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Impedance joint inversion of surface and borehole seismic data

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Summary

Impedance inversion of surface seismic data is a non-unique problem and the resolution is limited by the bandwidth of the seismic data. Make full use of the high frequency seismic information of borehole seismic data and the geologic information to constrain the impedance inversion is a better choice to improve these problems. With the sparse-spike inversion assumption, we set up an impedance joint inversion framework with the surface seismic and borehole seismic data. The surface seismic data, the borehole seismic data and the well logging data have been integrated into the joint inversion workflow to get a reasonable impedance inversion result. The high resolution inversion impedance with these multiple geophysical datasets is beneficial to improve the reservoir characterization. Two typical borehole seismic datasets were selected to joint inversion with the surface seismic data and the higher resolution of the impedance inversion result was presented respectively.

Introduction

Inversion of seismic reflection data for various lithological and petrophysical attributes is used broadly to characterize reservoirs and detect hydrocarbons (Morozov and Ma, 2009). Several authors have shown that the acoustic impedance derived from poststack seismic amplitude inversion can be useful for quantitative estimate of reservoir properties (Wagner, 2012). However, it is difficult to transform seismic data to reservoir properties because the solution of inverse problem is non-unique even for the noise-free data (Bosch, 2010). This is caused by the ill-posed of inversion problem, the lack of low-frequency and high-frequency information in the seismic data. The low-frequency component can be restored from sonic logs, predicted from the spectra or recorded in the field (Lindseth, 1979; Lloyd and Margrave, 2011). But the resolution of the impedance is limited by the bandwidth of the raw seismic data used in the inversion. We need some high frequency seismic information to improve the resolution of impedance inversion result from other related data.

New techniques for acquisition of seismic data that related with borehole can provide more high frequency information such as VSP/RVSP and crosswell seismic. These borehole seismic methods are helping to reduce the exploration risks and improve the development decisions by providing additional information to understand the accurate underground geology model. The advantages of borehole seismic data are the less attenuation, higher resolution, broad frequency bandwidth and closer to the reservoir target than the surface seismic data. In a word, the domain frequencies of borehole seismic data are much higher than the surface seismic data. There are full of borehole seismic data and well logging data in the reservoir geophysical stage of the oilfield. Make full use of these multi geophysical dataset is beneficial to describe the geology body and solve the reservoir problem at the stage of oil exploration and production.

The impedance joint inversion method is a valid reservoir characterization technology that allows integration of surface and borehole seismic datasets and logging data at the inversion level. With the joint inversion method, the impedance inversion result will improve the resolution, span a larger bandwidth and reduce the uncertainties of the inversion.

Method of joint inversion

In the case of noisy data,

$$d = Gr + n \tag{1}$$

Where d is the seismic trace, G is the wavelet matrix, r is the reflectivity sequences, and n is the additive noise vector.

According to the Bayesian theorem, the likelihood function can be used to integrate the different seismic data, the Cauchy distribution of prior probability density function(PDF) correspond to the sparse of the reflectivity. With the sparse-spike assumption of the reflectivity, taking logarithm transform to the poster PDF, the object function of the joint inversion of surface seismic data and borehole seismic data can be expressed as (Cao, 2009),

$$\begin{aligned} J &= J_S(\mathbf{r}) + \alpha J_B(\mathbf{r}) + \mu J_r(\mathbf{r}) + \rho J_I(\mathbf{r}) \\ &= \frac{1}{2}(\mathbf{G}_S\mathbf{r} - \mathbf{d}_S)^T(\mathbf{G}_S\mathbf{r} - \mathbf{d}_S) + \frac{1}{2}\alpha \cdot (\mathbf{G}_B\mathbf{r} - \mathbf{d}_B)^T(\mathbf{G}_B\mathbf{r} - \mathbf{d}_B) \\ &\quad + \mu \cdot \sum_{i=1}^{M} \ln(1 + r_i^2 / \sigma_r^2) + \frac{1}{2}\rho \cdot (\mathbf{Cr} - \xi)^T(\mathbf{Cr} - \xi) \end{aligned} \tag{2}$$

