2-D DEFORMABLE-LAYER TOMOSTATICS IN SICHUAN, CHINA

A Thesis

Presented to

the Faculty of the Department of Earth and Atmospheric Sciences

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Yukai Wo

August, 2015

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Yukai Wo

APPROVED:

Dr. Hua-Wei Zhou, Committee Chair
Department of Earth and Atmospheric Sciences

Dr. Stuart Hall, Committee member
Department of Earth and Atmospheric Sciences

Dr. August Lau, Committee member

Dean
College of Natural Sciences and Mathematics

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Abstract

Static correction for near-surface effects is a critical issue for onshore seismic data processing due to its significant impact on imaging the subsurface structure, especially for area with severe topographic and near-surface velocity variations. The key idea to determine static correction is to build an accurate near-surface velocity model, which leads to several methods such as refraction statics, uphole surveys and tomostatics. Among these methods, tomostatics, which builds the near-surface velocity models using tomography, is a promising method. However, in complex near-surface areas, traditional grid tomography is often unable to determine the static correction. This is mainly because the conflict between the need of smaller cell to describe the severe velocity variation and the increasing number of inversion unknowns which leads to solution's uncertainty.

The deformable-layer tomography (DLT) determines the complex near-surface velocity models by inverting for depth-varying velocity interfaces. Both synthetic and field data offer many cases illustrating DLT's effectiveness. The main advantage of DLT over grid tomography is that DLT builds a geologically reasonable model with less inversion unknowns, and can resolve the velocity model better with some constrains such as the result of uphole surveys, which is available in my study. Also, a reversed-velocity interface, which is common in mountainous area and has severe effect on near-surface imaging, may be better solved by DLT.

The survey area of my thesis is in the western Sichuan, China, which is mountainous and has a complex near-surface situation. Thus, I have been motivated to find whether the DLT can be a good solution to this problem. I use the DLT to build the near-surface velocity model and determine the static correction for the area.

The final velocity model produced by DLT holds close velocity-depth information compared to uphole survey, and static correction calculated from such model shows improvement, such as an increasing level of reflection coherency on stack section.

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Chapter 1

Introduction

1.1 Seismic imaging and static problem

In land exploration seismology, sources and receivers are usually deployed on the surface. A source generates energy (e.g., dynamite explosion) that penetrates through the Earth's subsurface and comes back to receivers when it hits certain types of structures (e.g., reflection interface). Such reflected energy carries information about the subsurface, and based on such information, geophysicists are able to analyze subsurface structures for the purpose of oil and gas exploration.

During processing, seismic data is sorted into different gathers for different purposes. Figure 1.1 introduces the geometry of three types of gathers. CMP gather is important because all the reflected energy focuses on one point (CMP1 in Figure 1.1 (c)), which means this point can be better imaged. In practice, seismic data

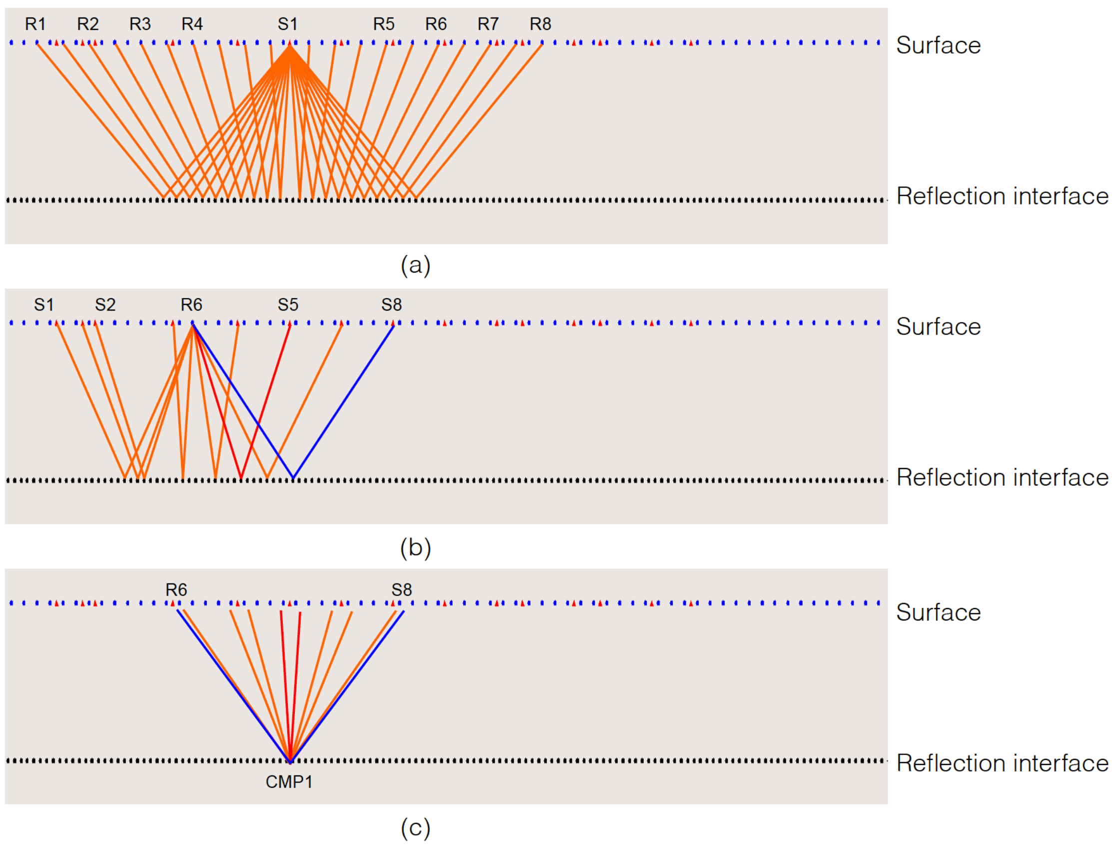

Figure 1.1: Geometry of reflection seismology. S is source and R is receiver. Figure (a) is common shot gather (CSG), (b) is common receiver gather (CRG), (c) is common mid-point gather (CMP).

from different source and receiver pairs(e.g., R6 and S8 in Figure 1.1) are stacked together to enhance the image of CMP point.

This simple geometry, however, depends on the assumption that the subsurface velocity is known, and sources as well as receivers are located on the same horizontal surface. In the real world, this assumption does not always stand, because the surface on which source and receiver are deployed is not totally flat and the subsurface velocity is unknown or not variable. This irregularity is adverse to seismic imaging, such that CMP stacking can not be done because acquired seismic data in CMP gather is not a perfect hyperbola.

Figure 1.2 shows CMP gather with the existence of surface topographic variation and near-surface velocity variation. In this case, what we would get from CMP gather in time domain are the seismic wiggles marked as 'Before correction'. This non-hyperbolic curve should be corrected like a hyperbola and therefore, static correction is introduced to overcome this problem.

As discussed, the simple geometry of reflection seismology is based on the approximation that sources and receivers are placed on the same horizontal level and near-surface velocity field is uniform. While this approximation may be roughly acceptable in cases with slight static problem, however, in areas with complex near-surface situation, such as mountainous regions with strong topographic variation, such assumption no longer stands since the heterogeneities can affect the seismic traces severely (Figure 1.2). Simply put, the task is to remove the mentioned effects (e.g., topography and velocity variation) so that we can perform processing procedures such as Normal Moveout (NMO) and stacking to enhance the images at

