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Integrated Analysis and Inversion of 3D Refraction Travel Times

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Summary

An integrated approach to first-break travel-time analysis and refraction statics inversion was developed. Pre-inversion travel-time analysis and modeling ensures consistent manual and automatic travel-time picking and also helps detecting errors in source-receiver patterns. By utilizing the τ-*p* parameterization, an initial subsurface model is automatically derived from the travel times and is further refined by iterative, non-linear travel-time tomography. Both surface-consistent and non-surface consistent statics are derived. Integration in a seismic processing system allows seamless interaction with other imaging operations, broad customization of the analysis, and incorporation of other data.

Introduction

Analysis of statics is the initial step of seismic data processing strongly influencing the quality of the final reflection images. It is also one of the most tedious procedures requiring extensive interactive travel-time picking and data analysis. The most accurate approaches to refraction statics (such as GLI3D; Hampson and Russell, 1984) also use sophisticated subsurface models and inversion algorithms.

Inversion for refraction statics is a specialized task which is usually conducted separately from waveform seismic processing. However, closer integration of refraction travel-time analysis with seismic processing could still bring numerous benefits. For example, conditioning of the first-arrival travel-time data for inversion is practically the only operation in which errors in survey geometry can be identified. Constructing travel-time surfaces during iterative travel-time inversion would provide powerful means for performing consistent automatic picking of first arrivals in 3D datasets (Morozov and Jhajhria, 2008). An ability to handle the datasets in their entirety during travel-time picking and inversion would allow quick and seamless inspection of the effects of statics on the images. Also, other seismic data attributes (such as differential statics and amplitudes in time-lapse surveys; cf. Morozov and Gao, this Convention) could be analysed and interpreted in ways similar to statics.

This study continues the work by Morozov and Jhajhria (2008) aimed at developing a new environment covering the full scope of first-arrival travel-time analysis. The environment is integrated with seismic processing which is, in its turn, fairly broad in scope and can incorporate wide-angle, multi-component, time-lapse, and even potential-field data analysis. Morozov and Jhajhria (2008) focused on ensuring consistent manual and automatic picking and quality control by using 3D visualization. Here, we discuss the construction of starting model, inversion, and testing consistency of the source-receiver geometry patterns. In the examples, we use a part of a large, 15000-shot Beaver Ranch dataset by Olympic Seismic (Figure 1).

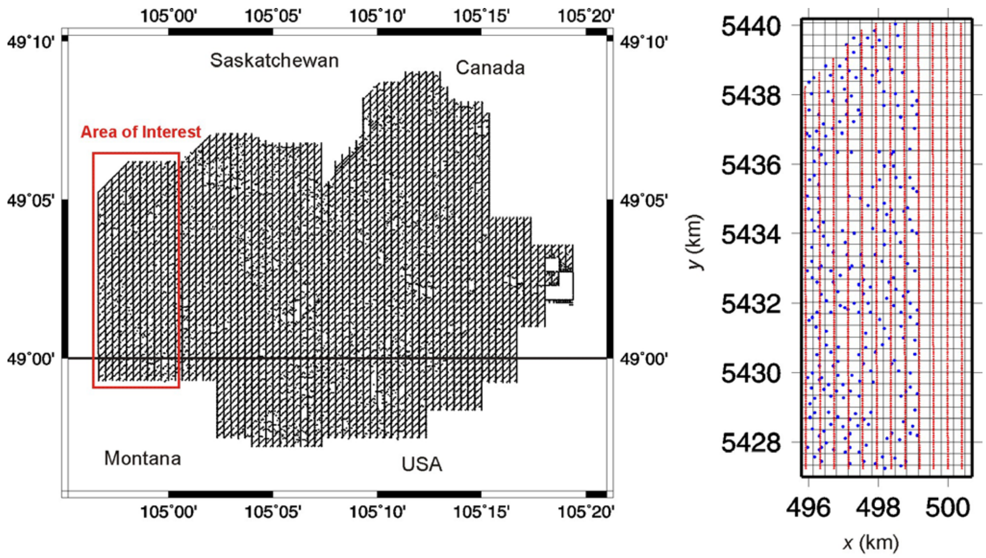

Figure 1: Left: source-receiver layout of the Beaver Ranch 3D dataset. Right: Area of this study. Sources are shown in blue, receivers in red, and the inversion grid in black.

