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STATIC CORRECTION ENHANCEMENT BY TURNING RAY TOMOGRAPHY

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ABSTRACT

This paper presents the use of turning-ray tomography to reconstruct the velocity distribution in the weathered zone from the first arrival times of seismic waves. This technique is a velocity-inversion approach, which uses turning-rays (incident rays, continuously refracted direct rays) from any acquisition geometry to find iteratively the velocity computations of the weathered zone between the source and the receivers. This method does not require simplified assumptions such as a constant velocity layered homogeneous model. The Turning Ray Tomography is very efficient and allows velocity computations even in complex geological area. The efficiency of this tomographic technique was tested on synthetic data and applied on real seismic data from southern Algeria as a typical case study. The obtained results show clearly an improvement in seismic section quality using the static corrections calculated by turning-ray tomography when compared to the one based on classical method known as DRM.

Keywords - Tomography - Seismic - Turning ray - Traveltime - Velocity - Weathered zone - SIRT.

AMÉLIORATION DE LA CORRECTION STATIQUE PAR LA TOMOGRAPHIE TURNING RAY

RÉSUMÉ

La présente contribution est dédiée à l'application de la méthode d'imagerie tomographique dite du "turning ray" pour illustrer la distribution des vitesses dans la zone altérée (WZ) à partir des temps des premières arrivées des ondes sismiques.

Cette approche repose sur la procédure d'inversion par les réfractions continues des rayons sismiques directs, quelque soit la géométrie d'acquisition. L'objectif attendu est une représentation significative de la répartition des vitesses dans la zone altérée entre la source et les capteurs. L'un des avantage offerts par cette méthode est qu'elle ne nécessite pas d'hypothèses simplificatrices telle que la supposition par exemple d'un modèle sismo-géologique de couches homogènes sans variation latérale de vitesse. La performance de la méthode repose sur son adaptabilité au modèle géologique même à tectonique complexe.

L'efficacité de cette méthode d'imagerie tomographique du "turning ray" est testée sur un modèle synthétique puis sur un cas de prospect d'une région du Sahara algérien.

L'influence des résultats induits par la méthode est reflétée par l'amélioration substantielle apportée à la section sismique après les corrections statiques utilisant précisément cette méthode

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d'imagerie tomographique du turning ray, par comparaison avec une approche classique connue sous le nom DRM (Diminishing Residual Matrices).

Mots-clés - Tomographie - Sismique - Turning ray - Temps de parcours - Vitesse - Zone altérée - SIRT.

1. INTRODUCTION

The structures imbedded in the weathered zone (WZ) are characterized by strong vertical and/or lateral variations of seismic velocity and lithology, and extremely thick weathering zones. Determining the velocity of the structures of the wz needed to calculate static corrections, as a first crucial step in seismic data processing and imaging. Until now, seismic refraction analysis has been limited to the conventional techniques that require simplified assumptions such as constant velocity layers and lateral homogeneity within each one (Hampson and Russel, 1984). We can build a near-surface velocity model using refraction methods which should also be constrained by the uphole data. After the long-wavelength statics, there could still exist relatively higher frequency statics called mid-wavelength statics. Because the magnitude of the mid-wavelength statics is much less than that of the long-wavelength statics, and greater than 1/4 wavelength, so the statics can't be obtained by reflecting residual statics method. We can calculate it using first-arrival residual statics method. When the first-arrivals can not be traced continuously, it means that the weathering zone has strong lateral velocity variations, and there are likely surface exposures of high velocities. Then the near-surface model will be built using synthetic modeling based on field uphole and refraction data. If the spread distance is very important, with surface exposures of high velocities and severe undulation of the bottom interface of the weathering zone, different reflections may cause different or "non-static" time shifts. In such case, we need to use some non-surface-consistent residual static methods to calculate the high-frequency statics for different reflecting layers.

