EVALUATION OF SPARSITY-PROMOTING MIGRATION TO SINGLE-WELL AND DUAL-WELL VSP DATASETS

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Summary

Borehole seismic datasets are often acquired with limited sources and receivers. As a result, the produced conventional borehole seismic images suffer from severe migration artefacts due to restricted acquisition aperture. Least-squares imaging can be utilized to suppress these artefacts and enhance the spatial resolution of the borehole migrated sections. However, least-squares migration might only provide suboptimal imaging results with mediocre spatial resolution and remnant of migration smiles due to the small number of shot or receiver points. A regularized solution that promotes the sparseness of the migrated image can significantly suppress the severe artefacts and enhance the borehole seismic image quality. We have demonstrated the benefits of a sparsity-promoting migration algorithm using synthetic dual-well VSP experiment and real look-ahead VSP dataset. Both cases demonstrate the ability of sparsity-promoting regularization to optimally enhance the spatial resolution and suppress the migration smiles of migrated borehole seismic images.

Evaluation of sparsity-promoting migration to single-well and dual-well VSP datasets

Introduction

Kirchhoff migration has been used to map primary seismic reflection data to a migrated image representing the subsurface structure. However, it often yields a heavily blurred representation of the actual structure due to the limited sources and/or receivers, acquisition aperture, subsurface illumination, and bandwidth of the deployed seismic source to acquire the data (Nemeth et al., 1999). Furthermore, multiples in the records further deteriorate the quality of the migrated image since the standard migration algorithms aim to image the recorded single-scattered energy (Wang and Schuster, 2012). In the case of borehole seismic acquisition, these effects are more pronounced as the number of sources and receivers is considerably smaller than surface seismic acquisition (Aldawood et al., 2017).

Least-squares migration (LSM) can retrieve the subsurface reflectivity image more accurately than standard migration. It aims to suppress the migration artefacts, compensate for low subsurface illumination, and deconvolve the acquisition fingerprint; thus, it enhances the spatial resolution of the migrated image (Nemeth et al., 1999). LSM is a linearized form of full-waveform inversion, which yields an approximate solution to the subsurface reflectivity distribution (Crase et al., 1990).

The least-squares migration minimizes the misfit between the recorded and simulated data, which can be a highly ill-posed problem requiring regularization to stabilize the inversion process. Tikhonov regularization (Aster et al., 2005) usually imposes least-squares problems to obtain smooth and stable solutions. Due to the bandlimited nature of the source wavelet, LSM is limited to producing subsurface images with limited bandwidth (Ribodetti et al., 2011). Given that the migrated image of subsurface reflectors (i.e., discontinuities) is sparse, one can utilize a sparsity-promoting (SP) regularization term to find a sparse subsurface reflectivity distribution, which can also fit the scattered data. Highly-resolved subsurface images can be obtained by imposing sparsity-promoting constraints (Wang and Sacchi, 2007; Herrmann and Li, 2012; Aldawood et al., 2014).

In this abstract, we extend the application of sparsity-promoting migration to borehole seismic data to enhance the poor subsurface spatial resolution of borehole seismic images. The objective is to demonstrate, using both synthetic and field data examples, the ability of SP migration to collapse the severe migration artefacts and deconvolve the acquisition fingerprint during imaging borehole seismic data. The synthetic data example resembles a planned field trial with dual-well fibre-optic cables to acquire borehole seismic data simultaneously in two adjacent wells separated by 2,900 meters. We applied SP migration to produce a high-resolution image of a deep target reflector at about 4 km depth. The field data example is a marine borehole seismic dataset acquired to look-ahead of the current drilled depth for salt-bottom imaging and to steer and optimize the drilling operation. Due to the limited resources, especially the downhole receivers, the conventional image is heavily smeared by migration artifacts and acquisition footprint. Therefore, we used sparsity-promoting imaging to significantly collapse the migration artifacts and enhance the spatial resolution of the salt-bottom image.

