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Imaging with a seismic-while-drilling dataset

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Summary

We explore the possibility of using drill bit-rock interaction as a seismic source. Drilling can radiate significant P and S wave energy. Unlike in standard seismic datasets, seismic-while-drilling (SWD) dataset have a continuous source signature. Understanding the drill bit-rock interaction is a key element in dealing with such datasets. We assume that every tooth of the drill bit can initiate a harmonic wave. Moreover, based on the impedances of the drillstring and rock, there will be some resonances in the radiated wavefield. Hence, pre-processing the SWD dataset before imaging is necessary. Source signature estimation is the fundamental step. We use a multichannel blind deconvolution method to remedy this problem, which is, statistically speaking, more robust than a simple cross-correlation with the pilot trace on top of the drillstring. Afterwards, depth migration of the processed SWD dataset is implemented by pre-stack reverse time migration. This feasibility study indicates that a SWD image can be formed capturing key subsurface geological features.

Introduction

Imaging the subsurface is one of the end goals of seismic data processing. Surface land and marine seismic data contain reflected waveforms from the subsurface which can be back propagated through a background medium for imaging purposes. However, in complex structures wave energy can penetrate quite weakly into some areas. Methods exist to compensate for this shortcoming (i.e., illumination problem). Data regularization before imaging can improve the illumination (Fomel and Guitton, 2006). In addition, illumination compensation can also be implemented by posing imaging as an inverse problem. Least squares migration is able to compensate partially for imperfect illumination (Nemeth et al., 1999; Kuhl and Sacchi, 2003; Kazemi and Sacchi, 2015). However, the computational complexity of this approach is high and so far, industry application of this technique is not routine. To reduce the computational complexity of least squares migration an approximate version of the inverse of the Hessian can be applied to the migrated image (Etgen, 2002; Guitton, 2004; Hu et al., 2001; Kazemi and Sacchi, 2014a).

Increasing the variability of the positions of seismic sources and receivers can significantly mitigate the illumination problem in imaging. The seismic drill bit generates significant elastic wave energy from within the medium of interest, at points normally not available to seismic sources, and could in principle play this role. Given the differences between drill-bit generated elastic wave energy and that generated by standard sources, we broach this possibility with a feasibility study. Our intent is to create and validate a workflow that creates clear images of the subsurface which can be used to optimize drilling parameters (Greenberg, 2008).

Pre-stack migration of SWD dataset

We start with the description of wave equation in a two dimensional constant density acoustic and isotropic medium

$$(\omega^2 s^2 + \nabla^2)P = f\, \delta(\mathbf{x} - \mathbf{x}_s), \tag{1}$$

where P is pressure wavefield, s is slowness (reciprocal of velocity), ω is temporal frequency, $\mathbf{f}$ is the drill bit force, $\mathbf{x}_s$ is source location and ∇^2 is Laplacian operator. To start the analysis we can assume that background smooth velocity (slowness) field is known. We can represent the squared slowness and the scalar field in terms of perturbations and backgrounds as

$$\begin{aligned} s^2 &= s_0^2 + m, \\ P &= P_0 + \Delta P, \end{aligned} \tag{2}$$

where s_0 and P_0 are background slowness and wavefield, respectively. The parameter m is the perturbation in slowness-squared. Similarly, ΔP is the perturbation in the wavefield due to m. The scattering potential m can also be considered proportional to the seismic reflectivity (Clayton and Stolt, 1981).

By inserting equations 2 into equation 1 we can now write

$$(\omega^2(s_0^2 + m) + \nabla^2)[P_0 + \Delta P] = f\ \delta(x - \mathbf{x}_s), \tag{3}$$

and by using the fact that

$$(\omega^2 s_0^2 + \nabla^2)P_0 = f\ \delta(\mathbf{x} - \mathbf{x}_s), \tag{4}$$

equation 3 simplifies to

$$(\omega^2 s_0^2 + \nabla^2)\Delta P = -\omega^2 m\, P, \tag{5}$$

where $\Delta P = \Delta P(\omega, \mathbf{x})$ and $P = P(\omega, \mathbf{x})$.

