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Joint Inversion of Refracted P-waves, Surface Waves and Reflectivity

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Summary

A joint inversion of P-wave first arrivals, surface wave dispersion curves and reflectivity image along picked horizons is proposed for estimating a high resolution P-wave (and S-wave) velocity model of the near-surface. The three inversion datasets are combined in a stochastic optimization process through normalization of cost function terms accounting for different data domains. The resulting velocity model is geologically consistent and reconciles P and S-wave velocities and shallow reflectivity as well.

Introduction

Characterization of the near-surface is a complex topic in seismic acquisition and processing, and can be partially resolved by different complementary methods. The most common technic used to characterize the velocity field of the first few hundred meters is refraction tomography (*RT*) of P-wave first breaks (*FB*) (Figure 1-a/b). It gives access to the P-wave velocity field but is characterized by a non-unique solution (ill-conditioned inversion) which reflects the duality between depth and velocity on arrival times, being thus insensitive to some geological features, e.g. a vertical velocity inversion. RT usually covers properly the model in middle range depth [100m - 1000m] but does not cover well the shallowest part due to acquisition geometry and a lack of the nearest offset picks. More recently, surface wave inversion (*SWI*) of dispersion curves (*DC*) has become a common way to build near-surface high resolution velocity models in the shallow range depth [0m - 200m] (Figure 2-a/b). It allows a better characterization of shallow structures in depth. But it is mainly sensitive to the S-wave velocity field. Moreover, the non-linearity of the velocity relationship induces non-uniqueness in the solution. Finally, the P-wave vertical reflectivity (*VR*) itself can be used to image the near-surface. Vertical two-way times (*VT*) of interfaces can help the interpretation of the structures. An interesting solution to image the shallow near-surface is to use the surface-consistent predictive deconvolution operators to produce a high resolution reflectivity volume of the near surface (Retailleau, 2015). We can measure the vertical two-way time for each main interface, but without reference to velocities (Figure 3-a/b)**.** This paper focuses on the combination of these three complementary data types in order to provide reliable P- (and S-) wave velocity models. To achieve this, an algorithm has been developed to jointly invert all three together. This methodology is applied to a dense 3D land survey acquired by Petroleum Development of Oman (PDO) in the Sultanate of Oman.

Background

For different purposes, such complementary methods (*RT*, *SWI* and *VR*) have already been merged, pair by pair, into joint inversions. The joint inversion of *FB* and *DC* has been proposed by several authors such as Dal Moro (2008). The merging of information decreases the ill-posed nature of the inversion, leading to a plausible solution and reliable velocity field. But without coupling assumptions linking layers and velocities together, the uncertainty on the shape of the shallow structures remains significant. Another coupling that has been experimented is the use of the *SWI*, jointly to *VR* (Dal Moro and Pipan, 2007). This was performed on high resolution shallow seismic and has shown that the link between velocity and structures can be driven by the combination of reflectivity and surface waves. Unfortunately, it cannot be applied on conventional 3D seismic data as no shallow information exists in the stacked data. Finally, a joint inversion combining *RT* and *VR* has been proposed by many authors including Allemand et al. (2017), to determine anisotropy parameters. Based on the use of conventional seismic data, it is more focused on middle range depths, as it uses stacked data.

Method

Regarding the uplift brought by the combination of these data into the different joint inversions, a joint inversion of refracted P-wave, surface wave dispersion curves and shallow horizon vertical two-way times has been developed. The inverse problem characteristics are described as follows:

Model parametrization: As horizons are inverted and expected to be velocity contrasts, model parametrization is limited to layered models, describing strong contrasts between smooth velocities in every layer (described by regular 3D B-spline grids). The velocity model perturbations (part of stochastic optimization) can be applied to V_P, V_S, V_P/V_S ratio or interface depth grids, but are partially distributed to every other fields thanks to similarity relationships.

Forward modeling: First, the P-wave travel-times of the refracted first arrivals are computed using the finite difference Eikonal solver proposed by Noble et al. (2014). Then, the dispersion curve forward modelling is based on the formulation of their relation with a 1D vertical P- and S-waves velocity profile, as proposed by Schwab and Knopoff (1972). This is combined with a 2D Eikonal solver to compute propagation times for each frequency. Finally, the horizon reflectivity two-way time is based on a simple vertical travel-time computation as the surface-consistent predictive deconvolution operators approximate a vertical trace of reflectivity at each receiver and source (Retailleau, 2015).