The faster and more powerful computers available today have led to the development of various seismic tomography routines that can be used to develop a powerful method of tomographic reconstruction of subsurface structure through certain parameters (velocity, absorption coefficient). In this paper, we present the method known as turning ray tomographic to determine the velocity of the structures in the weathered zone from first arrivals. It uses the first arrivals as direct body waves propagating along turning rays, and it represents the velocity of the structure with a grid model. The estimation of the grid's node velocities is formulated as an iterative inverse problem (Kim and Bell, 2000). The traveltimes and raypaths required for the inversion are calculated by a highly efficient grid raytracing technique (Zhu and Cheadle, 1999). Experiments with both synthetic and real data show that the new tomographic method is accurate and capable of velocity recovering near-surface structures in geologically complex areas, and that the velocity models obtained by this method have resulted in significant improvements over the traditional refraction methods in static calculation. This technique is designed to resolve velocity gradients and lateral velocity changes enabling it to be applied in settings where conventional techniques fail. In the following sections, we first describe the tomographic method and then demonstrate its applications with synthetic and real data.

2. BASIC CONCEPT OF TOMOGRAPHY

Tomography (tomo=slice+graph=picture) is a method to determine the internal structure of an object starting from a set of observations that, in some way, carry information of the inside structure of this object. Many research efforts in seismic tomography have been directed towards the definition of efficient and fast tools of tomographic reconstruction of velocity's image (Pratt and Worthington, 1988). The seismic tomography uses the measured traveltimes as input to calculate the velocity distribution of the subsurface structure as output (Bioshop and Styles, 1990; Bioshop and *al.*, 1985). Accordingly, the two dimensional image of the velocity variations can be deduced. The traveltime of a ray in a continuous velocity medium, is the integral of slowness along a ray path connecting the source and receiver that can be given by the following relation:

$$t = \int_{P(s)} s(x)dl \qquad (1)$$

Where **t** is the traveltime, **P** denotes an arbitrary path connecting a given source and receiver in a slowness model **s** and **dl** denotes the infinitesimal distance along the path P. Equation 1 is non-linear since the integration path depends on the velocity. This inherent non-linearity means that the inverse problem can be very difficult to solve.

Suppose, we have a set of observed traveltimes, t1,…,tn. From n source-receiver pairs in a medium of slowness s(x). Let Pi be the Fermat ray path connecting the ith source-receiver pair. Neglecting observational errors, we can write :

$$t_i = \int_P s(x)dl^{P_i} \quad \text{i=1,....,n.} \qquad (2)$$

Given a model with m cells equation (1) can then be written as :

$$\sum_{j=1}^{m} l_{ij} s_j = t_i \qquad (3)$$

Note that, for any given i, the ray path lengths lij are zero for most cells j, as a given ray path will in general intersect only a few of the cells in the model, Figure 1 illustrates the ray path segmentation for a 2-D cell model.

We can re-write the equation (3) in matrix notation by defining the column vectors **s** and **t** and the G matrix as follows:

$$S = \begin{pmatrix} s_1 \\ s_2 \\ . \\ s_m \end{pmatrix}, \quad t = \begin{pmatrix} t_1 \\ t_2 \\ . \\ t_n \end{pmatrix} \quad G = \begin{pmatrix} l_{11} & l_{12} & . & l_{1m} \\ l_{21} & l_{22} & . & l_{2n} \\ . & . & . & . \\ l_{n1} & l_{n2} & . & l_{nm} \end{pmatrix}$$

Equation (3) then become the basic equation of forward modelling for ray equation analysis:

$$GS=t. \qquad (4)$$

Note that this equation may be viewed as a numerical approximation to integral equation, it is just under a discretized form of the equation (1). We will study this equation at great length.

Equation (1) may be used for any set of ray paths, whether, those ray paths minimize (2) or not. If the ray paths used to form the matrix **G** actually are minimizing ray paths, then we should keep in mind that **G** is then implicitly a function of s.

Now, we can define three problems in the context of Equation (4).

1) In the forward problem, we are given s; the goal is to determine **G** and **t**, this entails computing the ray path between each source and receiver and then computing the traveltime integral along each path.

2) In linear tomography or inversion problems, we start from **G** and **t**; the objective is to determine **s**. the assumption, here, is that the ray paths are known *a priori*, that is justified under a linear approximation that ignores the dependence of the ray paths on the slowness distribution. Typically, the ray paths are assumed to be straight lines connecting source and receiver.

3) In non-linear tomography, we are given only **t** (along with the source and receiver location); the goal is to infer **s**, and consequently **G**. In this problem, the dependence of ray paths on the slowness distribution strongly influences the design of the inversion algorithm. Nonlinear inversion is required for problems with significant slowness variations across the region of interest, including many seismic inversion problems. The ray path in such media will show a large curvature which cannot be known before the inversion process begin.