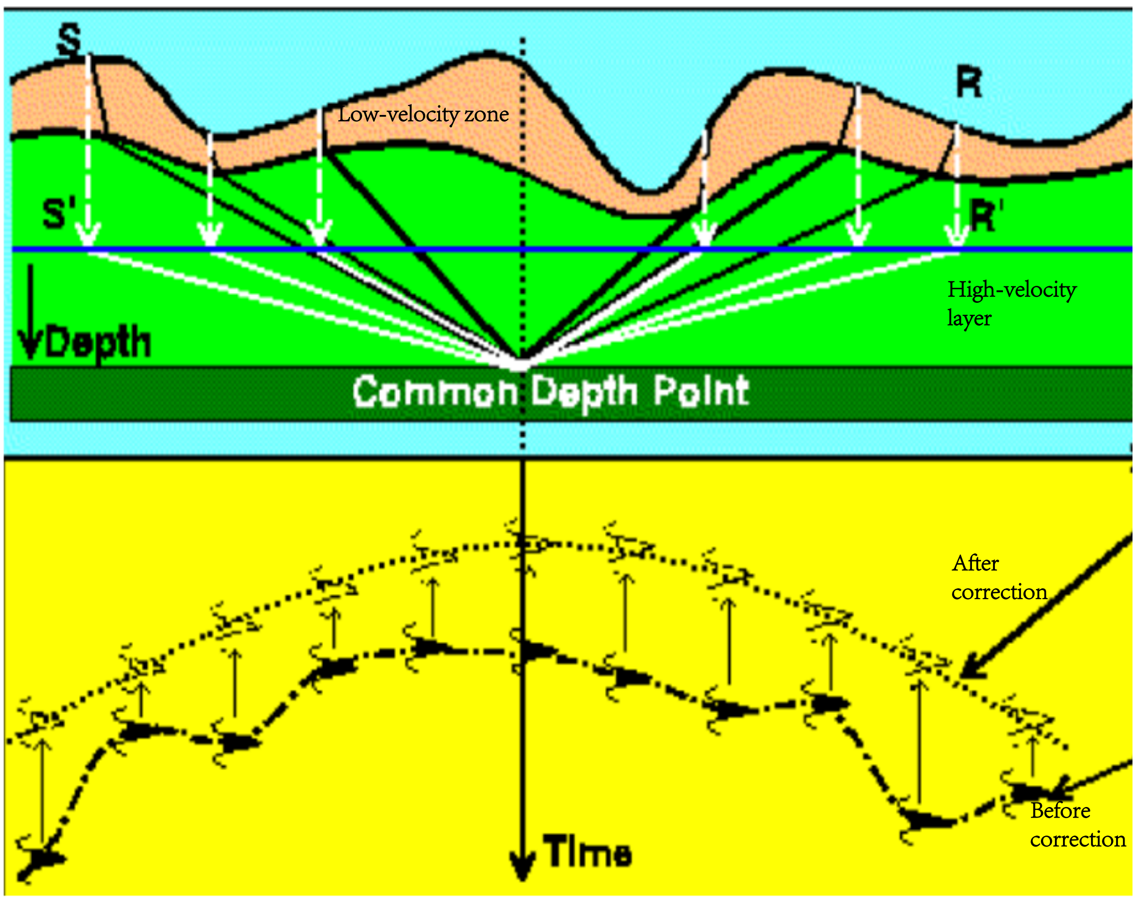

Figure 1.2: Upper picture is seismic survey with topographic variation and near-surface low velocity (different colors represent for different layers). Lower picture is the CMP gather before and after static correction.

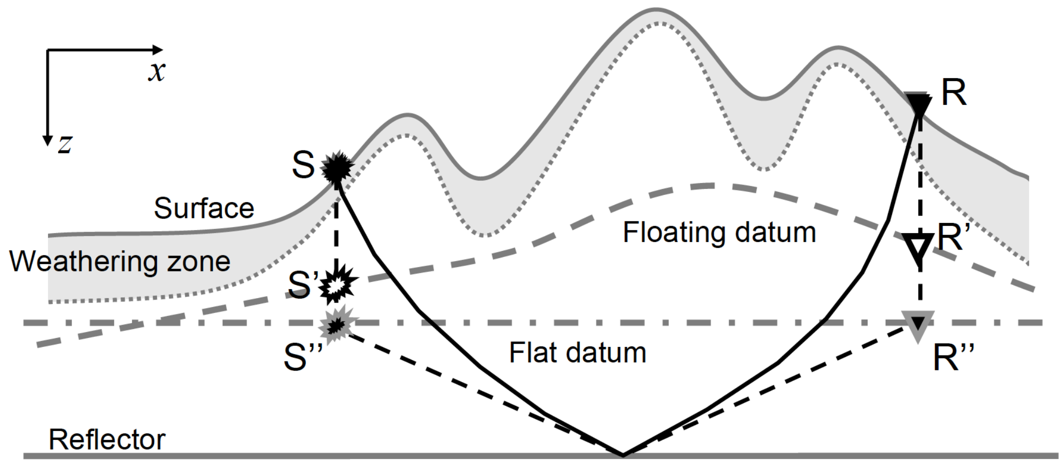

Figure 1.3: Schematic showing the idea of static correction. Topography, weathering zone, datum and reflector are included (Zhou, 2014). S and R are source and receiver locations.

each CMP location. The purpose of static correction is to compensate for the effects of variations in elevation, near-surface low-velocity-layer (weathering) thickness, weathering velocity, and/or reference to a datum (Sheriff, 2002a).

1.2 Static-correction methods

Figure 1.3 shows the common cross section of land seismic survey. Sources and receivers are located on the surface. Below the surface, there exists a weathering zone with low velocity. According to the assumption that source and receiver are on the same datum with uniformed subsurface velocity structure, static correction aims to move source and receiver to a new datum (S' and R' in Figure 1.3). Note that static correction itself is an assumption that the replacement of source and receiver are done vertically since the near-surface velocity is assumed to be low. This assumption would bring in errors, such that the true raypath (solid line) and corrected raypath (dashed line) are different.

In land seismic survey, the elevation values of source and receiver are available, which means the effect of elevation can be calculated accordingly. However, the quality of a seismic image after elevation correction is likely to be poor, since the elevation correction only compensates for the distortions caused by elevation changes. This poor quality is indicated by discontinuities of reflection events or, events that are untrue in terms of geology. The remaining distortions are caused by near-surface low-velocity layers, sometimes referred as weathering zone. Therefore, the need of an accurate near-surface velocity model motivates people to develop several velocity-model-building methods to correct for the distortions, such as refraction statics, uphole surveys, and tomostatics. Below are brief introductions to these methods.

1. Elevation correction

   Elevation correction is usually one of the first steps in land seismic data processing when the survey area has topographic variation. The target of elevation correction is to remove the distortions on seismic data caused by surface topographic changes. At this stage, the subsurface velocity field is unknown. Therefore, an estimated velocity (also referred as replacement velocity) is used when calculating the corrected traveltime. Some distortions can be removed after elevation correction. However, since the replacement velocity is just a rough approximation of near-surface velocity field, this procedure lacks accuracy and result shows limited improvement.

2. Refraction static correction

   As mentioned before, the key point in static correction is to find an accurate near-surface velocity model, based upon which we could determine the effect of near-surface low-velocity zone (LVZ). If we assume that near surface is a layer-cake velocity model, which means velocity increases with depth, then the refracted wave as the first arrival carries information of the each layer's velocity-depth information. This information helps to build the velocity model. Generally, refraction statics includes RM (Reciprocal Method), GRM (Generalized Reciprocal Method),and EGRM (Extended Generalized Reciprocal Method).

   If we extract the slope of first arrivals on a single shot gather, the interval velocity of each layer can be calculated according to the inverse slope of each line segment. Meanwhile, the layer thickness can be calculated based on traveltime and interval velocity. Based on this information, the static correction values can be determined.

   Refraction static correction has its own limitations. The near-surface velocity model is assumed to be layer-caked, and this method is based on refracted wave. If the layer surface has a dipping angle, some errors will exist in the interpretation result. Besides, the type of first arrivals includes more than just refraction, but also direct arrivals and turning waves. In mountainous area with outcrops and severe subsurface velocity variation, this method's reliability is questionable.

3. Uphole survey

   Besides refraction statics, another way to estimate the near-surface velocity model is to carry out uphole surveys. The drilling depth is usually shallow (50-100 meters) since the target is to explore the near-surface velocity field. The source is near the top of the well and the receivers are in the well. This survey provides the profile of the velocities at different depth. By extracting the up-going waves from the profile, we can even know the information of deeper part where the drilling does not reach.

   Uphole survey, however, is normally very costly, even though it provides a relatively accurate interval velocity profile. For seismic surveys in mountainous areas with severe topographic variation and lateral velocity variation, it is necessary to drill a large number of wells to know the velocity profile of the area, which is impractical considering the effort and cost. In many cases, the uphole survey provides velocity profiles for tomostatics as constraints.

4. Tomostatics

   Maybe the most promising way to build the near-surface velocity model for static correction is tomography, which is referred as tomostatics in this case. Following the example in Figure 1.3, when topography variation is severe and lateral velocity variation is strong, the image of subsurface structure is severely distorted (Zhou, 2014). However for such complex but common structure in land surveys, both refraction statics and uphole surveys are likely to fail, while tomostatics (static correction based on tomographic velocity model) has several advantages facing such problem.

Tomography is a method for finding the velocity and reflectivity distribution from a multitude of observations using combinations of source and receiver locations, or of determining the resistivity distribution from conductivity measurements using a transmitter in one well and a receiver in another well (Sheriff, 2002a). Compared to refraction statics, although tomography also depends on the information of first arrivals, it has the advantage over refraction method since it doesnt matter whether the first arrivals are refracted waves or not. In fact, first arrival for tomography can either be the arrival of direct wave, turning wave or refracted wave (Zhou, 2014). In practice, tomography is the commonly chosen method for static correction in areas with complex near-surface structures.

5. Deformable-layer tomostatics

In summary, we have to estimate the near-surface velocity field to determine static correction values. Thus, the quality of static correction directly depends on the accuracy of estimated velocity model. For complex near-surface cases, it is common that none of the mentioned methods works perfectly. This is simply because of the existence of LVZ and topographic variation, like mountainous areas and sand dunes. Even for grid tomography whose model parameterization is celled, it is difficult to describe near-surface features like pinchouts. Instead, a layered approach is geologically more reasonable under this situation. This inability of grid tomography motivates me to investigate the near-surface velocity field via deformable-layer tomography (DLT) (Zhou, 2006), which achieves many successes on similar scenarios (Li et al. (2009a), Li et al. (2009b), Liu et al. (2010), Zhou et al. (2009)). Detailed introduction on DLT is given in Chapter 2.