Cost function normalization: Due to the summation of different contributions (misfit between observed and modeled FB, DC and VT, and measurement of model lateral discontinuities), a normalization of the cost functions is needed. Hence misfit measurements are converted to a relative percentage of variation of modeled data compared to observation.

Optimization algorithm: Due to the complex relationship between P- and S-waves velocity fields and Rayleigh wave dispersion curves, no simple linear local optimization method can be applied for surface wave inversion without a significant risk of converging in a local minimum. Therefore, global optimization based on a stochastic approach is the methodology commonly used to invert surface waves. The data (*FB, DC, VT*) are inverted using a generalization of the laterally-constrained inversion proposed by Bardainne et al. (2017). The inverse problem is based on parallel simulated annealing, allowing fast and reliable convergence to a solution.

Lateral regularization: Some lateral constraints are applied using: (i) a multigrid approach; (ii) laterally extended perturbations of the velocity models; and (iii) a cost function measuring the lateral discontinuity of the model (Bardainne et al., 2017).

Estimated velocity model parameters: Instead of producing a single velocity field, our methodology jointly produces geologically consistent P-wave and S-wave layered velocity models. Hence, the *Vp/Vs* ratio can be directly used as an additional product for geomechanical purpose. VTI parameters would also be estimated thanks to the analysis of both vertical and horizontal P-wave propagation times.

3D real data example

The methodology is tested on a broadband 3D land survey acquired by PDO. The studied area (40 x 20 km) is characterized by 12.5 x 125 m spacing between receivers and 50 x 50 m spacing between sources. The datasets consist of 10 million *FB* picks between 50 and 1000 m offset, a 100m bin-size volume of Rayleigh *DC* (1.5 to 15 Hz, maximum penetration depth estimated as 200m), and 3 horizons (*VT*) picked on deconvolution operator image. Inversion is performed on a 100 x 100m grid with lateral constraints of 100m only and the model is parametrized by six layers, but the three picked horizons correspond to the deeper ones only.

Figure 1, 2 and 3 respectively highlight the improvement of velocity models obtained with *RT* only, *RT+SWI* and *RT+SWI+VR*. The *Vp* model obtained using *RT* of *FB* only is represented in Figure 1-c/d. Some lateral variations are visible, particularly a low velocity area in the north-west. Due to very poor coverage between 0 and 120 m depth, the resolution is weak and neither geological structure nor velocity inversion can be clearly retrieved. Furthermore, the velocity model is not consistent with the horizon picked from the deconvolution operators (Figure 3-b).

On Figure 2-c/d, the *DC* extracted from surface wave processing are introduced in the joint inversion in addition to *FB*. This combination (*RT+SWI*) strongly improves the lateral and vertical resolution of the *Vp* model. Indeed, the layered structure expected is well retrieved and characterized by a low velocity layer (Figure 3-b). The correlation with the horizons picked and converted to depth is acceptable in flat area, but not consistent where the geological structure is more complex.

This issue is solved by the introduction of the horizon vertical times (Figure 3-b) in the inversion (3 horizons picked between 0 and 200 ms), which now combines *FB*, *DC* and *VT* (Figure 3-a). The model obtained with this *RT+SWI+VR* inversion is characterized by high lateral resolution and is more consistent with the geological structures observed on the reflectivity (Figure3-c/d).

