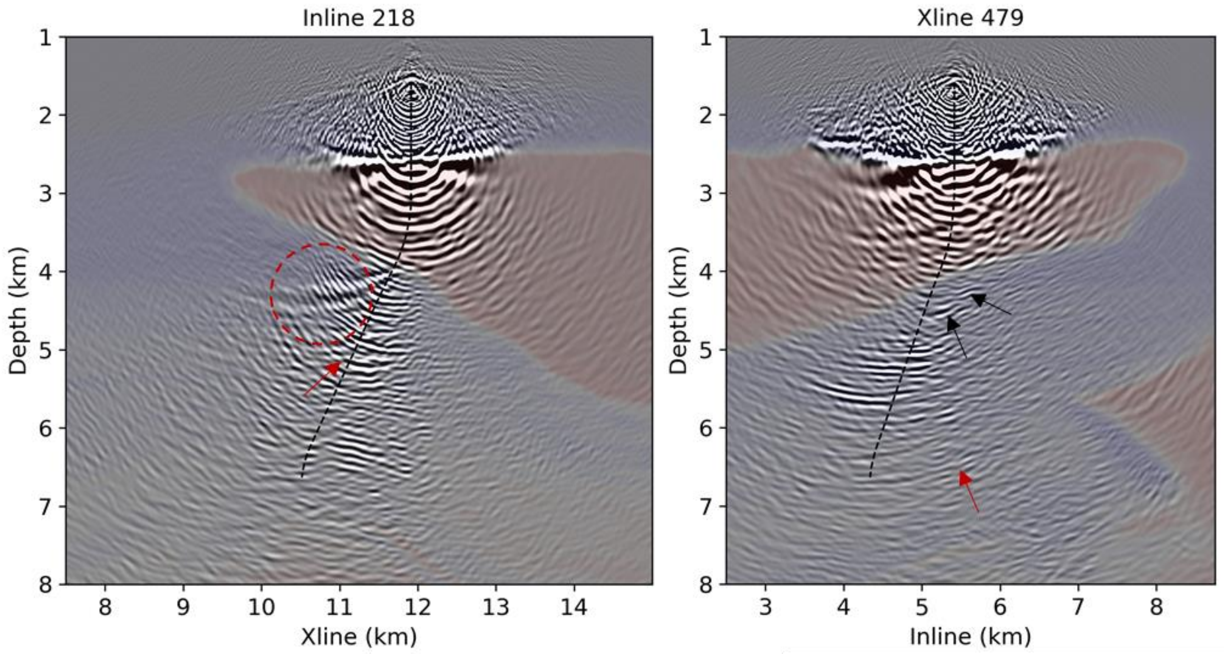

***Figure 2** Conventional RTM image of the DAS-VSP data. The left panel is one vertical section along the crossline while the right panel is along the inline direction. The black dashed line delineates the DAS receivers in the well. The seismic images are in grayscale and supposed on colored velocity models.*

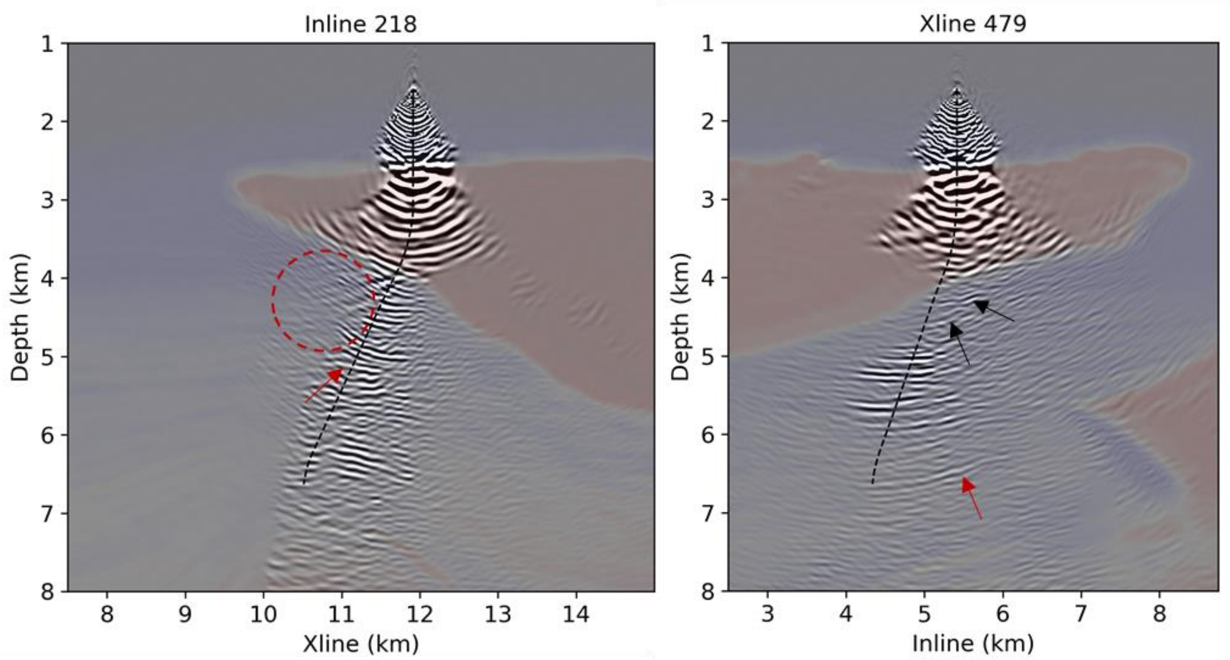

***Figure 3** RTM image of the DAS-VSP data using structurally adaptive aperture with opening angles less than 45°. The panels are similar to Figure 2.*

Conclusions

To enhance the subsurface image of DAS-VSP data, we propose the structurally adaptive aperture in RTM to mitigate the swing noise caused by the limited illumination of DAS-VSP acquasition. The adaptive aperture is automatically performed by controlling the opening angle of reflected waves during imaging associated with the input structure dip information. Application of the proposed method to the 3D field DAS-VSP data demonstrates that it can provide an image with much attenuated artifacts and higher fidelity beneath the complex salt bodies with minor additional computations.

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