1.3 Objectives and challenges

1.3.1 Objectives

In this thesis, my proposed work is tomographic velocity-model building and static correction application on field data. To be specific, the following are the objectives of this thesis.

1. Algorithm modification

   While the idea of static correction is straightforward, tomographic velocity model building is the key issue. In this thesis, the research code of DLT is from Dr. Zhou. This original code needs further modification for this specific dataset.

2. Field data processing

   Second objective is to process seismic data. Following the conventional seismic data processing flow described by Yilmaz (Yilmaz, 2001), which starts from geometry setup, first arrival picking, and stacking velocity analysis. DLT requires source and receiver locations and the corresponding first arrival traveltime. After tomographic velocity model building, I need to apply static correction value to both shot gathers and stack section for the purpose of comparison.

3. DLT velocity model building

   The key issue for static correction is an accurate near-surface velocity model, and it is also the main task in this thesis. For this part, I aim to apply DLT to synthetic test first in order to test its capability and then apply DLT to field data. Also for field data, I need to find methods to test the velocity model produced by DLT. It is necessary to find direct proofs from field data or, interpret uphole survey results and compare uphole interpretation with the DLT velocity model. Only after the DLT velocity model is supported by several ground-truth evidence can I calculate static correction based on such model.

4. Static correction application

   After tomographic velocity model building, the next task is to calculate static-correction values and apply them to seismic data. This application is carried out using commercial software. In this thesis, seismic data are processed on GeoEast and Omega, including geometry setup, first arrival picking, velocity analysis, and static correction application.

1.3.2 Expected challenges

The field data I am working on in this thesis was acquired from western Sichuan, China. The survey area is mountainous, with severe topographic variation. For instance, there is 1000 m elevation change within 8 km horizontal length (Figure 2.8). Also, previous survey (Figure 1.5) shows that the surface outcrops' lithology exhibits

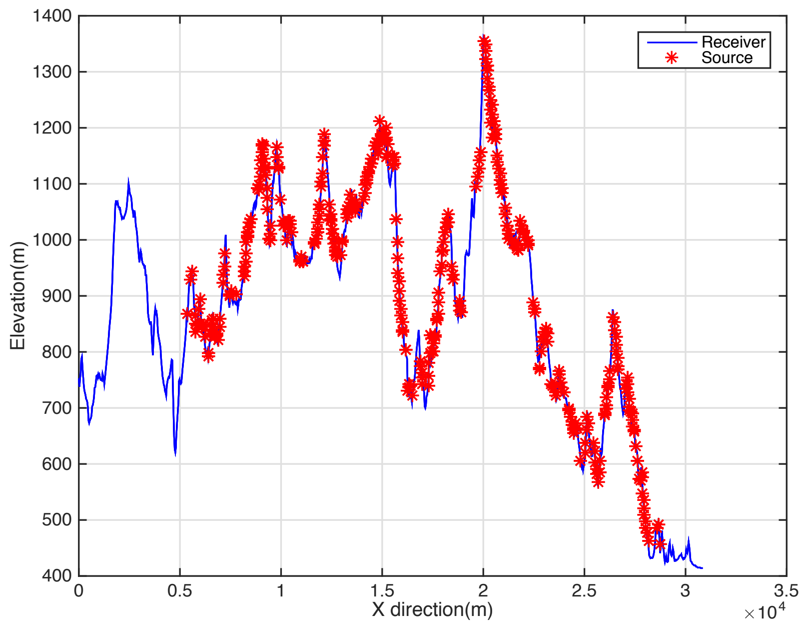

Figure 1.4: Topographic variation of field data. Note the 1000 meters elevation drop from 20 to 28 kilometers in X direction.

strong lateral variation, while in the meantime, the amount of uphole information is insufficient to describe such variation. Besides, because seismic survey was carried out in mountainous area, the data's signal-to-noise ratio (SNR) is low. Detailed seismic data descriptions and discussions are given in Chapter 2.

Even though DLT is a promising method for near-surface velocity model building according to previous examples, whether it could yields good results with such challenging dataset remains a question. Besides, it is common that for data acquired in mountainous regions, none of the static correction methods produces perfect result and the comparison between different methods varies from place to place.

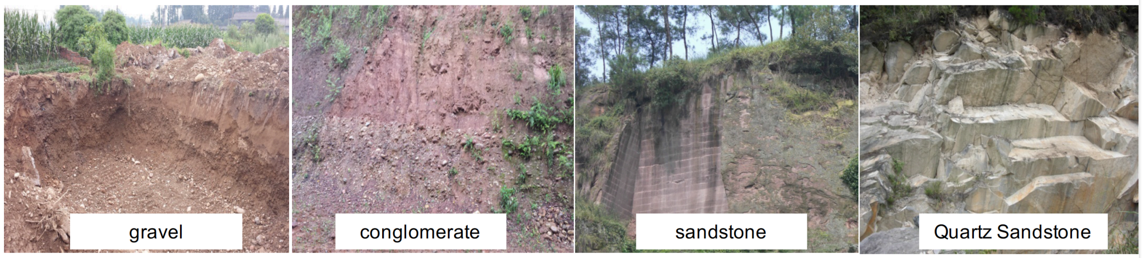

Figure 1.5: Lithology variation of outcrops in the study area.

For these complicated near-surface structures, sometimes even elevation correction can produce better results than tomostatics. This uncertainty also makes my tasks more challenging.

1.4 Thesis outline

First, I introduce the idea of DLT and discuss some synthetic test results, showing DLT's potential ability to deal with field data in complex near-surface areas. Second, the detailed introduction of the field data is carried out, including some preliminary processing results needed by DLT. After the introduction of the method and field data, there follows the DLT velocity model building on field data, and determined static correction result accordingly. Finally, I compare the results and comment on DLT's capability to deal with complicated near-surface situations.

Chapter 2

Methods and field data background

In this chapter, the detailed introduction of DLT is given, including basic concepts and procedures. Some synthetic tests are discussed as well, illustrating this method's ability to deal with synthetic data that is similar to this study case. After the discussion on methods, the field data's background (survey design, geological information) is given, followed by several preliminary processing results, including first arrival picking, uphole survey interpretation, and geometry setup.

Based on the introduction of field data, this chapter then aims to relate the real-world problems with potential feasible method (DLT), and in the meantime, explains DLT's effectiveness over other methods in this study case.

2.1 Deformable-layer tomography

2.1.1 Motivation

In traditional traveltime tomography, a velocity model is discretized into regular cells and each cell has a velocity value. In Figure 2.1, (a) is the initial velocity model and velocity values are differentiated by different colors. The curve in (a) is a raypath from source to receiver, and traveltime in different cells are marked by $\boldsymbol{T_n}$ (e.g., $\boldsymbol{T_5}$). This calculated traveltime from initial model is compared with true traveltime. Meanwhile, the velocity value within each cell is updated to minimize this difference. After several iterations, the initial velocity model in (a) is updated as (b) in Figure 2.1, which produces close traveltime profile compared to true traveltime. At this stage, we believe velocity model (b) represents the velocity field of true model (or true earth).

Grid tomography works well where a velocity field can be estimated by regular sized cells. However, for complex near-surface structures, it is difficult to model the subsurface by cells. Geologically speaking, near-surface usually consists of several sedimentary layers with varying thickness. It would be more reasonable to model near-surface by layer instead of cell.

Deformable-layer tomography is proposed by Zhou (2006), based on the assumption that near-surface velocity structures are layered. Compared to grid tomography, which characterizes the velocity model by grids, DLT relies on geologically reasonable model parameterization and yields better results with less inversion unknowns,