Now, by using the Green's function G_0 satisfying the wave equation corresponding to the background medium

$$(\omega^2 s_0^2 + \nabla^2)\ G_0 = \delta(\mathbf{x} - \mathbf{x}_s), \tag{6}$$

the perturbed wavefield can be calculated via

$$\Delta P(\omega, \mathbf{x}) = -\int G_0(\mathbf{x}, \omega; \mathbf{x}')\ (\omega^2 m(\mathbf{x}^{'})[P_0(\omega, \mathbf{x}^{'}) + \Delta P(\omega, \mathbf{x}^{'})]d\mathbf{x}^{'}. \tag{7}$$

The last equation is non-linear and it can be linearized by reinserting ΔP in the integral and by keeping first order terms

$$\Delta P(\omega, \mathbf{x}) \approx -\int G_0(\mathbf{x}, \omega; \mathbf{x}')\ \omega^2 m(\mathbf{x}^{'})\ P_0(\omega, \mathbf{x}^{'})\ d\mathbf{x}^{'}. \tag{8}$$

In general, if the explosive source is at position $\mathbf{x}_s$ and the receivers are at spatial coordinates $\mathbf{x}_r$, equation 8 can be written as

$$d(\omega, \mathbf{x}_r, \mathbf{x}_s) = \Delta P(\omega, \mathbf{x}_r, \mathbf{x}_s) \approx -\int G_0(\mathbf{x}_r, \mathbf{x}_s, \omega; \mathbf{x}')\ \omega^2 m(\mathbf{x}^{'})\ P_0(\omega, \mathbf{x}^{'})\ d\mathbf{x}^{'}, \tag{9}$$

which is the forward wavefield modelling operator. In other words, we have

$$d(\omega, \mathbf{x}_r, \mathbf{x}_s) = -\int G_0(\mathbf{x}_r, \mathbf{x}_s, \omega; \mathbf{x}')\ \omega^2 m(\mathbf{x}^{'})\ P_0(\omega, \mathbf{x}^{'})\ d\mathbf{x}^{'}. \tag{10}$$

where $\mathbf{d}$ denotes the seismic measurements represented by a vector and the vector $\mathbf{m}$ stands for the acoustic potential.

Now, by defining the adjoint of forward operator , we can migrate the measured data

$$m_{mig}(\mathbf{x}) = = -\int_{\mathbf{x}_s^{'}} \int_{\mathbf{x}_r^{'}} \int_{\omega} (\omega^2 P_0^*(\mathbf{x}, \omega; \mathbf{x}_s^{'})\ G_0^*(\mathbf{x}_s^{'}, \mathbf{x}_r^{'}, \omega; \mathbf{x})\ d(\mathbf{x}_r^{'}, \mathbf{x}_s^{'}, \omega))\ d\omega\ d\mathbf{x}_r^{'}\ d\mathbf{x}_s^{'}, \tag{11}$$

where m_{mig} is the migrated image of the subsurface. Interested readers can find detailed derivations in Kazemi (2017).

As it is clear from equation 11, to migrate the data we need to forward propagate the source side wavefield and then cross-correlate it with the backward propagated receiver side volume. For forward propagation of the source side wavefield we use second order finite difference modelling engine and convolve the modelled data with the estimated source signature. To estimate the drill bit-rock interaction source signature we implemented a multichannel blind deconvolution technique called sparse multichannel blind deconvolution (SMBD) (Kazemi and Sacchi, 2014b). SMBD solves for the reflectivity series and as a by-product, after solving for the reflectivity, SWD source signature can be estimated using the frequency-domain least squares estimator. We could also use a more realistic scenario and solve for wavelet estimation by surface consistent version of the SMBD algorithm (Kazemi et al., 2016).