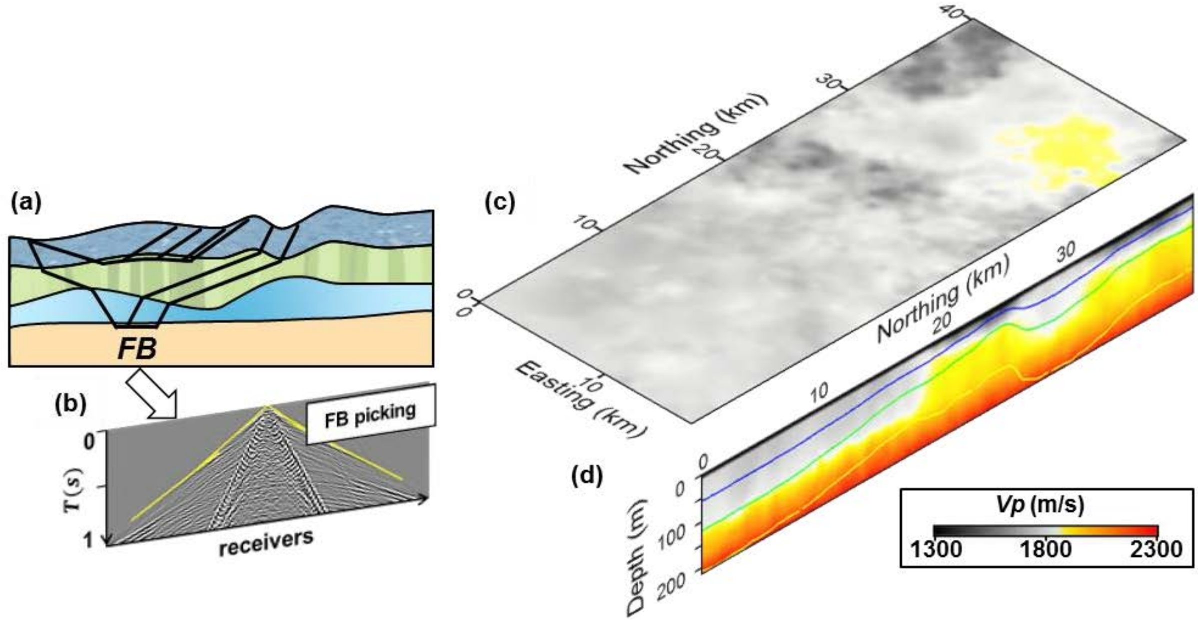

Figure 1: *P-wave near surface model using RT only:* ***(a)*** *P-wave propagation coverage;* ***(b)*** *example of first break picking;* ***(c)*** *map view (30m depth) of P-wave velocity model obtained;* ***(d)*** *cross-section view of velocity model with horizons picked on figure 3-b converted in depth;*

