Full Wave Inversion of OVSP seismic data for faults delineation and characterization in granite context: a synthetic sensibility analysis

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ABSTRACT

In the present paper, we consider the context of Soultz-sous-Forêts geothermal site (France). We have studied the application of the full-wave inversion method (FWI) to offset vertical seismic profiles (OVSP) in order to detect, delineate and characterize the heterogeneities and the faults in the deep granite geothermal reservoir. The main goal of this study is to evaluate the application of a method already used in the oil&gas industry to geothermal purpose and to assess the capability of the method for the specific goal of fault imaging. After having tuned the FWI to adapt to the specific target of faults, we have studied the impact of the acquisition geometry on the estimated parameter fields, namely, the P-wave and S-wave velocity model and the density model. We have shown that for noise free synthetic data and for fault orthogonal to the propagation plane, the fault signal in the data is sufficient to obtain good inversion results. However, several sources are required to better constrain the inverse problem. We have also studied the sensibility of the FWI for different fault thickness, dip and position as the scattered field depends strongly on these parameters. This study has to be continued by using 3D FWI to assess the fault azimuth effect.

Introduction

In deep geothermal exploration, the characterisation of fractured and faulted zones in the reservoir and its surrounding is very crucial for the project success and for the long-life geothermal project. Several geological and geophysical techniques have been developed and used according to different geological context. Borehole data including image logs, continuous coring, geophysical logs were already used, for instance in Soultz-sous-Forêts context (e.g. Dezayes et al. 2010, Genter et al 2010), and helped to understand the fractures network at the vicinity of the boreholes. In addition, various geophysical methods have been applied in geothermal context in order to delineate major faults and important faulted zones in the studied area. Non-seismic methods (magnetotelluric, CSEM, gravity, magnetic) as well as seismic method, mainly reflection seismic, has been successfully applied in such geothermal context (e.g. Rittershoffen, Vendenheim, Illkirch, St-Gallen). Surface reflection seismic is considered as a high-resolution method compared to non-seismic methods. However, as the sources and receivers are located at the earth surface, part of the high frequency information is often dissipated in the weathered zone and in the sediments. Vertical seismic profile (VSP) can help to overcome this limitation, because the receivers are placed in the borehole, near the target reservoir. Several VSP studies have been conducted for geothermal applications and showed its usefulness in reservoir characterization and faults imaging (e.g. Place et al. 2010; Reiser et al. 2017).

The classical processing sequence for VSP data, i.e., deconvolution and other preprocessing stages, separation of up-going and down-going wavefields, (possibly) removing shear waves and finally migration provides good results in sedimentary context, but much less when the geological objects to characterize are faults in deep granite. To address this issue, we can use the whole wavefield information through the full wave modelling (FWM) and inversion (FWI) methods. These techniques have been successfully applied in sedimentary context for oil and gas exploration but not for deep geothermal especially in granitic geological context.

In this paper, we applied the full-wave techniques, modelling and inversion, in granite context, to achieve an extensive sensitivity analysis and showed its added value and its capability in faults delineation and characterization in granite geological context.

Methodology

When applied to borehole seismic, the conventional imaging tool, the migration, has to overcome the problem of lack of redundancy compared to surface seismic. Moreover, considering the fault imaging goal, the conventional technique of downgoing and upgoing wavefields separation is no longer valid as the medium is not layered and the object geometry is far from sub-horizontal structures. In addition, the deconvolution of upgoing waves by downgoing wavefield is approximate when using offset borehole seismic data. The FWI method does not suffer from the above limitation except the weak redundancy which can be overcome by using additional constraints in the inversion process.

The borehole seismic inverse problem can be expressed as the minimization of a misfit function (Tarantola, 1987). For least squares, this function is a quadratic form scalar function defined over the model space (Tarantola, 1987; Barnes and Charara, 2010). The misfit function measures the discrepancy between observed and calculated seismic data, i.e. between amplitude of the signal for each trace. Due to the FWI non-linearity and the complexity of the forward modelling, the misfit is reduced iteratively using a local method based on derivatives: conjugate gradient is presently used.

The direct problem associated to the present fullwave inverse problem is the propagation of elastic waves in a medium, supposed to be isotropic. As the imaging target, i.e. the fault network, is one or several 3D objects in a 3D nearly homogeneous medium. However, as a first step, we will consider 2D wave propagation for the synthetic experiments used in the sensitivity analysis. Borehole seismic data generally exhibit a very informative wavefield containing energetic 2nd or even 3rd order scattered waves. Moreover, in most cases for borehole seismic with offset (OVSP, walkaway, 3D-VSP), once removing the downgoing direct P-wave 80% of the energy is provided by the S-waves (Barnes and Charara, 2010). The elastic rheology is then required and valuable. The discretization of the wave equation is achieved by a finite difference method based on the displacement and for the viscoelastic rheology. The numerical scheme is based on a 2nd order Taylor expansion explicit scheme in time and spatial derivatives are 4th order differential operators on a staggered grid.

