A COMPARATIVE STUDY BETWEEN 3-D DIVING-WAVE TOMOGRAPHY AND HEAD-WAVE REFRACTION METHODS

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SUMMARY

Refraction statics have long been associated with the study of head waves. Recently, diving-wave tomography has become a popular alternative to head-wave methods. In this paper a new diving-wave tomographic algorithm is introduced. Additionally, different aspects of refraction statics are discussed comparing methods based on head - wave and diving-wave assumptions. The application of several refraction methods to a 3-D land data set, where well control for the near surface exists, demonstrates greater accuracy for the diving-wave approach, and the inherent ambiguity between velocity and depth for all methods.

INTRODUCTION

Near-surface velocity anomalies produce severe distortions in seismic images. If one knew the structure of these anomalies, the best way to tackle this problem would be to perform wave-equation datuming or depth migration from the surface through the known structure (Taner and Berkhout, 1997; Zhu et al., 1998). However, 3-D prestack depth imaging and datuming are computational challenges.Therefore, statics applications assuming surface-consistent ray propagation through the near surface remain the main tool to account for near-surface anomalies.

The analysis of the stacking responses of reflection data works better for estimating the short-period part of statics (so called residual statics), while estimation of the long- period statics using reflection data alone is very unstable and inefficient (Wiggins et al., 1976). Therefore, the analysis of refraction data for statics estimation to reveal more information about the near surface, and correspondingly about statics, is customary in conventional seismic processing.

The generalized reciprocal method (Palmer, 1981) has been widely applied to 2-D data. Unfortunately, for 3-D seismic it is difficult to apply due to the lack of reciprocal data. The idea of delay times also appeared useful for 3-D refraction statics calculations (Barry, 1967). The delay-time method assumes a near-surface model consisting of locally flat layers (on the scale of offset range). First arrivals are assumed to be the onset of head waves propagating along refracting interfaces of these layers. First arrival pick times are decomposed into delay times and refracting-layer velocities. Delay times are then converted to layer thicknesses and velocities assuming a critical angle of incidence on the refracting layers. Western Geophysical's Refraction MISER is an example of the delay time method.

The model used in the delay-time method is also used in other approaches, such as Generalized Linear Inversion (GLI) by Hampson and Russell (1984) and head-wave refraction tomography (Docherty, 1992; Belfer and Landa, 1996; Taner et al., 1998). In these methods, instead of the two-step inversion via delay times, traveltimes are inverted directly for layer thicknesses and velocities. However, these methods also have to deal with the problem of velocity/depth ambiguity (Zanzi, 1990; Docherty, 1992). To address this issue, it is common practice to fix the weathering velocity prior to depth estimation (Hampson and Russell, 1984). Incorporation of reflection data for joint inversion with refraction data can reduce the velocity/depth ambiguity (Ditmar et al., 1997; Rossi and Vesnaver, 1997; Kosloff et al., 1997), but, unfortunately, near-surface reflections are very difficult to pick in normal production data.

One of the main problems with head-wave methods is that in areas with complex geology and rough terrains the simple model typically employed is not sufficient to explain important data features. Moreover, in order to fit the observed nonlinear moveout of first arrivals one has to either limit the offset range or include more layers in the model. Both approaches make inversion even more unstable and ambiguous. The theoretical amplitudes of head waves are expected to be several orders of magnitude less than for body waves (Cerveny, 1971), and therefore head waves should be poorly represented in the data. On the other hand, even a small positive vertical velocity gradient can produce a variety of interference waves (Cerveny, 1971) or modes (Brekhovskikh, 1960) that include diving (turning) waves with much larger amplitudes than head waves. The kinematics of diving waves are nonlinear (Greenhalgh and King, 1981). In most cases, diving-wave modeling fits the observed first-arrival moveouts better than head-wave modeling.

The reasons above make diving-wave tomography, assuming first arrivals as onsets of diving waves, a very attractive alternative to head-wave methods for statics calculation (Zhu et al., 1992; Bell et al., 1994).