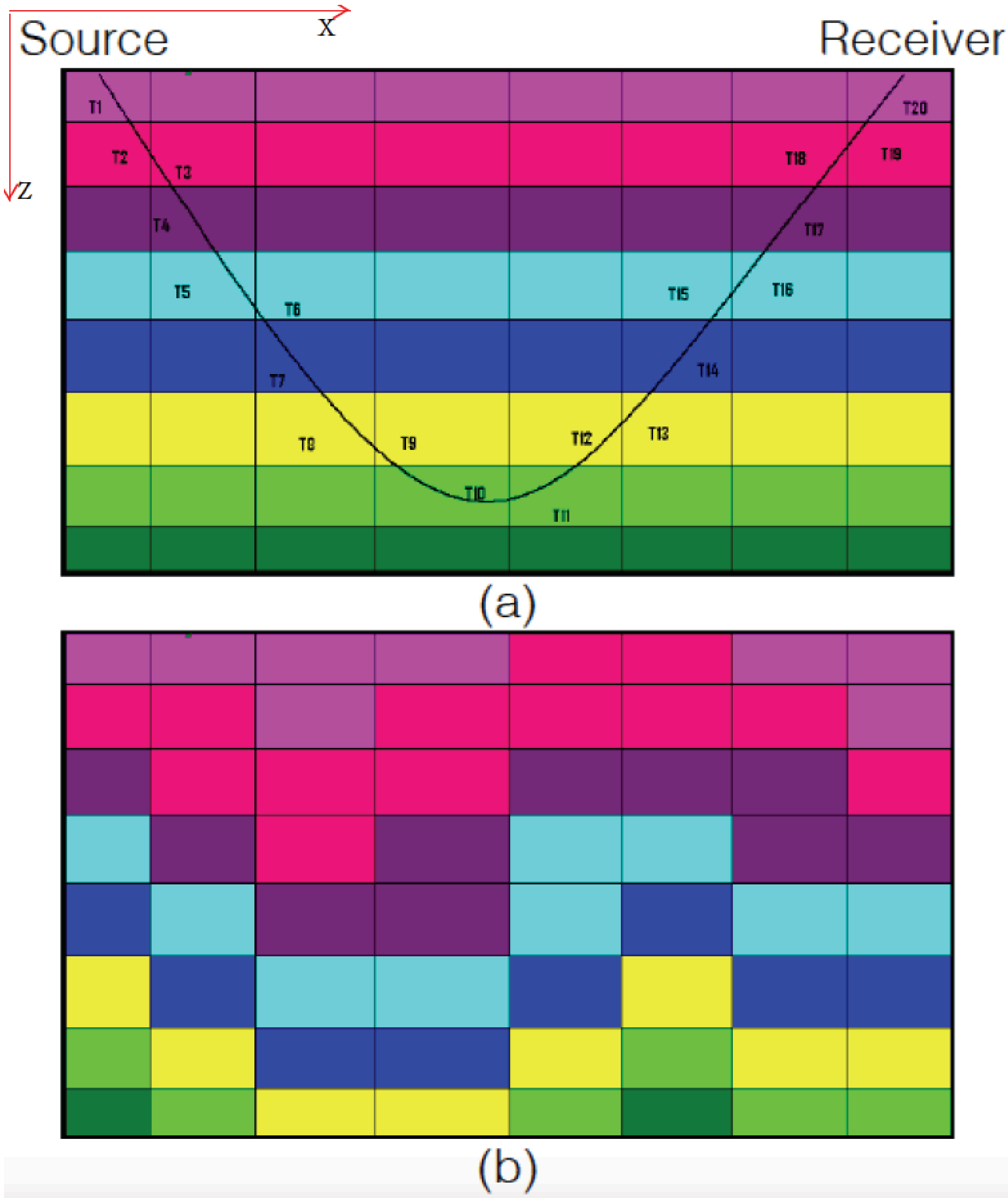

Figure 2.1: Example of grid tomography. (a) The initial velocity model of grid traveltime tomography. (b) The updated velocity model. $\boldsymbol{T}$ is the traveltime in each cell.

especially with some known information of subsurface, such as uphole survey results. Many cases, including both synthetic test and field data, show DLT's effectiveness. Liu et al. (2010) apply DLT to invert the Yilmaz model, which has topographic variation, LVZ and reversed-velocity interface. Their work draws the conclusion that DLT delivers better results compared to grid tomography, and image after static correction matches well with true model. Zhou et al. (2009) apply DLT to field data in sand-dune area and constrain the depth range of shallow reflectors during inversion. Their work shows better reflection coherency on the stack section and yields better results compared with two commercial grid tomography package.

2.1.2 Model parameterization

In DLT, a layered model parameterization is applied. This approach makes geologically reasonable assumption, due to observations that many near-surface geological features tend to be layered, such as weathering zone or pinchout, which can be better modeled using layers rather than cells. On top of that, this approach also reduces the number of unknowns for inversion, which reduce the degree of inversion uncertainty.

Figure 2.2 demonstrates the model parameterization of DLT. This model has 3 layers, and the layer geometry is controlled by controlling points (or columns), which are denoted as the vertical dotted line. Within each block, which is segmented by solid line and dotted line, a constant velocity value is assigned. If we assume that velocity value is constant within the same layer, then all the velocity blocks in the same layer

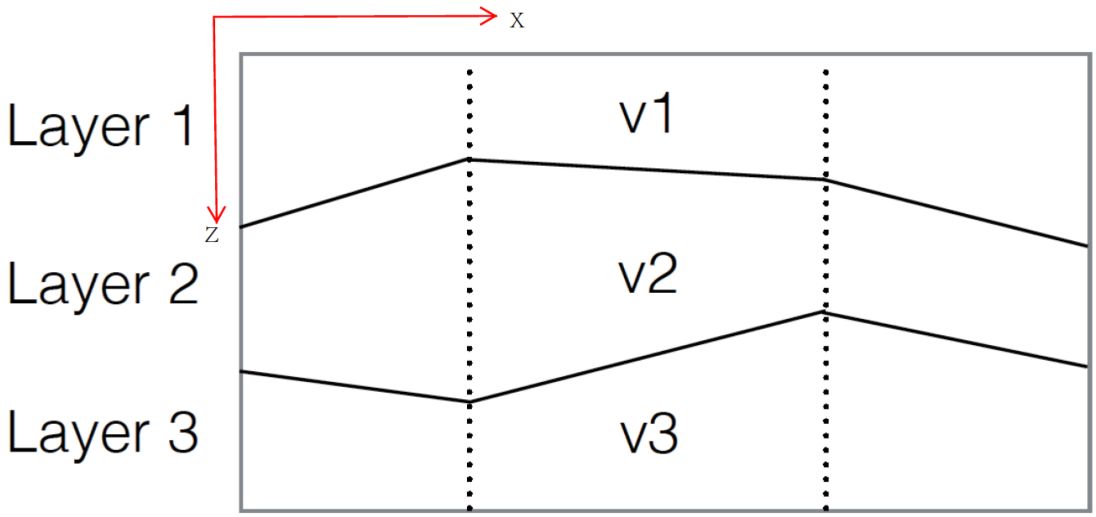

Figure 2.2: Model parameterization of deformable-layer tomography.

hold the same velocity. This layered parameterization can invert layer geometry as well as velocity within each block.

2.1.3 Forward modeling

For this study case, the forward modeling is done via shortest-path ray tracing. Compared to reflection events on seismic records, first arrivals are relatively easier to be recognized. First arrived rays are the combination of direct arrived, refracted, and turning rays, whichever come first. First arrivals carry the near-surface velocity information, which is needed for tomographic velocity model building.

In order to simulate first arrival rays, a shortest-path ray tracing method is introduced. This shortest-path calculation method is proposed by Moser (1991).

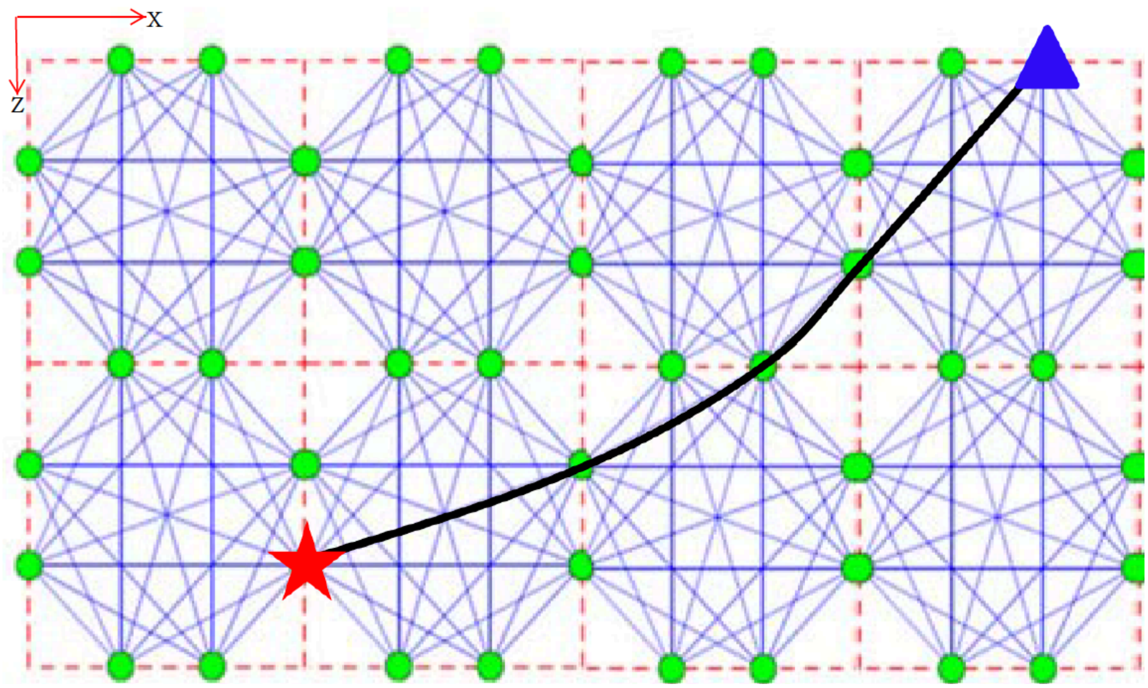

Figure 2.3: An example of shortest-path ray tracing.

The basic idea of shortest-path ray tracing is to devide the model into grids, and search for the shortest traveltime between two grids (marked as red star and blue triangle in Figure 2.3), and update this searching iteratively until it is done.