Theory

The Kirchhoff modelling operator $\mathbf{L}$ can be used to map the subsurface reflectivity distribution $\mathbf{m}$ into single-scattered (i.e., primary reflections) borehole seismic data $\mathbf{d}$. Mathematically, generated borehole seismic data can be represented by the following matrix-vector multiplication:

$$\mathbf{d} = \mathbf{L}\mathbf{m}. \quad (1)$$

Conventional Kirchhoff migration $\mathbf{m}_{\mathbf{mig}}$ of borehole seismic data is obtained by applying the adjoint of the forward modelling operator $\mathbf{L}^{\mathrm{T}}$ to the primary reflections (Claerbout, 1992):

$$\mathbf{m}_{\mathbf{mig}} = \mathbf{L}^{\mathrm{T}}\mathbf{d}. \quad (2)$$

This approximate solution yields a blurry depiction of the true subsurface reflectivity distribution. The least-squares solution is reconstructed by solving the following objective function:

$$\mathbf{J} = \frac{1}{2}\|\mathbf{Lm} - \mathbf{d}\|_2, \quad (3)$$

where the least-squares solution $\mathbf{m}$ is obtained by solving the following corresponding normal equation to equation (3) iteratively:

$$\mathbf{L}^{\mathrm{T}}\mathbf{Lm}_{\mathbf{lsqr}} = \mathbf{L}^{\mathrm{T}}\mathbf{d}. \quad (4)$$

The sparsity-promoting migration is obtained by imposing an L1-constraint on the migrated image, which can be added to the objective function as follows:

$$\mathbf{J} = \frac{1}{2}\|\mathbf{Lm} - \mathbf{d}\|_2 + \frac{\alpha}{2}\|\mathbf{m}\|_1, \quad (5)$$

where α is a non-negative scalar chosen based on trial and error. Similar to solving the LSM problem, we solved this L1-regularized objective function iteratively. We seek a sparse solution that fits the scattered borehole seismic data. Solving this objective function with the competing L2-norm misfit term and the regularization term ensures that the solution has a sparse representation at the expense of the L2-norm misfit term.

Synthetic data example

The proposed acquisition geometry for an upcoming distributed acoustic sensing (DAS) borehole survey is shown schematically in Figure 1a. The borehole seismic data will be recorded simultaneously by a DAS recording cable at two adjacent wells separated by about 2,900 meters. This dual-well vertical-seismic-profiling (VSP) acquisition aims to delineate a deep target at about 4 km depth. A velocity model is constructed from a checkshot profile, as shown in Figure 1b. A high-velocity refractor is present in the shallow part of the velocity model. Thus, the ignited surface source will emit seismic energy that primarily refracts at this boundary. Therefore, the effect of this shallow layer poses a significant imaging challenge of the deeper target. There are five major acoustic-impedance contrasts in this velocity model, which we will try to image using the SP migration as shown in Figure 1c. The shallow two contrasts are known seismic refractors. In contrast, the deeper ones are seismic reflectors, with the deepest one representing the targeted horizon.