In inverse problem of tomography, major difficulties arise in solving the corresponding equation :

1. G is not a square matrix;
2. G is often rank deficient;
3. G is often poorly conditioned.

Because of these three possible states, we cannot simply solve equation 4 in terms of an inverse matrix of **G**, because it is possible an inverse doses not exist.

There are four main approaches for calculating the slice image given by the set of observations. These are called **reconstruction algorithms**. There are a number of numerical algorithms for solving the system (4) and some of these are especially suitable when **G** is poorly conditioned. These methods include in particular :

1) the standard tomographic reconstruction methods (eg. ART and SIRT);

2) the iterative matrix methods (eg. Gauss-Seidel and Jacobi method);

3) the conjugate direction/gradient method;

4) the simple iteration (backprojection method).

These methods may be analyzed most conveniently in terms of their convergence to the pseudoinvere. The difference between these methods is how the successive corrections are made: ray-by-ray, pixel-by-pixel, or simultaneously correcting the entire data set, respectively. As an example of these techniques, we will look at SIRT.

3. IMAGE RECONSTRUCTION USING THE SIMULTANEOUS ITERATIVE RECONSTRUCTION TECHNIQUE (SIRT)

The Simultaneous Iterative Reconstruction Technique (SIRT) was developed for ray tomography and applied in geophysics first for high-frequency electromagnetic and for seismic travel-time methods (Dines and Lytle, 1979).

The SIRT consists of assuming an initial earth model, computing the travel in times to be expected at the surface by so-called forward modelling, and comparing them with the measured ones. If there are discrepancies, the initial earth model is varied somewhat and the process is repeated again. This whole process can be repeated until the parameters are not varying significan-tly or all the observations are matched closely enough (Jiang and Wang, 2003). This so-called trial-*and-error-search-approach* obviously involves a lot of human interaction and can be tedious. Nevertheless, its relative computational simplicity has made it historically a successful approach for determining the Earth structure. The full description of these methods can be found in (Stewart, 1991; Kissling and *al.*, 2001).

The unknown distribution of seismic velocity is calculated by an iterative projection of the traveltimes measured on the surface along the ray paths. The basic principle of the SIRT method is to project the measured traveltimes into the cells of the discretised object according to their slowness (Peterson and *al.*, 1985).

In more detail, the algorithm works according to the following scheme:

1. Pick the traveltime t_i from the i^{th} raw record, and construct the nx1 traveltime vector t constitute of n traveltime picks. A finite-difference solution to the eikonal equation to quickly compute these traveltimes. Discretize the earth model into n slowness cells, where each j^{th} cell has an unknown constant slowness s_j.

2. Denoting the segment length of the i^{th} ray in the j^{th} cell by l_{ij}. In this case the traveltime integral reduces to a summation of weighted slowness, where the weight is the segment length of the rays :

$$t_i = \sum_{j=1}^{m} l_{ij} s_j \tag{5}$$

3. For some initial guess slowness model s^k we have $t^k = Gs^k$ which can be used to form the perturbed set of traveltime equations:

$$\Delta t^k = t - t^k = t - Gs^k \tag{6}$$

4. if the Δt^k is sufficiently small, output s^k and stop.

5. Find a model correction ∂s and update s to new model by adding the model correction :

$$s_j^{k+1} = s_j^k + \frac{1}{N} \sum_{i=1}^{N} \frac{t_i^{k+1} l_{ij}}{\sum_{i=1}^{N} l_{ij}^2} \tag{7}$$

6. The steps 3, 4 and 5 are repeated until the rms error between calculated and measured values decreases below a given threshold or a given number of iterations is reached.

4. APPLICATIONS

We use a 2-D turning ray tomography technique to build a near surface velocity model and calculate static corrections (Stefani, 1995). This technique is a velocity inversion procedure which uses turning rays (incident rays, continuously refracted direct rays) from any acquisition geometry to iteratively solve for velocity in the near surface between the source and the receivers (fig. 1). Implementing a tomographic velocity algorithm requires several steps. These steps include **(1)** first break travel time picking, **(2)** image plane parameterization, **(3)** ray tracing and segmentation, **(4)** residual time (error) computation, and **(5)** velocity updating to minimize the error (Kim and Bell, 2000). Basically, this procedure involves a forward process problem where travel times are calculated for any source receiver (s/r) pair and an inverse problem where the velocity is iteratively updated to generate a velocity model which provides a match with field seismic data. Velocity updates are performed by a SIRT.