Ray theory is based on the assumption that seismic energy travels at infinite high frequency that the trajectory can be calculated as rays. It is a practical approach when dealing with complex subsurface structures, especially those with severe topographic variation and strong velocity variation, since waveform methods have difficulties in handling such problem. For DLT, even though the shape of grids is not regular, the idea remains the same when tracing the shortest raypaths.

2.1.4 Inversion

After the forward modeling, the traveltime of different rays is calculated. Then, the traveltime difference is derived. This difference, also referred as traveltime residual, together with kernel matrix derived from reference model, are used to invert for the perturbation in the model.

In DLT, the traveltime residual is affected by two terms: perturbation of slowness in each single cell as well as perturbation of vertical location of controlling points (or the geometry of each layer interface). This relationship is given by Zhou (2006).

$$\boldsymbol{\delta t_i = \sum_{j}^{J} k\_s_{ij} \delta s_j + \sum_{l}^{L} k\_z_{il} \delta z_l} \tag{2.1}$$

In equation 2.1, $\boldsymbol{\delta t_i}$ is the traveltime residual between true data and predicted data, and $\boldsymbol{\delta s_j}$ is the perturbation on velocity in grids. As discussed before, the traveltime residual is also affected by another term $\boldsymbol{\delta z_l}$, which is the perturbation on interface. $\boldsymbol{k\_s_{ij}}$ and $\boldsymbol{k\_z_{il}}$ are the slowness kernel and interface kernel, respectively.

2.1.5 DLT procedure

Tomographic inversion normally starts from an initial model and updates the initial model by inversion, until the stopping condition is reached. This procedure usually contains tens of iterations. Each iteration includes forward modeling, kernel calculation and inversion. Detailed procedures are introduced as following:

1. Initial velocity model building

   Some prior information may help to build the initial model. For example, we may estimate the near-surface structure by measure the slope of first arrivals in order to get approximate layer velocities, or we may locate or constrain some subsurface structure such as shallow reflectors based on shallow reflection events on shot gathers (Zhou et al., 2009).

2. Forward modeling and kernel calculation

   Forward modeling is carried out on the initial velocity model built in step 1. By comparing the forward modeling results with true data, the traveltime residual $\boldsymbol{\delta t}$ is calculated. In the meantime, by perturbing the initial velocity model, inversion kernel (e.g., $\boldsymbol{k\_s_{ij}}$ or $\boldsymbol{k\_z_{il}}$) is calculated based upon the perturbation and corresponding traveltime changes.

3. Inversion

   Next step, the calculated traveltime residual and inversion kernel are used to invert for model updates. The new inverted model is then the reference model and the procedure starts from step 1 again. This iteration lasts until the final result converges. The process from 1 to 3 may iterate tens of times in practice, and some other stopping conditions may apply too, such as whether the inverted model and ground-truth information (uphole information) are close enough.

2.1.6 DLT synthetic test

In this section, a DLT synthetic test is introduced to examine DLT's ability when dealing with complex near-surface structure. The original DLT research code is from Dr. Hua-wei Zhou. Some adjustments are done afterwards to run on different platforms for the concern of computation efficiency.

The test model is proposed in the paper by Zhou et al. (2009). In this study case, due to the poor quality of field data (which will be shown later), the shallow reflection events are almost unrecognizable. Thus in this synthetic test, the code version is DLT without constraint.

The true model is shown in Figure 2.4. This model has 6 layers, and the layer velocities from shallow to deep are 0.6, 0.92, 1.24, 1.56, 1.88, 2.20 km/s. This model is 300 meters in depth and 24 kilometers in horizontal direction, with topographic variation all along the whole model. The synthetic test has 2401 receivers and 29 sources, and the data are generated by shortest-path ray tracing.

Figure 2.5 shows the initial velocity model. The initial velocity model has the same layer velocity as the true model (in this case we assume the interval velocity is known), but the geometry is very different from the true model, indicated by flat layer interfaces. Shortest-path raytracing is done on this model and we invert the interface geometry.

Figure 2.6 shows the inversion results of the six iterations. We can see that the layer interfaces start to converge to the true model step by step, and the sixth iteration model is already very similar to the true model. Also, statistical records show the

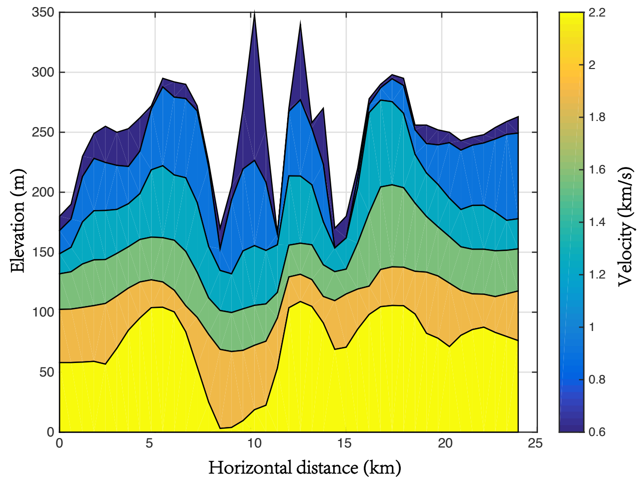

Figure 2.4: True model for synthetic test.

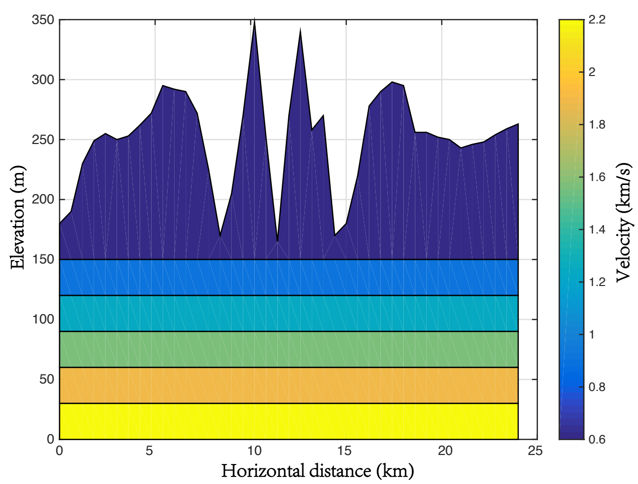

Figure 2.5: Initial velocity model for test.

convergence of inversion. The average misfit reduces from -184 ms to nearly 0 ms, and the standard deviation reduces from 98 ms to 20 ms. Both model space and data space support DLT's result.

Another way to check traveltime tomography's fidelity is to examine ray coverage. Simply put, the ray coverage situation suggests the level of connection between model space and data space. If we have good ray coverage, then we are more confident in the correctness of inverted model. On top of that, cross raypaths, instead of parallel raypaths, is also a key issue for inversion fidelity, since the latter situation is likely to cause smear artifacts (Zhou, 2003). Figure 2.7 demonstrates the ray coverage of every 3 shots on the final resulted model. The raypaths reach the deepest interface. This feature strengthen the fidelity of DLT since the model space and data space are well connected for most part of the model. Note that at places with poor ray coverage (like the right ends of the model), the inversion result does not match with the true model.

This synthetic test illustrates DLT's effectiveness in the following aspects when dealing with complex near-surface structures. First, the layered parameterization not only approximates the near-surface structure more precisely in terms of geology, but also limits the number of inversion unknowns. In order to describe detailed velocity model information, we need fine sized grids instead of coarse sized grids for grid tomography. However, this intention totally conflicts with the fact that increasing number of inversion unknowns results in increasing degree of uncertainty, because a number of grids would not be covered by rays if there were too many of them. By the layered approach, we limit the number of inversion unknowns. Also we