Method

In our approach (Morozov and Jhajhria, 2008) the travel times between locations $\mathbf{x}_S$ and $\mathbf{x}_R$ are represented as a sum of several characteristic terms:

$$t(\mathbf{x}_S, \mathbf{x}_R) = t(\mathbf{x}_S) + t(\mathbf{x}_S \mid \varphi, d) + t(\mathbf{x}_R) + t_u + t_S + t_R + t_{err}, \quad (1)$$

where $t(\mathbf{x})$ is the surface-consistent time delay, $t(\mathbf{x}_S|\phi,d)$ is the offset/azimuth dependent first-arrival travel time from a shot at point $\mathbf{x}_S$, t_u is the shot uphole time, t_S and t_R are the non-surface consistent static terms for the source and receiver, respectively, and t_{err} is the residual travel-time errors of the particular pick. Importantly, the terms $t(\mathbf{x}_S)$, $t(\mathbf{x}_R)$, and $t(\mathbf{x}_S|\phi,d)$ represent continuous 2D travel-time surfaces, and their visualization provides convenient ways for quality control of the travel-time data.

The integrated picking/inversion process broadly consists of three stages, with several options available in both of them. First, prior to any type of inversion, the travel-time consistency is ensured. Regardless of the velocity model, these travel-time data should be represented by the sum (1) with sufficiently small t_{err} values. The most important consistency relation comes from the travel-time reciprocity of the surface-consistent part of eq. (1):

$$t(\mathbf{x}_S) + t(\mathbf{x}_S \mid \varphi, d) + t(\mathbf{x}_R) = t(\mathbf{x}_R) + t(\mathbf{x}_R \mid -\varphi, d) + t(\mathbf{x}_S). \quad (2)$$

In 3D recording, numerous shots are reciprocal to each other and provide ways for verifying picking quality and for automatic picking of most shots (Morozov and Jhajhria, 2008). In addition, geometry pattern quality can also be verified by perturbing the patterns (i.e., by assuming typical layout errors) and comparing the residual errors t_{err} in fitting the travel-time dependence (1) to the individual shots. We use a Genetic Algorithm approach to accomplish this pattern testing.

Once the travel-time decomposition (1) is achieved, an inversion for an equivalent subsurface model is performed in the second stage. To allow an efficient and fully automatic inversion, the distance dependencies of travel times $t(\mathbf{x}_S|\phi,d)$ in eq. (1) are parameterized in the τ-p form, i.e., as series of head-wave segments of fixed slownesses p. With a sufficient number of constant-p segments, such parameterization is suitable in all practical cases. Further, the travel times are "sorted" into the common-midpoint domain, resulting in "vertical" head-wave times $t(\mathbf{x}_M|\phi,d)$ beneath any point $\mathbf{x}_M$ at the surface of the model.