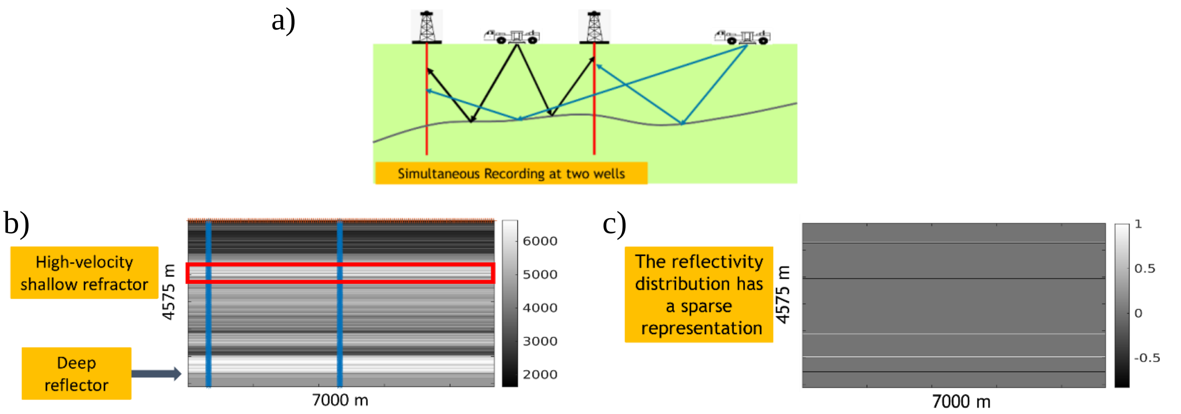

Figure 1 *Synthetic modelling: a) a schematic figure demonstrating the dual-well simultaneous VSP acquisition; b) a representative velocity model showing a high-velocity shallow refractor and a deep target. The red crosses and blue lines represent the source and receiver locations, respectively; c) the assumed reflectivity distribution with five major target horizons.*

The Kirchhoff modelling operator was used to model borehole seismic data recorded at the two wells simultaneously. The utilized source is a negative-polarity Ricker wavelet with a dominant frequency of 20 Hz. The acquisition geometry in Figure 1b consists of surface sources and downhole receivers denoted by the red crosses and blue lines, respectively. There are 234 shot points with a spacing of 30 m along the 7 km profile. Each well has 305 receiver points extending from the surface to 4,575 m depth with receiver interval spacing of 15 m. A total of 610 receivers, representing the proposed stations along the DAS cable, are placed in the two wells separated by around 2.9 km.

The modelled seismic data was imaged using the Kirchhoff migration in equation (2), and the result is plotted in Figure 2a. The image is a heavily blurred representation of the true reflectivity model in Figure 1c. The figure shows the fingerprint of the left well's receivers and the migration kernel, especially for the shallow refractor. LSM was applied to the recorded data to alleviate these problems, and the least-squares migrated image is shown in Figure 2b after ten iterations. The result shows a remarkable enhancement in the spatial resolution of the migrated image and the de-blurring of the refraction and reflection events. However, there are remnants of the acquisition fingerprint and migration smiles. The SP migrated solution is obtained by solving equation (5) iteratively, and the solution after ten iterations is shown in Figure 2c. The figure shows a remarkable enhancement of the seismic events' spatial resolution and the significant collapse of the acquisition fingerprint and migration smiles. The convergence curves for both the least-squares and sparsity-promoting migrations are shown in Figure 2d. Although the least-squares solution yields a better fit to the data, the L1-regularized solution yields a highly resolved image at the expense of reducing the data misfit.