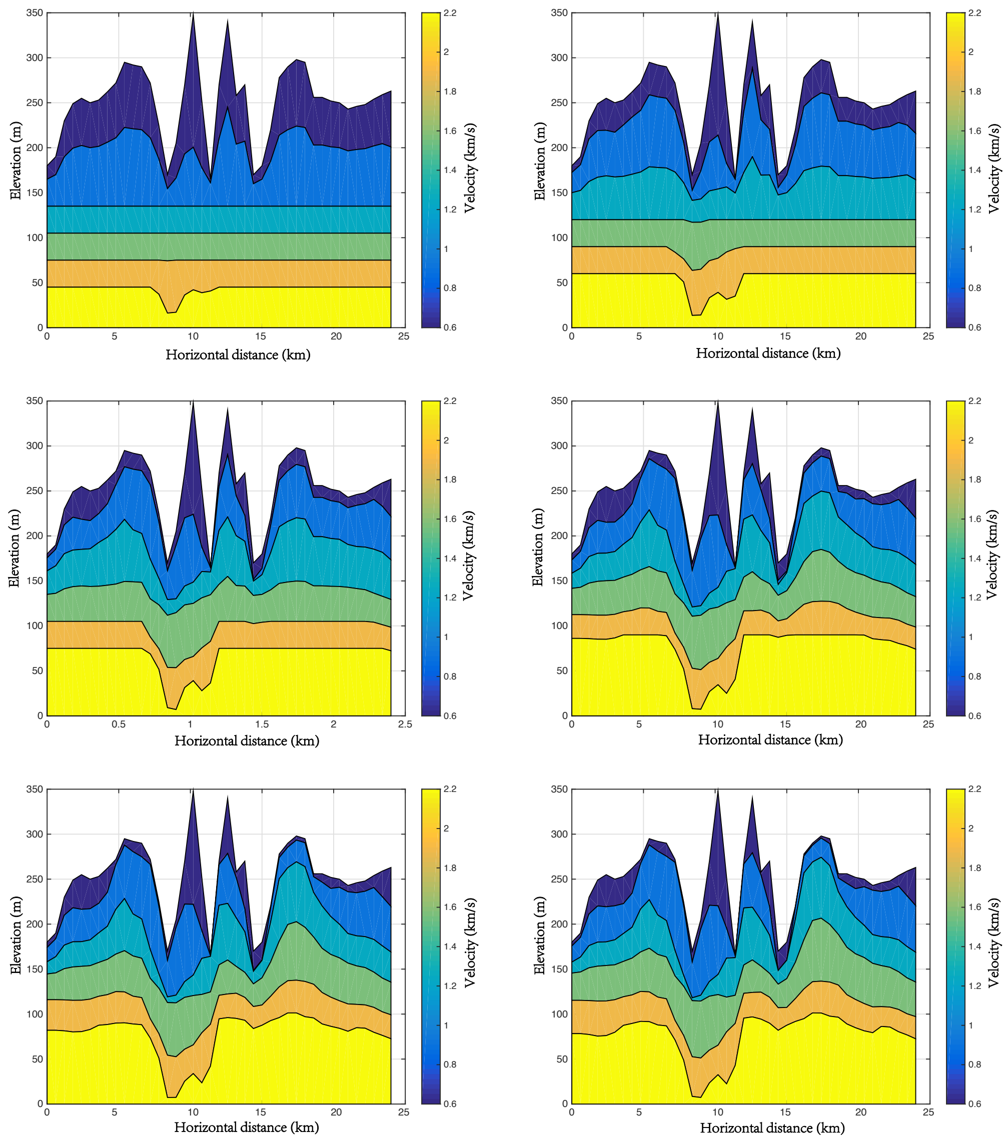

Figure 2.6: From left to right, top to bottom, inverted models of iteration 1, 2, 3, 4, 5, 6.

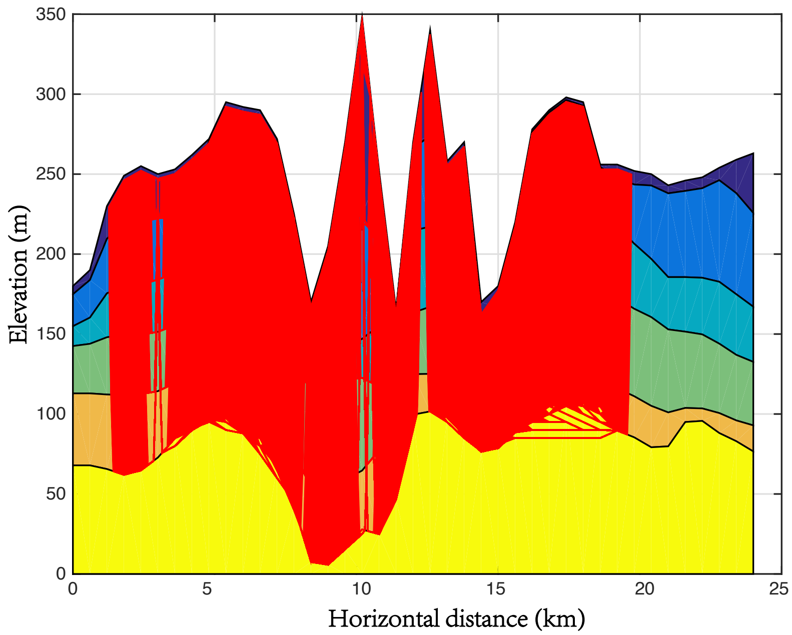

Figure 2.7: Ray coverage indicated by first arrival raypaths (red curves) on the inverted velocity model.

are able to describe some features such as pinchout, and invert for long wavelength velocity variation by inverting for the interface geometry. Second, the synthetic test shows good result, both in model space (true model and inverted model) and data space (converged average misfit and standard deviation). Note that as long as the estimation of interval velocity is correct, the DLT inversion process actually does not highly rely on the initial model. This feature also broadens the applicability in practice.

2.2 Field data introduction and preliminary processing

In this section, detailed introduction of field data is given. This introduction includes basic settings of the seismic survey and some geological backgrounds that may help with the velocity model building. The preliminary processing of field data is demonstrated as well. First arrival picking, uphole survey interpretation and some shot gathers are included in this part. After all these discussions, this section aims to link the field data with the potential method DLT.

2.2.1 Introduction to the seismic data

This survey was carried out in the western Sichuan, China. The survey area is mountainous, with severe topographic variation. The total length of the 2D line is approximately 24 kilometers, with 391 shots and 360 receivers for each shot. The receiver interval is 30 meters.

The geological age of outcrops all along the section ranges from early Triassic Period to early Cretaceous Period. Surface outcrops' lithology variation is shown in Figure 1.5.

The seismic data contains the SEGY files and standard SPS geometry files. Besides, some uphole survey data are available along the 2D line.

2.2.2 Preliminary processing

The target of this thesis is overcome the static problem in field data. In order to calculate static correction values, DLT is introduced as the primary method to invert for the near-surface velocity structure. Deformable-layer tomography, as demonstrated in the synthetic example, needs following input data: source information, receiver information and first arrivals. The source and receiver information, such as identification numbers and coordinates, is in the SEGY file's trace headers. I wrote program codes in Matlab to read SEGY file and extract needed information.

1. Seismic survey geometry

   Since this survey was carried out in mountainous area, the condition for deploying sources and receivers is critical. This limits results in non-alignment of source and receiver locations, especially for dynamite sources due to local residents and farm lands. Thus, the 2D profile's direction is determined by the

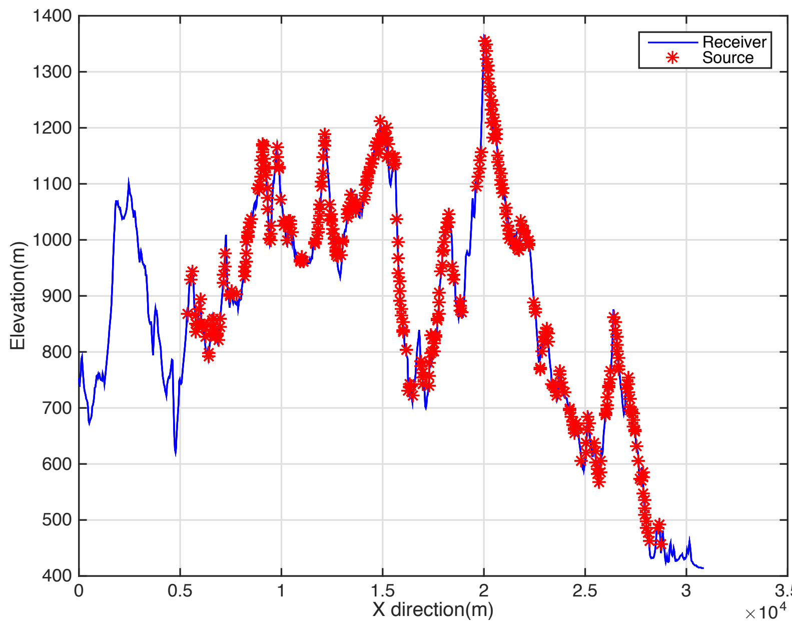

Figure 2.8: Locations of sources and receivers.

locations of receivers.

Figure 2.8 shows the locations of sources and receivers. This figure reveals the severe topographical variation of this 2D line, whose highest point reaches 1350 meters and while the lowest point is just above 400 meters. Further more, for the right end of this profile, there exists a an almost 1000 meters drop in elevation within 8 kilometers. This strong topographic variation indicates that elevation might have the dominant distortion effect on seismic traces, compared to other causes such as near-surface LVZ.

2. First-arrival picking

First-arrival picking is accomplished on both Omega and GeoEast software.