In this approach the medium is parameterized as a number of cells, diving rays are traced through the model, and traveltime residuals are backprojected or inverted for slowness perturbations in every cell crossed by rays. Since diving waves fit the nonlinear moveout of first arrivals better than head waves, broader offset ranges can be included for processing, reducing ambiguity in the inversion. However, limiting the incidence-angle aperture at the weathering layer still makes inversion for parameters of this layer ambiguous. Another big problem with tomography is the huge number of unknowns, especially for 3-D. This requires special efforts to make the inversion feasible and stable.

In this paper I will introduce a new algorithm for 2-D and 3-D diving-wave tomography. Then I will compare three refraction-statics methods using a 3-D land data example.

DIVING-WAVE TOMOGRAPHY ALGORITHM

The cell parameterization conventionally used in tomography is very ineffective for modeling near-surface geological structures and requires a large number of unknowns. Furthermore, if the primary goal is to derive statics, then the model should be surface consistent in the sense of statics applications. This means that the velocity of the subweathering half-space should be smooth on the scale of the offset range to avoid coupling with velocities.

Taking the above into account, the model presented here includes a weathering layer with a laterally-varying thick- ness and velocity, and a subweathering half-space with a laterally-varying velocity and a vertical gradient. This model is essentially a hybrid: a weathering layer with explicitly defined thickness as in head-wave methods, and a vertical-gradient velocity function producing diving waves. Due to variable station coupling and the uncertainty in defining true ray onsets, weathering velocities correspond to effective velocities below every station. The thickness of the weathering layer, subweathering velocity and the vertical gradient are parameterized by Fourier coefficients corresponding to the appropriate horizontal spatial frequencies for each function. In marine applications, an additional water layer is included in the model. The model representation above has several advantages over cell parameterization. Namely, the number of unknowns can be easily minimized to fit the data, and the parameters of the subweathering half-space are assumed from the beginning to he smooth in the sense of surface consistency. This simplifies the inversion and reduces discretization errors.

Ray tracing for the model can be done very efficiently by approximating the subweathering half-space between the source and receiver by a constant vertical-gradient model. First, the ray parameter is calculated from the velocity at the turning point, then incidence angles and corresponding ray geometrics for the weathering and water (if any) layers are computed. Finally, traveltime and partial derivatives for the velocity-gradient unknowns in the subweathering half-space are calculated analytically for input to the inversion.

The aim of inversion is to fit the picked traveltimes with a theoretical function that depends nonlinearly on the model vector of unknown parameters described above. This is a nonlinear optimization problem.

For each iteration the problem is linearized with respect to a reference model:

$$\mathbf{y} = \mathbf{Gm} + \mathbf{u}, \qquad (1)$$

where $\mathbf{y}$ is the vector of traveltime residuals, $\mathbf{m}$ is the vector of parameter perturbations, $\mathbf{u}$ is a vector of observation and modeling errors, and $\mathbf{G}$ is a mapping or structural matrix whose elements are the partial derivatives relating traveltime variations to model updates.

As mentioned earlier, direct inversion for all parameters simultaneously is ambiguous and unstable. Furthermore, data errors may cause a nonphysical solution. Incorporation of *a priori* information may help to overcome this problem. The *a priori* information may be obtained from wells, upholes, and near-offset refraction and reflection data. This information is especially useful for constraining the weathering velocity. If *a priori* constraints on the model parameters are available, then for the solution of equation (1) the Bayesian approach may be used (Tarantola, 1987):

$$\hat{\mathbf{m}} = \mathbf{C}(\mathbf{G}^{T}\mathbf{D}^{-1}\mathbf{y} + \mathbf{C}_0^{-1}\mathbf{m}_0), \qquad (2)$$

$$\mathbf{C} = (\mathbf{G}^{T}\mathbf{D}^{-1}\mathbf{G} + \mathbf{C}_0^{-1})^{-1}, \qquad (3)$$

where $\mathbf{m_0}$ is an *a priori* model parameter vector, $\mathbf{C_0}$ is the corresponding *a priori* covariance matrix, $\mathbf{D}$ is a data error covariance matrix, and C is *a posteriori* covariance matrix.