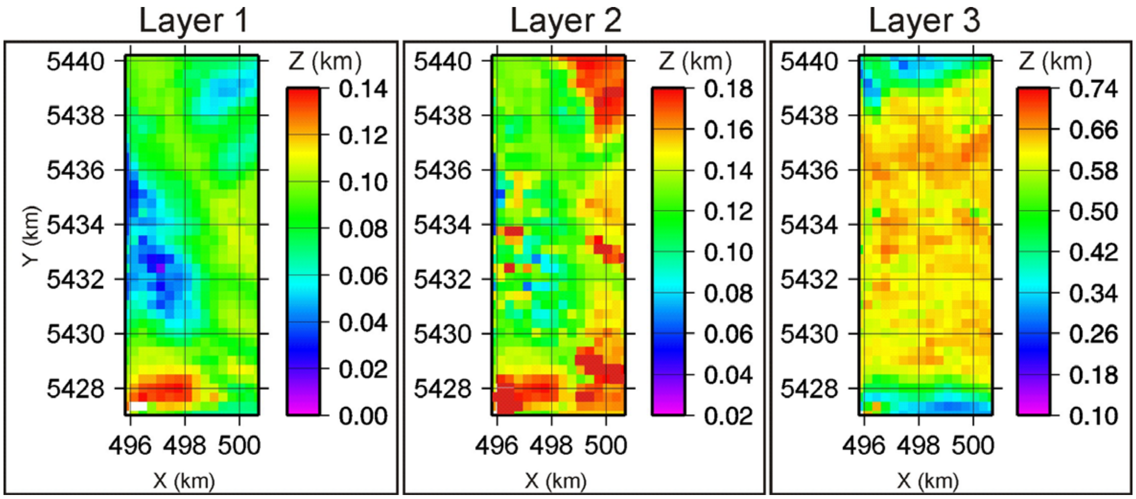

Figure 2: Depths to the bases of the three layers in the starting model for refraction statics inversion. Layer velocities are 0.67, 1.5, and 2.0 km/s, respectively, over a half-space of 3.0 km/s.

From these vertical times, a layered model can be constructed by inverting the standard head-wave travel-time equations. Combined at all points $\mathbf{x}_M$, these models form a 3D, layered model (Figure 2) which serves as a starting model for further inversion. Note that this model is derived from the travel-times alone, and it already predicts all refracted travel times with good accuracy.

At the final stage, the final inversion is performed by using 3D ray-tracing in the layered model, with rays constrained to the source-receiver planes. A non-linear travel-time tomographic problem is formed, which is solved by Simultaneous Iterative Reconstruction Technique (SIRT). The inversion grid and source-