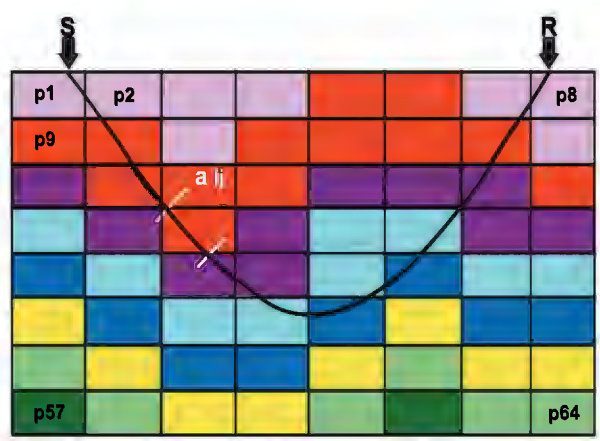

Fig. 1 - Velocity model, parameterization, turning ray tracing.

Modèle de vitesse, paramétrisation, tracé de courbure du rayon.

4. a) Synthetic data set

One of the major advantages of tomography is the ability to image complex geological structure. To demonstrate the efficiency of the turning ray tomography we propose to reconstruct the image of the model shown in the (fig. 2), characterised by vertical and horizontal velocity variations. Seismic response from this model was simulated by ray tracing method, in the (fig. 3), we presented as example of first break calculated on this model. We used this calculated first break and simplify model shown in the (fig. 4) as the input of turning ray tomography. A comparison of (fig. 2) and (fig. 5) shows a close agreement between the inverted and true velocity models, indicating that tomographic method is able to recov near-surface velocity structure in geologically complex areas. This allows us to use its application with real data.

4. b) Real seismic data

Imaging of complex velocity structures by seismic reflection is a challenging task. Particularly in thrust belt environments, on-land seismic exploration may be hampered by complex velocity structures and rough topography, which often lead to poor quality images. Data quality may be strongly affected by diffraction, scattering phenomena and unmodelled multiples. In

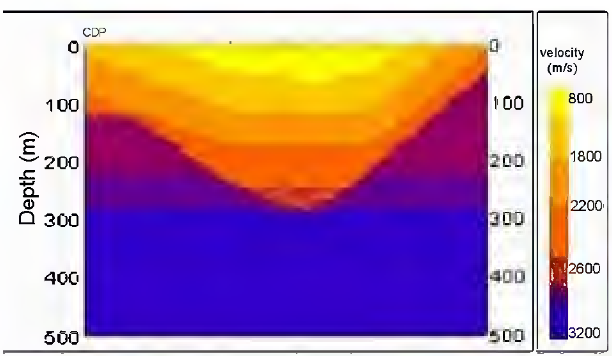

Fig. 2 - Proposed model for tomographic reconstruction.

Modèle proposé pour la reconstruction tomographique.

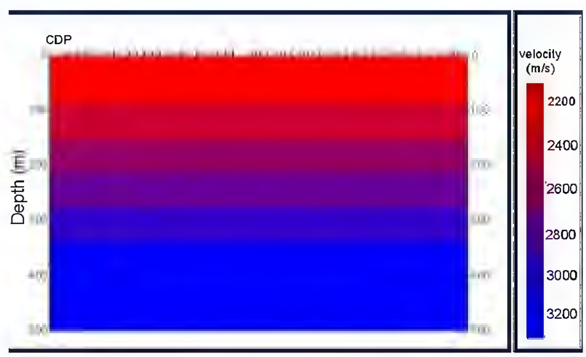

Fig. 3 - Proposed initial model for tomographic reconstruction.

Modèle initial proposé pour la reconstruction tomographique.

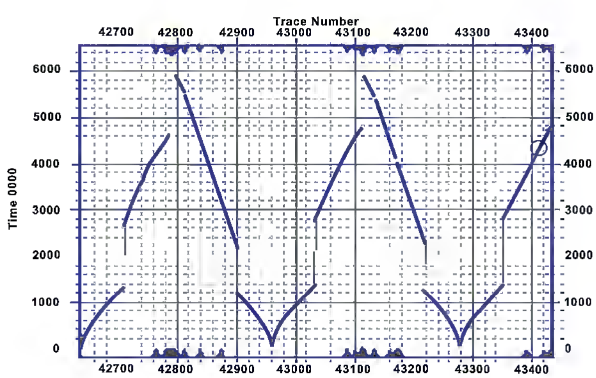

Fig. 4 - Simulated first breaks.