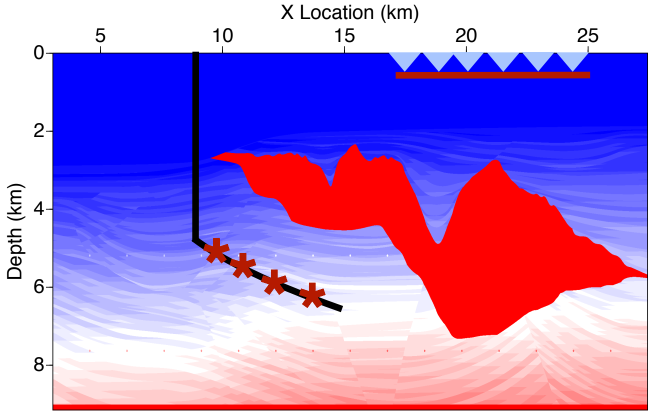

Figure 1 *Seismic-while-drilling acquisition.*

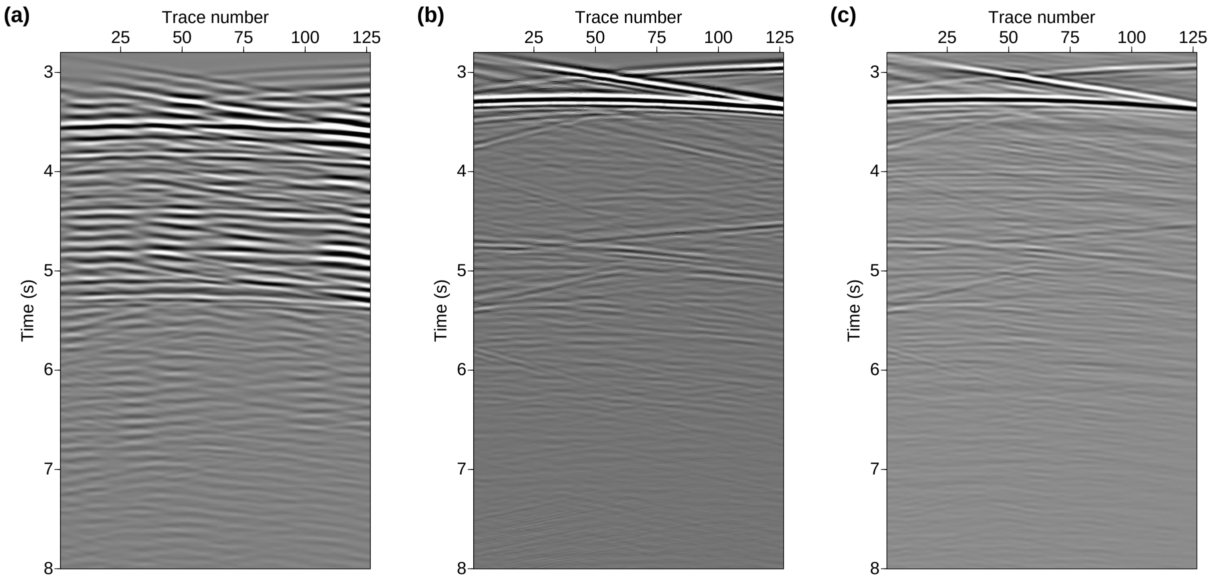

Figure 2 *Windowed version of SWD data. a) SWD shot gather. b) True drill bit source removed data. c) Estimated drill bit source removed data.*

Example

To evaluate the performance of the SWD imaging technique, we used drill bit-rock interaction as source in the deeper part of the well and receivers near the surface with 9 km offset from the well's location (Figure 1). To generate the data, we used a second order acoustic finite difference modelling and then convolved the data with a drill bit source signature. To simulate the drill bit-rock signature we followed Poletto (2005). The source signature has harmonic and non-harmonic components and due to the impedances in the drillstring and rocks at the source locations there are some resonances. To

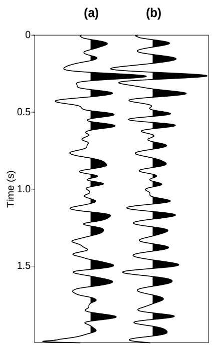

Figure 3 *Drill bit source signature. a) True and b) Estimated source signatures.*

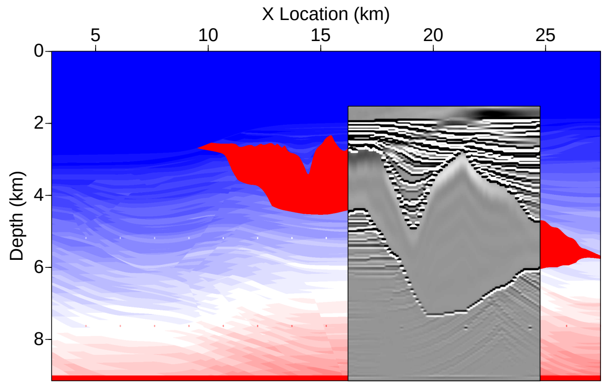

Figure 4 *Imaging result of SWD data over Sigsbee2a model.*

make the source signature broadband we added a band limited white Gaussian noise to the wavelet (see Figure 3a). To image the data, we estimated source signature by applying SMBD algorithm on one of the shot gathers. A windowed version of the data is depicted in Figure 2a. True drill bit source signature removed data and the estimated version of it are shown in Figures 2b and c, respectively. Later, we use the estimated drill bit signature removed data and drill bit data to estimate the drill bit source signature. The estimated signature is shown in Figure 3b. After estimating the source signature, we feed the wavelet to the pre-stack reverse time migration algorithm to image the subsurface (see Figure 4). It is clear that RTM is successfully imaged the subsurface.

Conclusions

We simulated seismic-while-drilling dataset and successfully imaged the subsurface with this synthetic after processing the dataset. We showed that for pre-stack imaging we need to know the source signature of drill bit-rock interaction. Source signature estimation was done by implementing a multichannel blind deconvolution algorithm. The next steps involve analyzing a field data set with similar features as the synthetic, and incorporating both surface and SWD data in the imaging problem.

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