Characteristics of the synthetic FWI experiments

The reference model without fault and used as starting model for the inversion procedure is based on a WE 2D profile of Soultz-sous-Forêts crossing the GPK3 well head (Figure 1). The model building is based on a structural model provided by surface seismic and velocities based on logs and travel times. As illustrated on the cross-sections, the top granitic basement is covered of sediments and started at about 1.5 km deep. The shots are pressure source located 5 m below the surface; the source function is a first derivative of Gaussian with a central frequency of 50 Hz. The receivers are 198 geophones in a vertical well located 200 m west from the actual GPK3 well from 500 m depth down to 4500 m depth. P- and S-wave velocities in the fault are 20% less than in granite and density in fault is 7% less. These contrasts are comparable to those observed in geophysical well logs in Soultz wells GPK1 and GPK2.

The synthetic inversion procedure is the following: We consider a model (the reference model with in addition one or several faults) and a given acquisition geometry. This model is called the true model of the synthetic FWI procedure, it is used to obtain the observed data by full-wave modelling and it is the model we want to retrieve using the FW inversion synthetic procedure. The starting model, i.e. the model used as first model in the iterative non-linear inversion procedure is the reference model (without the fault). We run the FWI from the starting model and the observed data obtained from the true model. After applying FWI, we obtain the estimated model from the inversion process after several iterations. Finally, we compare the estimated model to the true model.

As a first step, the inversion has been adapted to the faults in granite targets: several inversion parameters were tuned. We tested the following features: adding polarization constraints, adding isotropic spatial correlation with different lengths, and crosscorrelation between physical parameters Vp, Vs and density. Spatial correlations according to some fault dipping angle have not been checked. In conclusion, polarization constraints was not selected, isotropic spatial correlation using a Laplace correlation function (L1) with a 20 m range was selected and even if it provides good results, we do not select the parameter crosscorrelation option in order to better understand the impacts of FWI on the P-wave, S-wave and density estimated fields, separately.

Acquisition geometry effects on FWI results

The goal of this parametric study is to quantify the effect of the acquisition geometry and to optimise the acquisition design. We performed several experiments in order to assess the quantitative effects of the following parameters: i) number of shots, ii) inter-shot distance, iii) maximum offset. The results for a small part of the FWI experiments are presented in Figure 1d to 1i. Only the P-wave velocity estimated models obtained by FWI are shown when increasing the number of shots from 3 up to 15 and the maximum offset meanwhile from 500 to 5000 m. In summary, when using only 3 shots (Figure 1e), we recovered the general shape of the fault, especially its upper parts near the receivers. The lower part is not recovered. When using more shots (from Figure 1f to 1i), the results are getting better. For this fault with a thickness of 20 m, using only 3 sources and a maximum offset of 500 m it is not enough to recover the fault. Please notice than the P wavelength λ_P is around 100 m, thus the fault thickness is around $\lambda_P/5$. The upper part of the fault is better recovered as both reflected P and S phases from the fault to the well are present while there is only P-to-S converted energy for the lower part. We can notice an artefact at the symmetric location with respect to the well for small number of sources. Adding the far offset shots help to delineate the lower part of the fault. We can also notice that the estimated P-velocity value in the centre of the fault is around 5000 m/s (in the upper part) while the true value is 4800 m/s, the FWI recover only 70% of the contrast due to the fault thickness. For wider faults, the FWI is able to recover the true values of velocities in the fault centre.

Fault characteristics effects on FWI estimated fields

The goal of this parametric study is to check the ability of the FWI to retrieve the fault with a good delineation, at the correct location and with the correct parameter contrasts. We performed several experiments in order to assess the FWI capability i) by varying the fault thickness (from 5 m to 50 m width, not shown here); ii) by varying the fault dip (from 30 to 90°); iii) by varying the distance of the fault from the well. Part of the FWI experiments results are presented in Figure 2 for different faults. Faults are 20 m thick with the same contrasts, 11 shots are used and the same conditions applied in these experiments. The results depend strongly on the dip as expected. Effectively, the energy of the scattered waves coming from the fault depends on the angle between the incident wave and the fault.