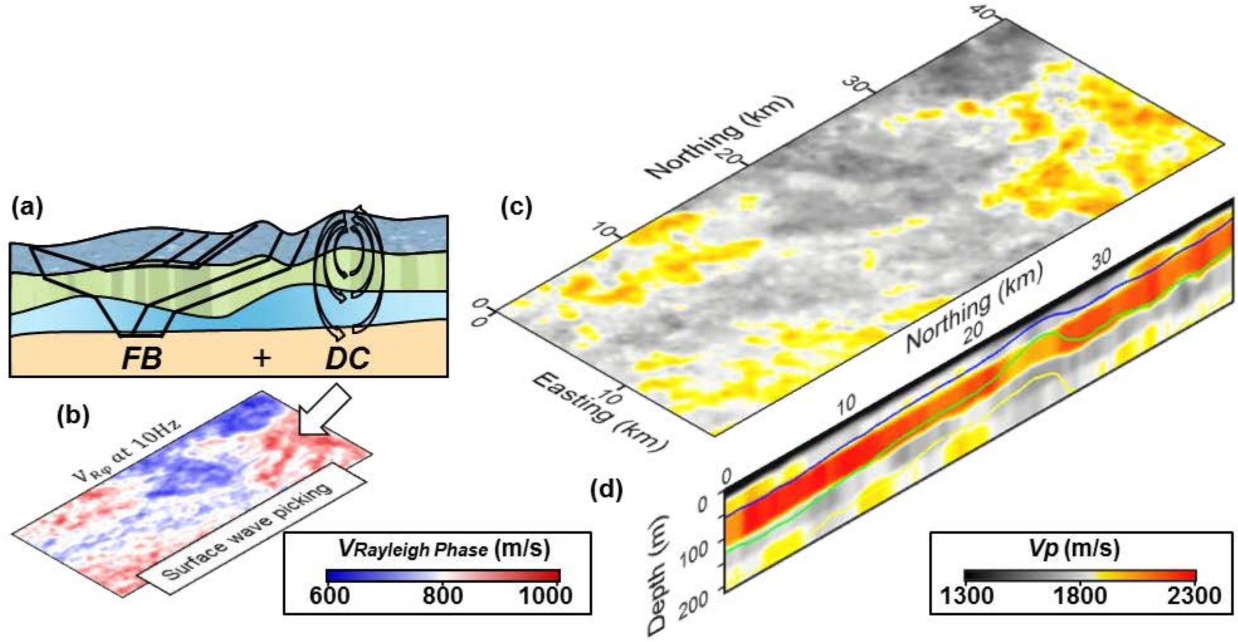

Figure 2: *P-wave near surface model using RT+SWI joint inversion:* ***(a)*** *Surface wave coverage;* ***(b)*** *Rayleigh phase dispersion curve volume (slice at 10Hz);* ***(c)*** *map view (30m depth) of P-wave velocity model;* ***(d)*** *cross-section view of velocity model with horizons picked on figure 3-b converted in depth;*

Conclusion

A joint inversion of P-wave refracted data, dispersion curves from the surface wave and the vertical travel-time from the P-wave shallow reflection data has been developed. It produces a reliable layered velocity model which is consistent with geological structures and recovers low velocity layers. First breaks control the trend of the P-wave field and acts as lateral constraints that regularize the model through its horizontal information. Then, the lateral and vertical resolution is improved by the introduction of dispersion curves in the inversion. Finally, the information brought by horizons picked on the reflectivity image (obtained from the deconvolution operators) improves the structural content of the model. Hence, the combination of these three methods reconciles the velocity model and the reflectivity of the shallow part of the near-surface.

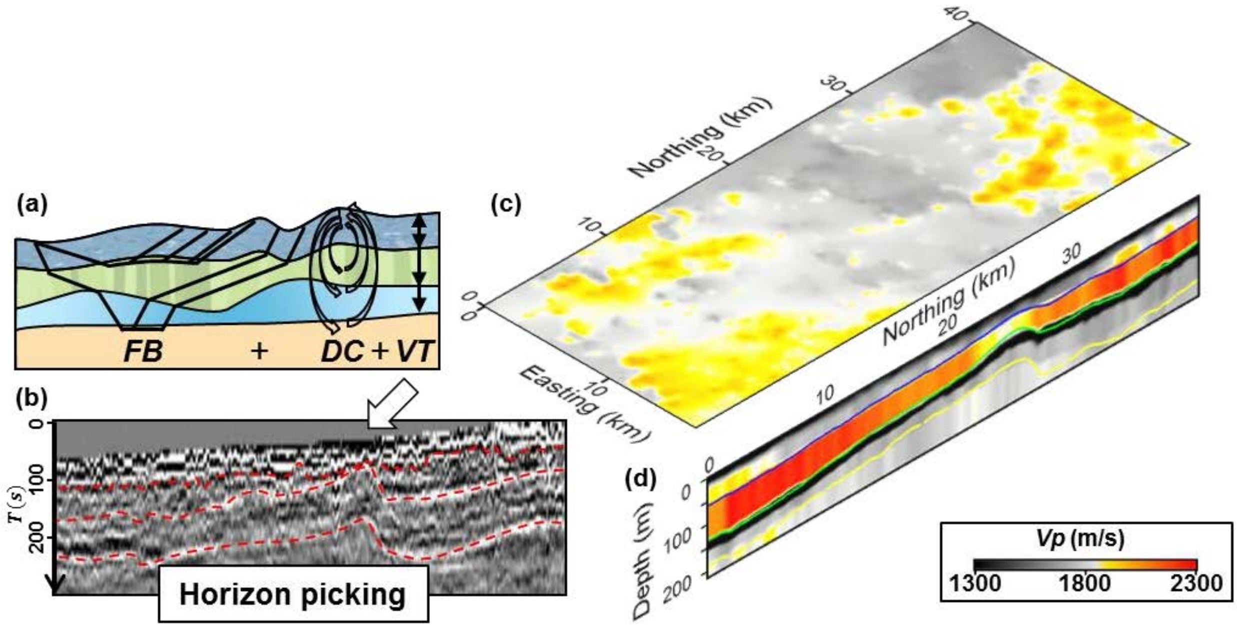

*Figure 3: P-wave near surface model using RT+SWI+VR joint inversion: **(a)** shallow horizon picking information coverage; **(b)** main horizons picked on surface-consistent predictive deconvolution operators image;**(c)** map view (30m depth) of P-wave velocity model; **(d)** cross-section view of model with horizons picked on (b) converted in depth ;*

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