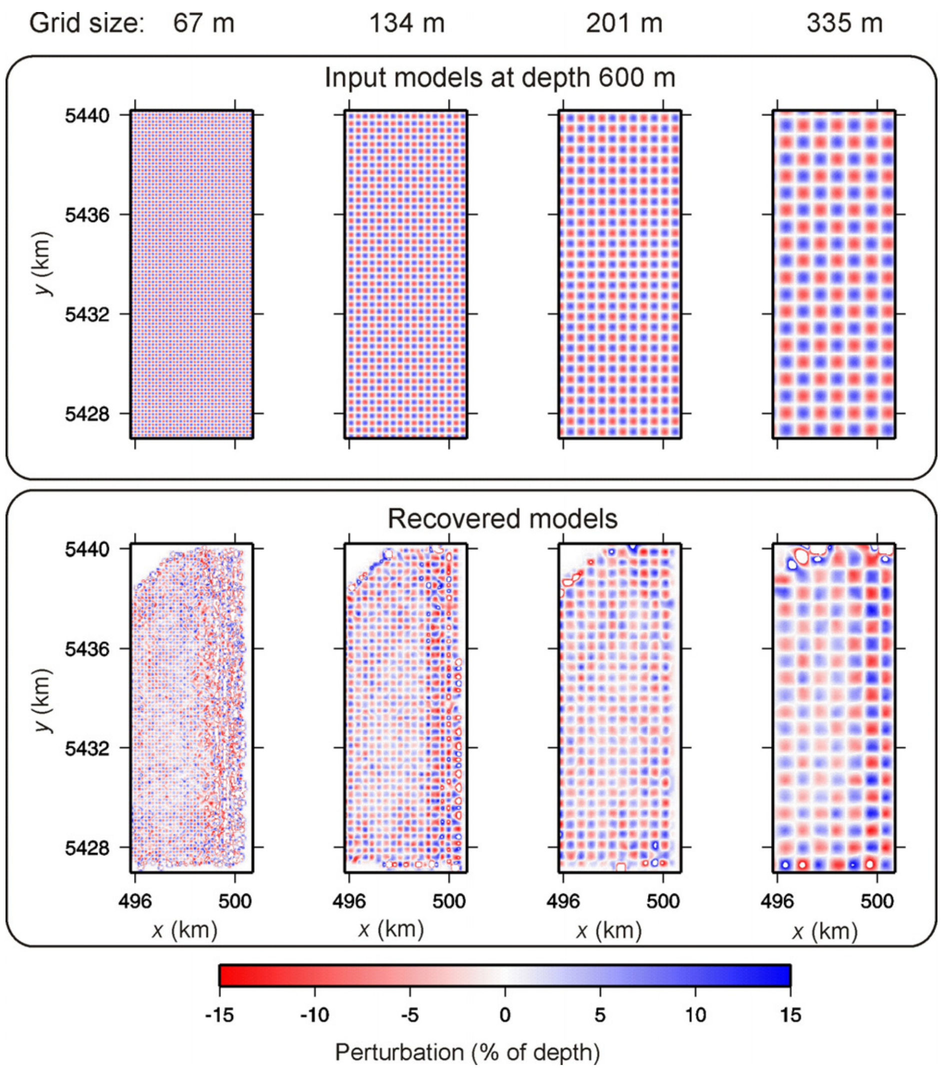

Figure 3: Checkerboard model resolution tests for several inversion grid sizes (labelled). Top: synthetic models of the interface at 600-m depth. Bottom: the interface shape recovered by the inversion.

receiver distribution are shown in Figure 1.

As with any inversion scheme, it is important to measure its resolution and to select the inversion grid accordingly. To perform this check, we created several “checkerboard” depth patterns on selected interfaces, generated synthetic travel-time datasets by using the actual experiment geometry (Figure 1), and inverted them (Figure 3). By distortions of the shapes and amplitudes of the cells, as well as by the acquisition footprint effects, we judged that the selected 335-m size inversion grid was optimal for this dataset (Figure 1).

After the depth model is inverted, statics are calculated by using the travel times of vertically-propagating rays. In our dataset, these statics were sufficient for aligning the reflections (Figure 4). In addition to this model-based, surface-consistent statics, terms t_R, t_S, and t_{err} in eq. (1) can also be used to provide additional, non-surface consistent static corrections.

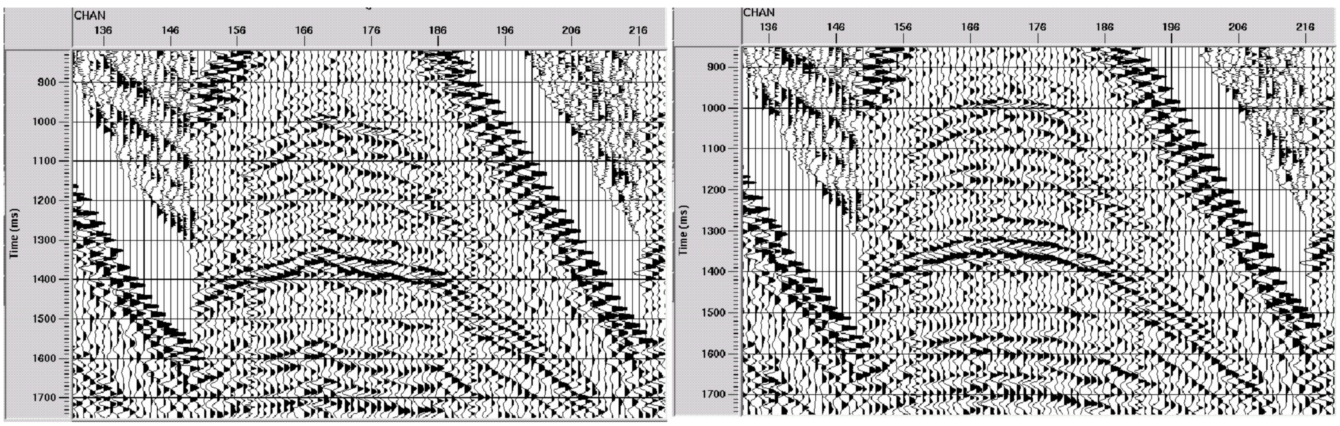

Figure 4: A fragment of a shot section before (left) and after (right) application of model-based refraction statics.

Conclusions

Integrated approach to first-arrival picking, quality control, and inversion for refraction statics was developed. Consistent and accurate travel-time dataset is achieved by checking travel-time reciprocity and testing the source-receiver patterns for consistency. A detailed starting model was derived directly from the travel-time data and further refined by ray tracing and tomographic inversion. The procedure was integrated with seismic data processing, which allowed seamless interaction between the time statics analysis with other imaging operations.

Acknowledgements

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References

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