Premières arrivées simulées.

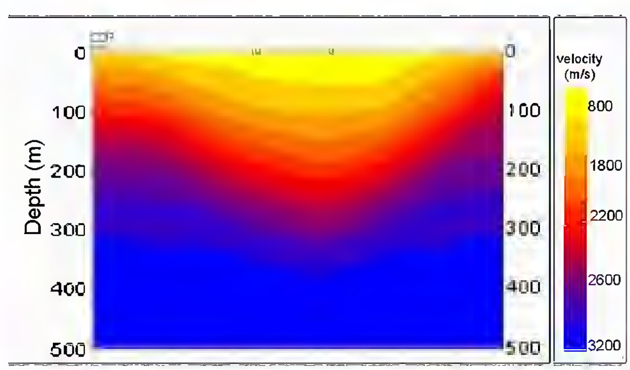

Fig. 5 - Result of reconstruction.

Résultat de la reconstruction.

addition, in the presence of both a rough topography and sharp near surface velocity variations, refraction and tomo-statics, which assume vertical raypaths approximation, often fail to properly correct prestack data, since raypaths can have significant horizontal components. As a consequence, static shifts may distort the wavefield, thus degrading the velocity analysis and the quality of migrated images. The success of seismic imaging methods such as prestack migration strongly depends on data quality and on the accuracy of the adopted background velocity model.

We applied the turning ray tomography to a 2-D data set from the South of Algeria. The survey area is characterized by rugged terrain, extremely variable surface geology and severe vertical and lateral velocity variations at all depths. The 2-D profile is 12.3km long with 410 sources and 320 traces for each source. The group interval is of 30 m with a maximum offset of 4.830 km. The main interest in this analysis is the upper 600 m. The velocity field in this area is well known; a weathered layer of nearly 500 m/s overlying a constant velocity layer of 2100 m/s. Such a very dense land data set, along with the extreme complexity of the investigated structure, represent a unique opportunity to test the efficiency of the turning ray tomography to improve the quality of the interpretation.

Image plane parameterization involves discretizing the 2-D image with specific number of cells (Kissling and *al*., 2001), and defining a starting velocity model from a prior geological and geophysical information (check shot) (fig. 6). Ray tracing and segmentation involve computing travel times and ray paths between the source and receiver location as well as obtaining a ray segment in each cell crossed by a ray (Zhu and Cheadle, 1999, 2000). A ray density plot shows the number of ray segments within each cell (fig. 7). Some authors (Crosson, 1976; Brzostowski and McMechan, 1994) have suggested that a lower limit of 10-15 segments per cell provides better image reliability. First-arrival traveltimes were picked on seismograms arranged in Common Receiver Gathers (CRG). We preferred to use these data gathers, instead of Common Shot Gathers (CSG), for two reasons. First, the shorter trace spacing of the CRG record sections (30 m), with respect to the CSG record sections (60 m), allows us to exploit fully the phase coherence, thus making picking easier. The second reason is that all the CSG sections show strong lateral variations

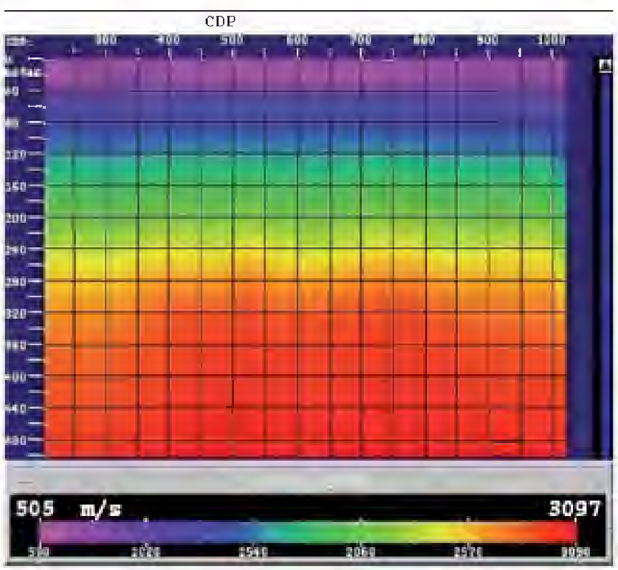

Fig. 6 - The initial model and its discritazation.