An efficient way to perform matrix inversion in equation (3) is via matrix repartitioning (Mao and Stuart, 1997) allowing us to sequentially invert smaller matrices corresponding to the separate, unknown functions. Due to the surface consistency of refracted rays through the weathering layer, the part of the covariance matrix in equation (3) corresponding to weathering slownesses is almost diagonal. This remarkable feature allows us to significantly simplify the inversion of the weathering submatrix. Overall, the nonlinear optimization is a hybrid of full Newton and Jacobi methods.

DATA EXAMPLE

A comparative study of refraction statics methods was performed on a 3-D dynamite survey in the thrust belt region of the Northwest Basin of Argentina (courtesy of Compania General de Combustibles S.A.). This survey is remarkable due to the existence of extra control for the new surface in the form of uphole experiments for twelve wells of 150 m depth. Topographic variations are about 150 m within 100 km^2 of the survey. Figure 1 is an inline brute stack severely corrupted by static anomalies. For study purposes no information from the uphole experiment was used in the refraction-statics methods except for the mean weathering velocity. All methods input the same pick times. Figures 2-4 demonstrate the inline stack after application of Refraction MISER (delay-time method), GLI (head-wave tomography), and the diving-wave tomography algorithm described above. The first two stacks are very similar. However, the diving-wave tomography result contains significantly different timing of events caused by a different estimate of the long-period statics. Additionally, the overall quality of the diving-wave tomography stack is comparable , if not better, than the others. The discrepancy in the stacks is due primarily to the fact that the diving-wave tomography jointly inverts for weathering velocity and depth, while other two methods assume all long-period variations caused by changes in refractor depth. These examples illustrate the velocity/depth ambiguity that occurs when an infinite number of models can fit the data. The application of residual statics did not produce much improvement in any of the sections.

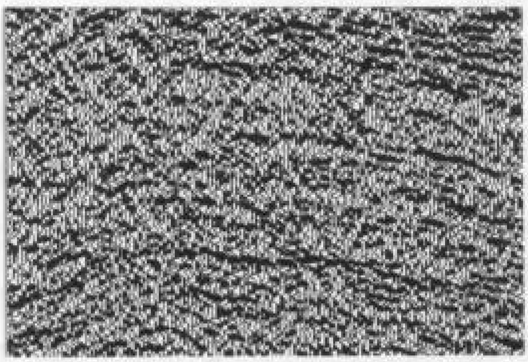

Fig. 1: Brute stack.

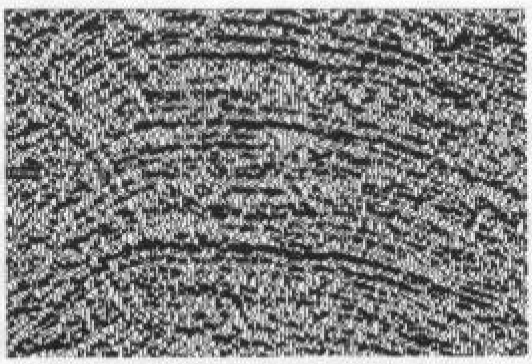

Fig. 3: Stack after application of GLI.

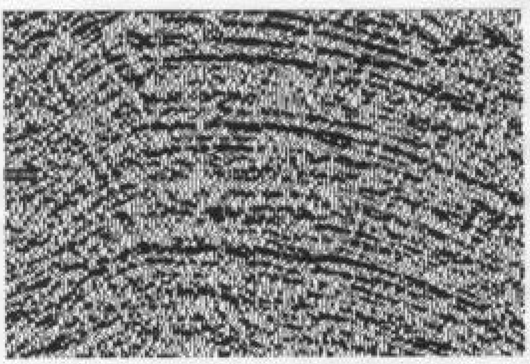

Fig. 2: Stack after application of Refraction MISER.