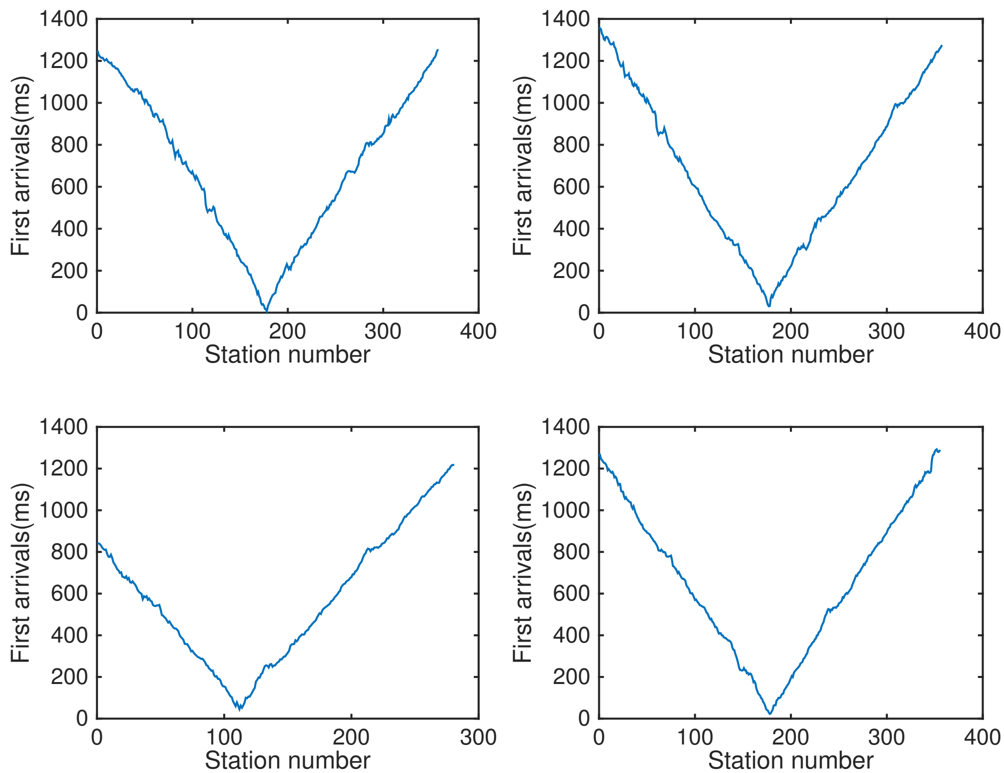

Figure 2.9: First arrivals of 4 common shot gathers (CSG). Distance between two neighboring stations is 30 meters.

It follows the routine procedure. First I determine the operation window size, then operate linear moveout (LMO) and auto-picking, and finally adjust abnormal pickings.

Figure 2.9 demonstrates the first arrival picking results of 4 common shot gathers. These shots are selected randomly all along the whole 2D profile. Based on these first arrival plots, the distortions caused by elevation are obvious. Besides, the estimated apparent velocity on these plots generally exhibits a high value ($> \boldsymbol{2500m/s}$) for even small offset ($< \boldsymbol{300m}$), which suggests the near-surface structure is not perfectly horizontally layered but rather a rugged one, combined with outcrops or potential reversed-velocity interfaces (layer with higher velocity is above and layer with lower velocity is below).

3. Uphole surveys

   The uphole data are also available in this study. The purpose of these uphole surveys is to give more accurate information of the near-surface velocity values. There is one uphole every 2 kilometers along the profile. The source for the uphole surveys is a hammer, thus the energy's penetration depth is shallow (less than 20 meters). Velocity-depth information is interpreted from the traveltime recorded by the receivers deployed in the uphole. This information can be used to test the inversion result. Figure 2.10 shows the uphole velocity profile of 3 locations along the 2D profile. This chart indicates the layered structure of near surface in this area, for which a layered modeling approach is geologically more reasonable compared to celled modeling. All the uphole profiles' interpretation shows no existence of reversed-velocity interface and in the meantime, provides ground-truth near-surface velocity information for tomographic velocity model building.

4. Data display

   The quality of studied seismic data is poor, indicated by strong ground rolls, distortions caused by static problems, and low signal-to-noise ratio (SNR).

	H1(m)	V1(m/s)	H2(m)	V2(m/s)	H3	V3(m/s)
Uphole1	3.2	573	5.4	1636		2328
Uphole2	3.2	944	6.1	1622		2470
Uphole3	3.2	720	5.9	1438		2584

Figure 2.10: Uphole velocity interpretation of 3 different locations (2 km between each uphole). $\boldsymbol{Hn}$ is the thickness of each layer and $\boldsymbol{Vn}$ is the layer velocity.

Reflections can hardly be recognized in Figure 2.11, and strong ground rolls dominate all along the whole 2D profile. This is a typical situation for seismic data acquired in mountainous areas, and this is also the reason I choose traveltime tomography to invert the near-surface velocity model, considering the first arrivals' SNR is high.

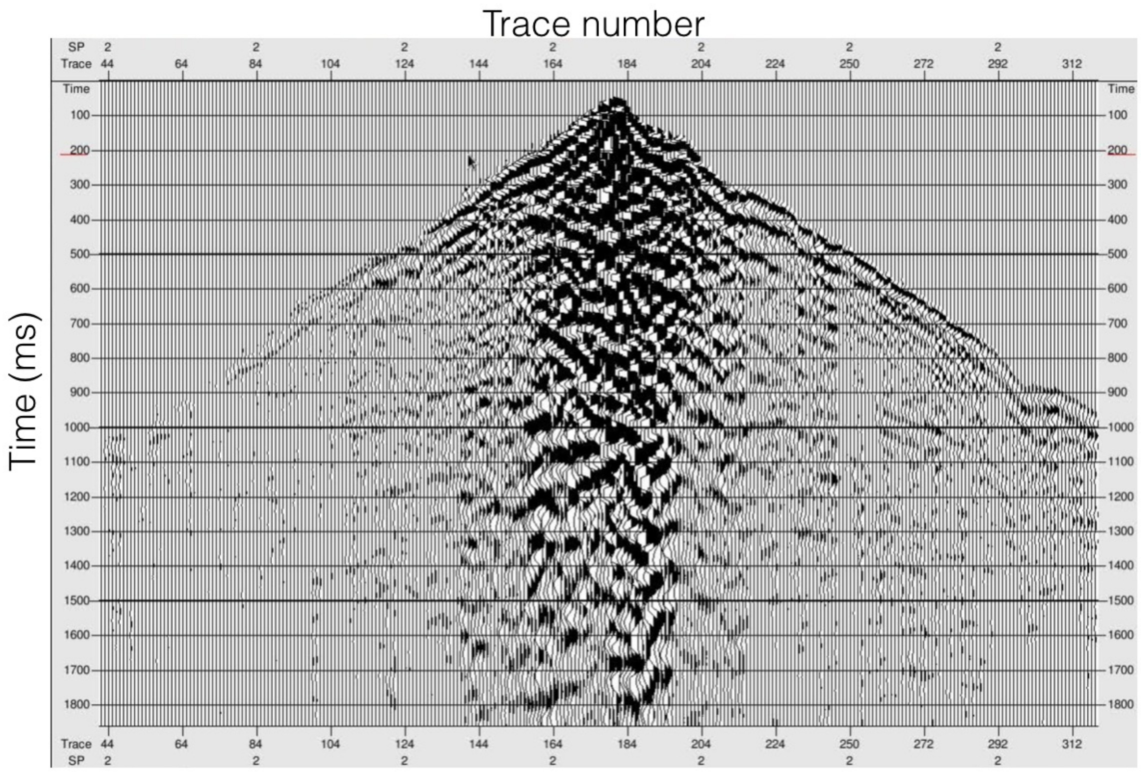

Figure 2.11: Raw seismic data of common shot gather (SP is the source number). Vertical axis is 2-way traveltime in ms and horizontal axis is trace number (30 meters interval).

2.3 Discussions

In this section, I first introduce DLT, followed by some synthetic examples. Then I show the preliminary processing of field data. DLT's effectiveness on near-surface problems are clearly illustrated, and the synthetic test shows good inverted result, which motivates me to choose DLT as the method since the synthetic test is similar to the case I am dealing with. On the other hand, the field data exhibits poor quality as displayed, and first arrivals are the events with relatively high SNR. Also, the first arrivals reach the top of high velocity interface and come back, bringing back velocity information of the near surface. This is why static correction via tomography, which is referred as tomostatics, is one of the most effective methods to calculate static correction values.

To sum up, the survey area has complex near-surface structures. This conclusion is supported by topographic variations, lateral geological variations and seismic data. However, this problem may be solved by DLT according to the synthetic test results. Next Chapter discusses the application of DLT on this dataset.

Chapter 3

Application of deformable-layer tomostatics on field data

In this chapter, DLT is applied to field data. DLT inverts near-surface velocity model to determine the static correction values. Issues on model parameters are discussed in detail. Several tests with different parameters are done and the results are compared. Finally, some conclusions are drawn based on these results and comparisons.

3.1 Tomostatics

Tomostatics determines static correction values via tomography. Many previous studies show the ability of tomostatics to solve static correction problems (Taner et al., 1998; Zhu et al., 1992). Basic introduction is given in chapter 1. Generally, the procedure of tomostatics can be divided into 5 steps:

1. Geometry setup

   A correct geometry setup is fundamental to determine the spatial relationship between sources and receivers. For 2D tomography, sources' and receivers' locations (horizontal axis and vertical axis) are needed.

   Another practical issue is how to determine the topography. In synthetic tests, the topography can be created arbitrarily, on which placed sources and receivers. However, in practical cases, the only information concerned with topography is the elevation of sources and receivers. To put it in another way, sources' and receivers' positions represent the topography. This kind of representation is based on the assumption that the survey is 2D, which may not be strictly true due to the limitations on deploying sources and receivers in land surveys. An alternative way is to draw a 2D line that fits most sources and receivers and then project all the sources' and receivers' locations to this 2D line.