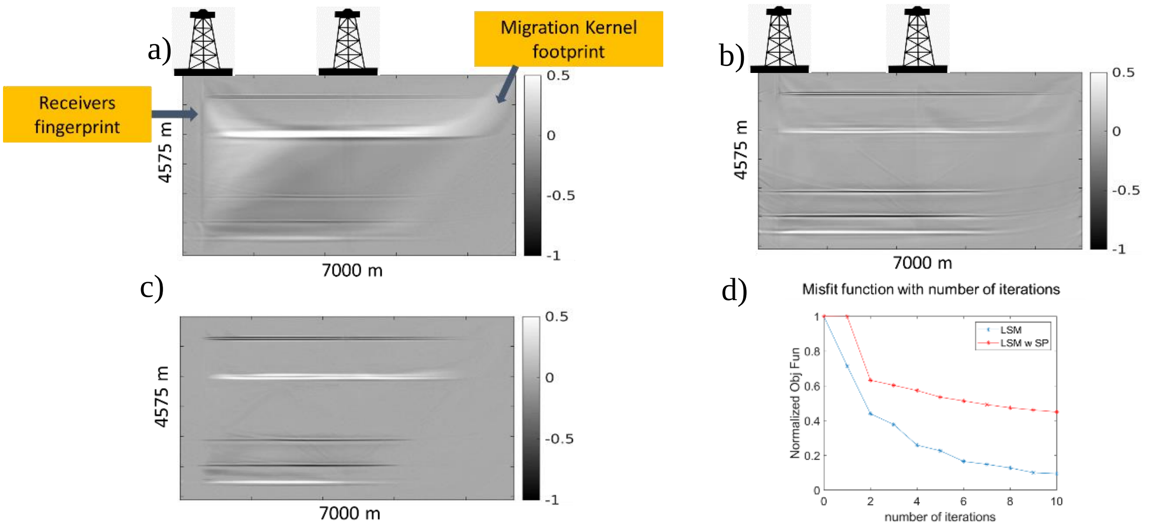

Figure 2 *Images of synthetic VSP data: a) Standard VSP Kirchhoff migration. Migration artefacts heavily smear the image, and the left well receivers' fingerprint is quite notable; b) The least-squares migration suppresses the acquisition fingerprint and de-blur the migrated image; c) SP migration collapses the remnant migration smiles and enhances the spatial positioning of the reflector; d) The convergence curves for both the least-squares solution and the least-squares with sparsity-promoting constraint.*

Field data example

We applied the SP migration to a field marine dataset to test the robustness of the proposed approach. A VSP acquisition survey was conducted during the drilling operation through a salt body to delineate the salt bottom reflector better. The surface seismic image in Figure 3a suffers from poor resolution, and the VSP was acquired to obtain a more highly resolved image of the bottom-salt reflector. Due to the high cost of rig time, the VSP survey was acquired with a single 40-level geophone tool with a 15 m spacing between receivers. There are 225 shot points centered around the vertical well with spacing of 25 m. The dominant frequency of the upgoing reflection data is around 20 Hz.

We initially migrated the upgoing reflection using conventional Kirchhoff migration and present the result in Figure 3b. The image is heavily blurred by low- and high-wavenumber migration artifacts highlighted by yellow and red circles. Figure 3c presents the least-squares migrated image, which shows the suppression of the low-wavenumber migration smiles. Finally, we applied the SP migration to the recorded data, and the image is shown in Figure 3d. This high-quality image shows the significant collapse of the high- and low-wavenumber migration; thus, the image better delineates the salt's bottom than the standard and least-squares Kirchhoff images.

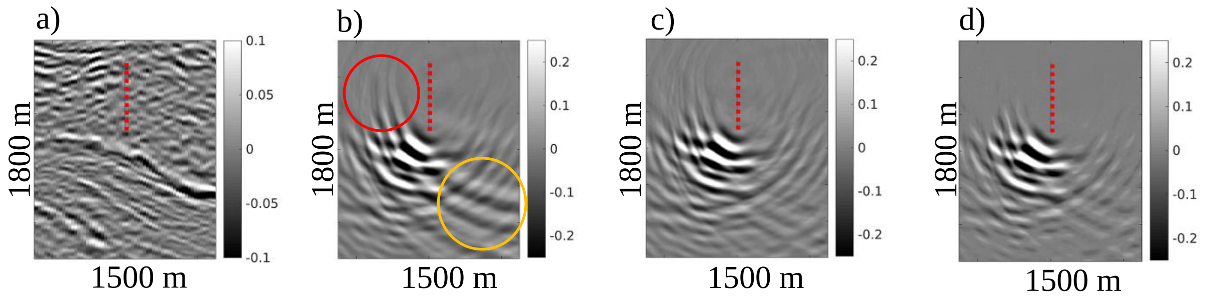

Figure 3 *Field data example: a) The low-resolution surface seismic image; b) The VSP Kirchhoff migrated image showing low-wavenumber (yellow circles), and high-wavenumber (red circle) artefacts; c) The least-squares migrated image helps suppress the low-frequency artefacts; and d) The SP migrated image shows the collapse of both low- and high-wavenumber artefacts.*

Conclusions

We demonstrated that sparsity-promoting migration could be extended to include the linearized inversion of borehole seismic data. We applied sparsity-promoting migration to a synthetic data example with borehole seismic data recorded simultaneously in two adjacent wells. We demonstrated that SP migration could help focus a deep reflector at around 4 km and produce an image with higher resolution than both standard and least-squares migration. We also applied SP migration to a look-ahead field VSP dataset and showed how it could help collapse both low- and high-wavenumber migration smiles optimally compared with standard and least-squares migration.

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