Modèle initial et sa discrétisation.

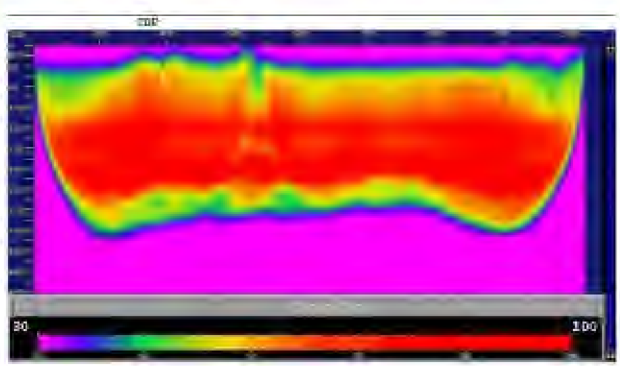

Fig. 7 - Ray density per pixe.

Densité de rayons par cellule.

in the data quality at large offsets, even among close traces, which complicate the picking of first arrivals. Comparing CRG and CSG sections, we found that data quality critically depends on the local condition of the recording site. Thus, in order to make picking easier and more accurate, we selected the best quality CRG sections, being careful to keep a good coverage all along the profile. Over 6400 first arrivals were used to determine a background velocity model by the traveltime tomography. The application to highly redundant data makes the inversion process very stable and robust and allows for a reliable and an accurate model building.

Approximately 64 iterations were performed with a new raytracing at every 10th iterations until the average residual decreased from the magnitude around 100ms (fig. 8) to an acceptable limit (fig. 9). We used a simultaneous iterative reconstruction technique (SIRT) for this purpose. The velocity field obtained from the tomographic inversion is shown in (fig. 10).

Both the turning ray tomographic method (fig. 10) and the DRM (Diminishing Residual Matrices) (fig. 12) were used to compute statics corrections for the survey. A comparison of the stack sections corrected with these methods shows that both methods work well except for the middle portion of the profile. Stack sections from this part of the profile are compared in (fig. 11) and (fig. 12), which shows that the tomographic statics solution has significantly improved the image quality, especially in the central portion of the section. The turning ray tomography on the other hand better accommodates the rapid change in the near surface in the vicinity of the anomaly, resul-

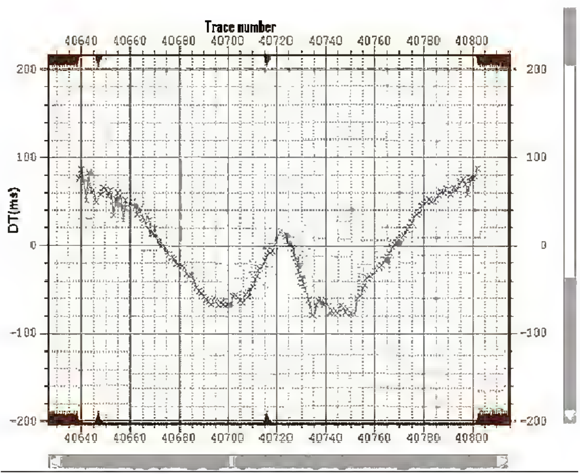

Fig. 8 - Residual times.

Temps résiduel.

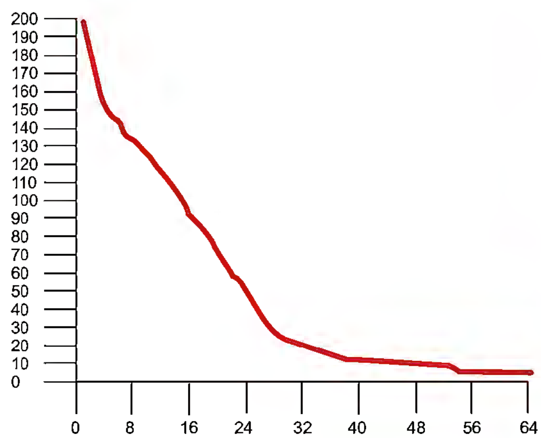

Fig. 9 - Average time residual.

Résidus du temps moyen.