Where $J_S(\mathbf{r}) = \frac{1}{2}(\mathbf{G}_S\mathbf{r} - \mathbf{d}_s)^T(\mathbf{G}_S\mathbf{r} - \mathbf{d}_s)$ is the fitting error term of the surface seismic between observed data $\mathbf{d}_S$ and the predicted data from $\mathbf{r}$, $J_B(\mathbf{r}) = \frac{1}{2}\alpha \cdot (\mathbf{G}_B\mathbf{r} - \mathbf{d}_B)^T(\mathbf{G}_B\mathbf{r} - \mathbf{d}_B)$ is the fitting error term of borehole seismic constraint that calculated from the observed data $\mathbf{d}_B$, $J_r = \sum_{i=1}^{M} \ln(1 + r_i^2 / \sigma_r^2)$ is the sparse constraint term that related with the reflectivity distribution characteristic, $J_I = \frac{1}{2}(\mathbf{Cr} - \xi)^T(\mathbf{Cr} - \xi)$ is the model constraint term that defined by the relative impedance ξ.

In equation (2), parameter α is the weighting factor of borehole seismic data, when α is large, the inversion result is influenced more by the borehole seismic data. Parameter μ and σ_r are combined to control the sparse of the reflectivity. Parameter ρ is the model constraint factor and $\mathbf{C} = \int_{t_0}^{t} d\eta$ is the integral matrix, when ρ is large, the inversion result is more close to the impedance model constructed from the well logs that guided by the picked seismic horizons. In addition, the regularization parameter μ and ρ controls the distribution characteristic and accuracy of the reflectivity, the inversion stability is strengthen when these parameters is large.

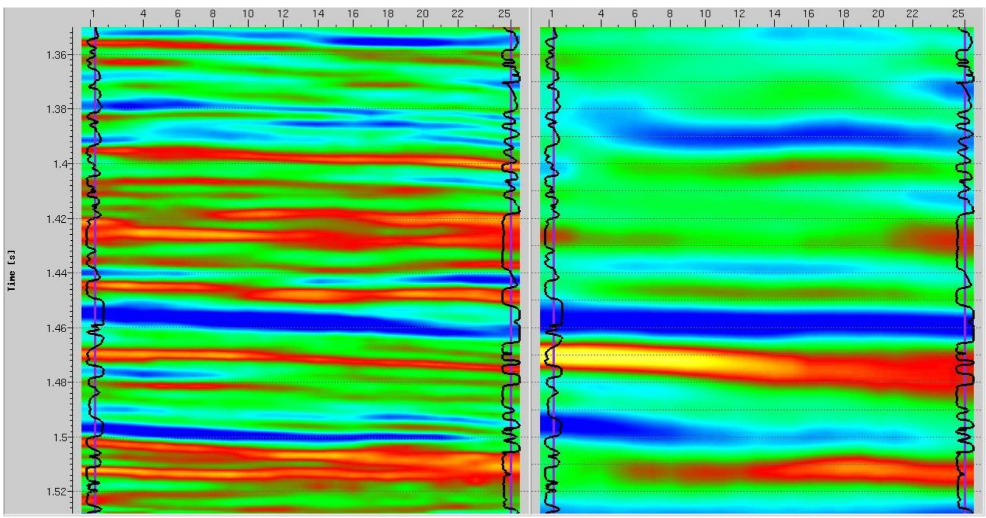
The impedance joint inversion workflow of borehole and surface seismic data is similar with the well logging constrained impedance inversion. The borehole-side trace match between borehole and surface seismic data is very important for the joint inversion. With the help of the checkshot or VSP data, the precise depth/time relationship can be built to calibrate the surface and borehole seismic dataset respectively. It's means that the surface and borehole seismic data are matched at the well-side trace according to the bridge of the logging curve. Then, the deterministic wavelet of the surface and borehole seismic data can be extracted respectively with the well-side seismic data and logging data. This well tie and matching is essential to the impedance inversion for the reservoir quantitative interpretation (Alfaraj, 2010; White, 2003).

The spatial range of borehole seismic data is concentrated to the well and narrower than the surface seismic data. The extrapolation of the borehole seismic data is needed to satisfy the cost function at every surface seismic trace location. The reliability of this extrapolation is limited by the quality of the seismic data. When the surface seismic data can match well with the borehole seismic trace, we can extrapolate the borehole seismic data to the wider range and joint inversion with the surface seismic data.