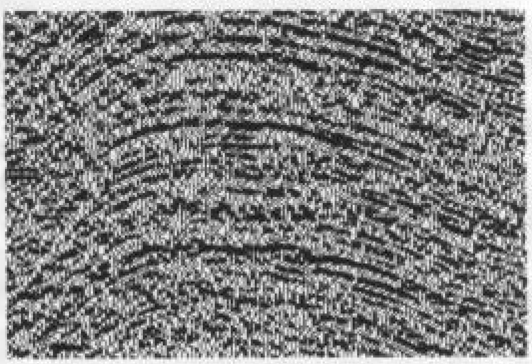

Fig. 4: Stack after application of the diving-wave tomography.

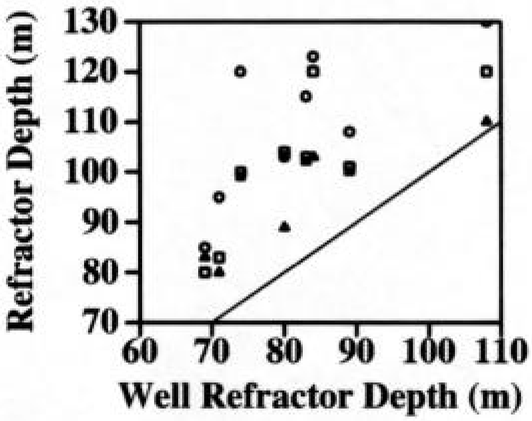

Fig. 5: Cross-plot of estimates of refractor depths obtained by Refraction MISER (circles), GLI (squares), and diving-wave tomography (triangles) versus values from wells. The solid line shows the solutions coinciding with the well values.

Figure 5 shows the refractor depths at the well locations versus the estimates obtained by the three refraction statics methods.Note that the refractor corresponds to the base of weathering layer.The general bulk shift in the estimates may be explained by the deviation of picked traveltimes from actual first arrivals. There is greater correlation between the diving-wave tomography estimates and the well values than for other two methods.

DISCUSSION AND CONCLUSIONS

Although diving-wave tomography demonstrates a better result on the data example, it must be emphasized that the velocity/depth ambiguity is inherent for all methods, including tomography. The main advantage of the new tomographic algorithm is its ability to incorporate *a priori* information about the near surface to reduce this ambiguity. Particularly, the tomographic technique can include the maximum offset range for inversion, using the near offsets to constrain the weathering velocity, and far offsets to better estimate the gradient parameters controlling the nonlinear moveout in the first-arrival data. The main drawback of the algorithm presents here is the assumption of smoothness of the subweathering velocity at the scale of offset range. This is necessary for surface-consistent statics applications, but may not he sufficient to fit the refraction data for purposes of depth imaging. However, this drawback is the price of computational efficiency in processing large 3-D volumes.

Fundamental issues, inherent for all refraction statics methods, include the difference in velocities between refracted and reflected waves, and the violation of surface consistency in the areas containing thick permafrost or deep water on top of mudflows. The former issue is partly due to the deviation of picked times from the onsets of “true” arrivals, and partly to the differences between group velocities of refracted interference waves and velocities of reflected waves. These differences may be corrected by introducing an effective anisotropic coefficient. The issue of violation of surface consistency may be overcome only by applying wave-equation datuming or imaging from the surface through the tomographic model.

In general, diving-wave tomography offers an adaptive method of modeling the near-surface and producing static corrections in geologically complex areas. In structurally simpler areas, the method is an efficient alternative to the traditional approaches using head-wave assumptions.

ACKNOWLEDGMENTS

I thank Bruce Hootman, Scott MacKay, Douglas Hart, Charles Carvill, Paul Fowler, Gennady Ryzhikov, Paul Docherty and John Scales for fruitful discussions, and also Compania General de Combustibles S.A. for permission to publish the data.

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