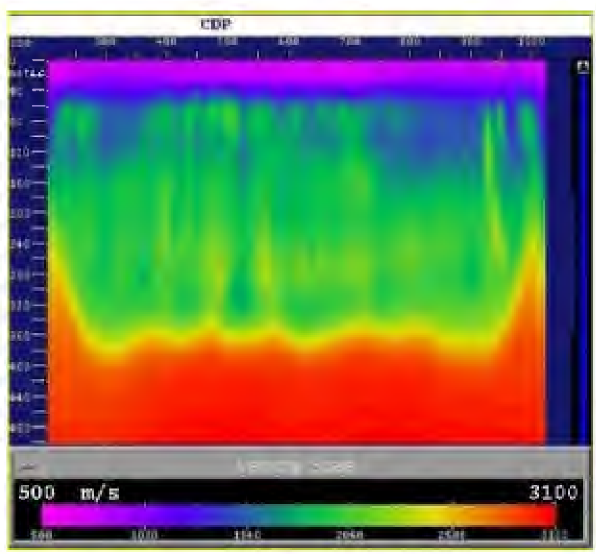

Fig. 10 - Final image.

Image finale.

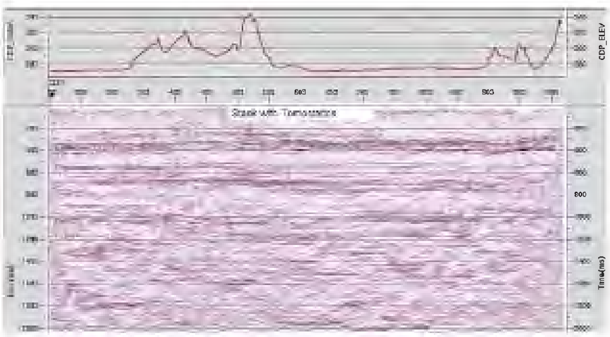

Fig. 11 - Stack after the application of static correction corresponding to the tomographic model in fig. 10.

Stack après le calcul de la correction statique sur la base du modèle obtenu dans la fig. 10.

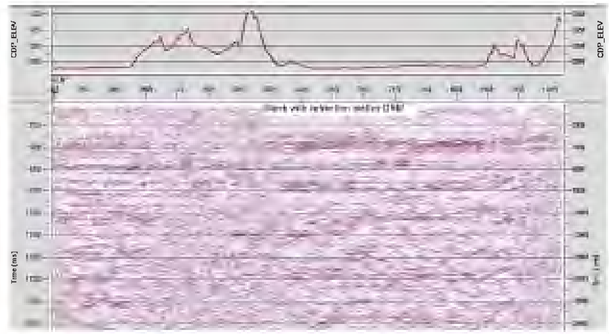

Fig. 12 - Stack after the application of static correction based on DRM.

Stack après le calcul de la correction statique sur la base de la méthode DRM.

ting in significantly reduced residual time structure and improved reflector continuity. This indicates that the tomographic method is more flexible in an environment of strong lateral velocity variations.

5. CONCLUSION

We have developed a turning ray tomographic method for inverting first arrivals of seismic records for near surface velocity structures. It treats the first arrivals as direct body waves propagating along turning rays, and represents the velocity structure with a grid model. Estimation of the grid's node velocities is formulated as an iterative, regularized, linear least-squares problem. The traveltimes and raypaths required for the inversion are calculated by a highly efficient grid raytracing technique. Experiments with both synthetic and real data show that the new tomographic method is accurate and capable of recovering near-surface structures in geologically complex areas, and that the velocity models obtained by the method have resulted in significant improvements over the traditional refraction methods in statics.

This method differs from conventional tomographic approaches in the sense that it is based on parametrization by pixels although its formulation is more robust method to approximate ray paths and first break, based on ray theory. Moreover, the main advantage of turning-ray tomography is the fact that it is more flexible in adapting to large variations in both vertical and lateral velocity, since it is not restricted to the same limitations as refraction methods. Moreover, one of the major advantages of tomography is the ability to image gradients.

Through synthetic modeling and analysis of field experimental data, it has been in addition shown that turning ray tomography provides a means to monitor the structure of weathered zone for improvement of static correction.

Experiments with synthetic and real data have shown that estimation of near-surface velocity by turning ray tomography is very encouraging and improve substantially the processing sequence.

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