Examples

The typical borehole seismic method is VSP/RVSP and crosswell seismic methods in the oil exploration and production. The joint inversion of surface seismic, VSP and crosswell seismic data has been presented by Cao (2009). We will give two examples of the joint inversion with different borehole seismic datasets. The crosswell seismic data and reverse VSP (RVSP) data have been selected and joint inversion with different surface seismic data respectively. The crosswell seismic data can provide the very high frequency image of the interwell region at reservoir scale. The RVSP having the source deeper in the well allows obtaining higher frequency and reaching deeper targets (Pereira and Jones, 2010). These two typical borehole seismic datasets can provide abundant high frequencies information for the joint inversion.

The first example of the joint inversion is concern on the overlap range of the surface seismic and borehole seismic data. The surface seismic and crosswell seismic data are coming from the land reservoir geophysical test of Shengli oilfield. The distance of the crosswell seismic data between the two holes is 250 meters. The joint inversion result with these two seismic datasets and the well logging constraint inversion result are shown in the Figure1. For convenience, the joint impedance inversion result was displayed with the sample interval of the surface seismic data.



(a) (b)

Figure 1 The impedance of the joint inversion with the surface and crosswell seismic data (a) and the impedance of the well logging constrained inversion of surface seismic data (b)

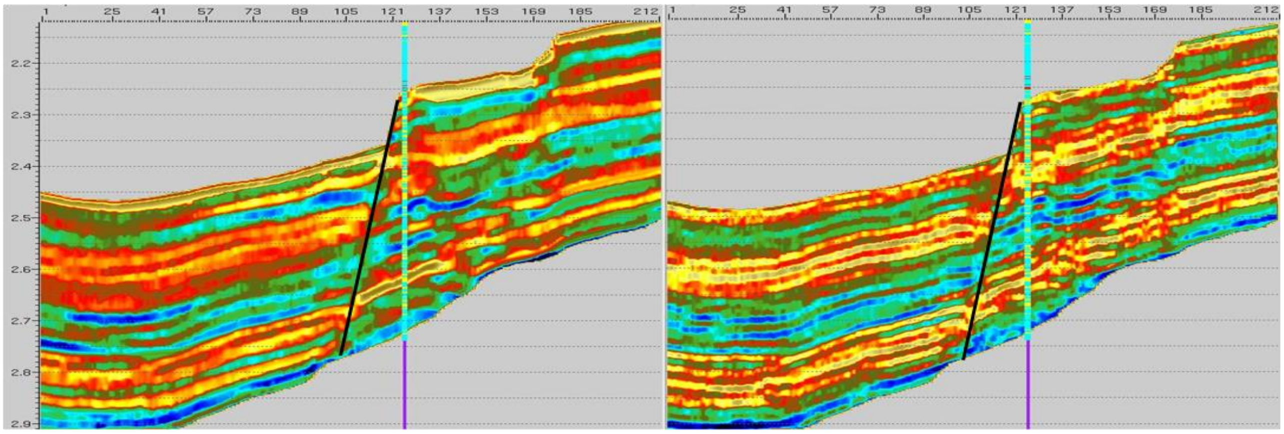
The range of impedance joint inversion is limited by the spatial range of the borehole seismic data that determined by the data acquiring system. It is lack of high frequency information to constrain the impedance inversion of the surface seismic data outside the acquiring area of the borehole seismic data. Fortunately, the borehole seismic data can be extrapolated to the range of surface seismic range if these seismic datasets are matched well enough.

In the example of RVSP and surface seismic data, the RVSP data range is close to the well and smaller than the surface seismic data range. With the match filter extracted from these two seismic datasets, the RVSP data has been extrapolated to the range of the surface seismic data. Then, the impedance joint inversion result can be got with these seismic data. This joint inversion result of surface seismic data and RVSP data is shown in the Figure2 at the range of surface seismic data.

From these two impedance joint inversion examples of the surface seismic data with the borehole seismic data, it is obvious the resolution of the joint inversion is higher than the well logging curve constrained surface seismic inversion result. The impedance joint inversion at the well-side trace is matched well with the well logging curve.

Conclusions

The impedance joint inversion method of the surface seismic and borehole seismic data is valid to integrate different kinds of seismic data. Joint inversion with these high frequencies and broader bandwidth information of borehole seismic data is beneficial to overcome the narrower frequency bandwidth defects of the surface seismic data. Field data inversion result shows that the resolution of impedance joint inversion is higher than the well logging constrained inversion method and match better with the well logging curve at the well-side trace. It is beneficial to improve the reservoir characterization with seismic data.



(a) (b)

Figure 2 The impedance of the well logging constrained surfaced seismic data (a) and the impedance of the joint inversion with the RVSP and surface seismic data (b)

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