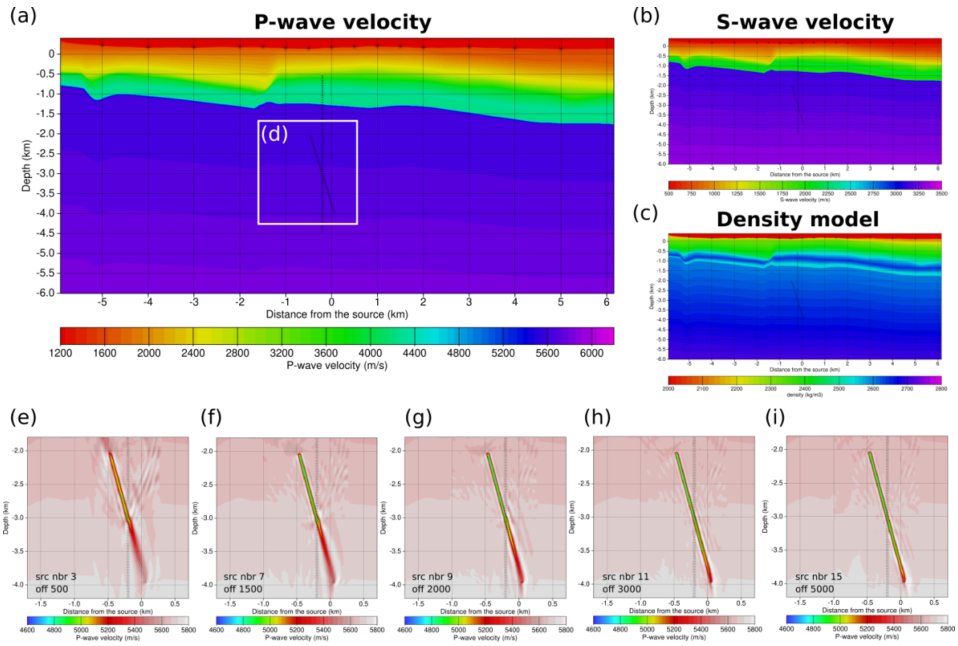

Figure 1 *Synthetic FWI results for different acquisition geometries. We consider one fault with 75° dip, 20 m thick. a) The reference P-wave velocity model built for Soultz-sous-Forêts plus the fault, the acquisition geometry is denoted by stars for source at the surface and small triangle for receivers in the vertical well. b) The reference S-wave velocity model. c) The reference density model. d) The target area. e) FWI results using 3 sources and 500 m maximum offset. f) FWI results for 7 sources and 1500 m max offset. g) FWI results for 9 sources and 2000 m max offset. h) FWI results for 11 sources and 3000 m max offset. i) FWI results for 15 sources and 5000 m max offset.*

Conclusions

We have presented and discussed the synthetic FWI results for fault imaging and characterization in a granite context as Soultz-sous-Forêts. The acquisition geometry study shows that for perfect data and in 2D, at least 3 sources are required to well delineate and characterize the fault and from 9 for noisy data. The sensitivity study concerning the fault characteristics show that the fault signal in the data is sufficient to obtain significant FWI results both in the P- and S-wave velocity models that can be interpreted further. This study has to be continued by adding 3D FWI to quantify the fault azimuth effect. This paper confirms that faults in granite context can be detected and characterized using FWI.

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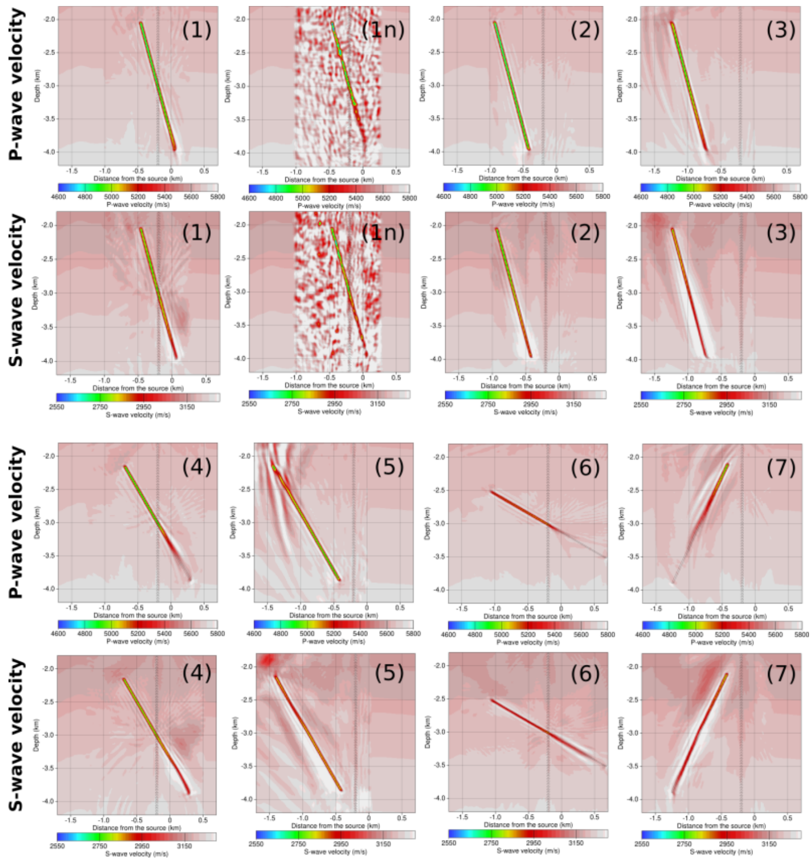

Figure 2 *Synthetic FWI results for different fault dips and locations. Both P-wave and S-wave velocity estimated fields are shown. 1) and 1n), the results for noise free data and noisy data respectively are provided in order to assess the robustness against noise. 1n) the noise is an additive Gaussian noise with the same amplitude spectrum than the data with ambient noise of 15% of the data energy and coda noise of 25%. Results allow fault delineation and characterization but the results quality depends on the fault dip because the energy of the scattered waves depends strongly on the incidence angle of the incident wave on the fault. We can also notice that the fault is less recovered when the scattered waves are only conversion (and not reflection) on the fault like in 7). In 1), 2), 3) and 5), the P-wave contrast is better retrieved than the S-wave one.*

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