2. First-arrival picking

   First-arrival picking gives first arrivals' traveltime for tomographic inversion. Some first-arrival pickings of this study case are displayed in Chapter 2. The first arrival picking's quality directly affects the quality of inversion, thus the abnormal first arrivals must be discarded during the picking process.

3. Tomography

   After geometry setup and first-arrival picking, the input data needed for tomography is now ready. Tomographic inversion is an iterative process, and

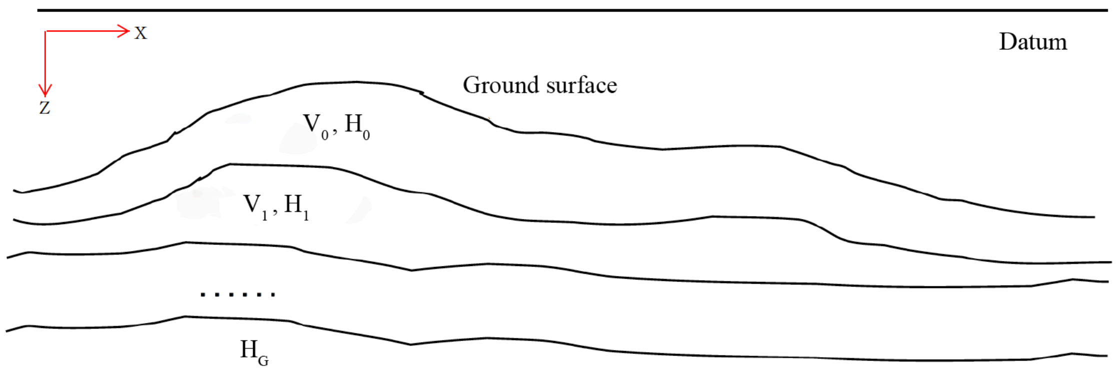

Figure 3.1: Schematic of static correction calculation.

its stopping condition is concerned with statistical convergence of data misfit. Other constrains may apply such as shallow reflector depth range or uphole surveys.

4. Static correction calculation and application

   The target of static correction is to remove the distortions on seismic traces caused by topography and near-surface LVZ. We assume that the near-surface velocity value is low, so that the raypath in low-velocity layer is nearly vertical and can be calculated directly based on velocity model.

   Figure 3.1 shows the idea of static correction calculation. In this thesis, we define that minus-time correction means moving sources and receivers down to a lower datum and plus-time correction means moving sources and receivers up to a higher datum. Following Figure 3.1, the calculation of static correction values of receiver and source are:

$$\boldsymbol{R_t} = -\left(\frac{\boldsymbol{h_0}}{\boldsymbol{v_0}} + \frac{\boldsymbol{h_1}}{\boldsymbol{v_1}} \cdots + \frac{\boldsymbol{h_i}}{\boldsymbol{v_i}}\right) + \frac{\boldsymbol{H_{DATUM}} - \boldsymbol{H_G}}{\boldsymbol{V_{RE}}} \tag{3.1}$$

$$\boldsymbol{S_t} = \boldsymbol{R_t} - \boldsymbol{T_{uphole}} \tag{3.2}$$

Where $\boldsymbol{R_t}$ and $\boldsymbol{S_t}$ are correction times of receiver and source, respectively. $\boldsymbol{h_i}$ is the thickness of $\boldsymbol{i_{th}}$ layer and $\boldsymbol{v_i}$ is the velocity of $\boldsymbol{i_{th}}$ layer. $\boldsymbol{H_G}$ is the elevation of high-velocity interface and $\boldsymbol{H_{DATUM}}$ is the elevation of target datum. $\boldsymbol{V_{RE}}$ is the value of replacement velocity. $\boldsymbol{T_{uphole}}$ is the correction time for dynamite sources placed in wells.

In this thesis, I calculate the static correction values using Equation 3.1 and 3.2, based on the inverted DLT velocity model. Then I write the static correction values to SEGY trace headers and apply them using GeoEast software.

3.2 Deformable-layer tomostatics on field data

3.2.1 Model parameterization

Before applying DLT, I check all the field data to determine the parameters of layered model. Shot gather like Figure 2.11 is common all along this profile. No shallow reflections are recognizable. First arrival slopes indicate that the highest velocity of turning wave is around 4.5 km/s.

Apart from field records, uphole surveys are important as they offer direct velocity value along the profile. Since no reversed-velocity interface is interpreted from uphole surveys, we assume that the velocity increase with depth linearly, which is roughly true in many near-surface cases.

Another issue in model parameterization is the range of first arrivals taken into calculation, quantified by the source-receiver offset length. Generally speaking, since the target zone is LVZ, and in mountainous areas in western Sichuan, the depth range of LVZ is shallow, first arrival of 2 km offset already reaches the top of high-velocity interface. However, in order to ensure that the top of high-velocity layer is covered by first arrival rays, I choose 3.5 km as the offset parameter compared to other ranges.

Finally, the model depth is an important issue for tomographic velocity model building. The model has to be deep enough to ensure that the turning rays do not reach the bottom of the model. This issue is checked by plotting raypaths on the model.

3.2.2 Velocity model building

After the model parameters are settled, all input files for DLT are prepared accordingly. In this test, I assume that the near-surface velocity increases linearly with depth, ranges from 0.55 km/s to 4.75 km/s with a constant increment of 0.7 km/s per layer. The model is divided into 7 layers. During inversion, the velocity value of each layer is set to be unchanged, and the layer geometry is updated. Note

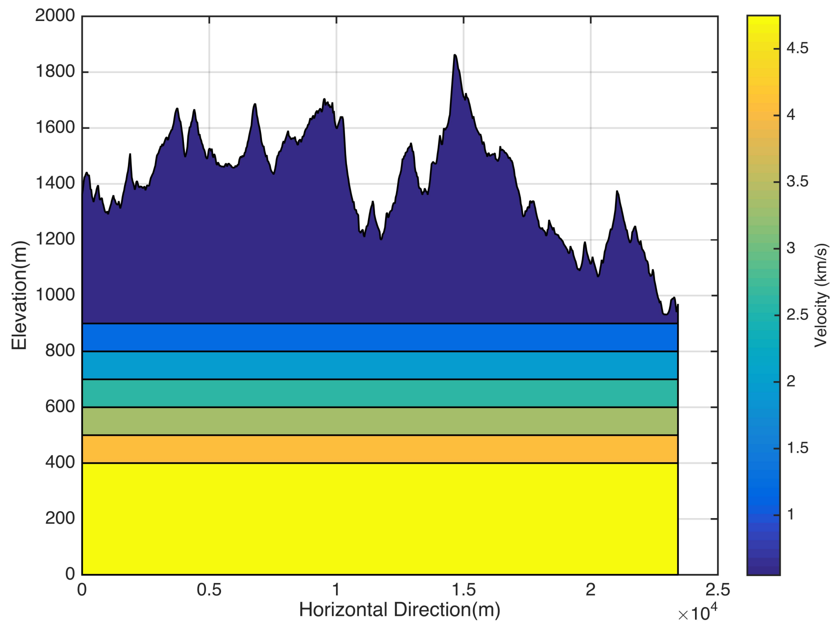

Figure 3.2: Initial velocity model for DLT inversion.

that the elevation is lifted up by 500 meters to increase the model's depth range, otherwise the right end of this model is likely to suffer from insufficient depth.

Following the example of synthetic test, the initial reference velocity model is different from the true earth, which is indicated not only the structure but also a large minus average misfit around (-600 ms) between the picked first arrivals and the forward modeling results.

DLT is based on traveltime, which is calculated from ray tracing results in the reference model. Then the traveltime difference between true data and forward modeling data is calculated. The inversion is then carried out using least-square method (Paige and Saunders, 1982) and multi-scale scheme Zhou (2003). The tomography shows a good convergence in data space. After 20 iterations, the absolute value of average misfit reduces from 600 ms to 5 ms, and standard deviation reduces from 500 ms to 20 ms. Figure 3.3 shows the inverted models during iterations.

Figure 3.4 is the final velocity model and its ray coverage plot. The ray coverage plot illustrates that the model is deep enough. Statistically, the average misfit of this model is -0.2 ms and the standard deviation is less than 20 ms. This indicates this model's fidelity in terms of data space. On the other hand, this inverted model also shows a similar near-surface velocity-depth profile compared to the uphole information. Figure 3.5 demonstrates the thickness of layers above the high-velocity interface (3.3 km/s) along the 2D profile. It is clear that LVZ thickness is relatively small in mountainous regions (left hand side), and increases as the topography elevation drops (right hand side), which is close to a river on map. This LVZ thickness variation is closely related to geology changes. To sum up, the DLT's result shows fidelity in terms of both model and data space, which suggests we can calculate static correction values based on this result.

3.2.3 Static correction

Following the procedure in section 3.1, the final step is to calculate the static correction values based on the inverted velocity model. According to the deformable-layer tomographic model, I calculate the static correction values and write these values to the corresponding SEGY trace headers. The application of static correction is then done on GeoEast software. In this thesis, the final datum for correction is

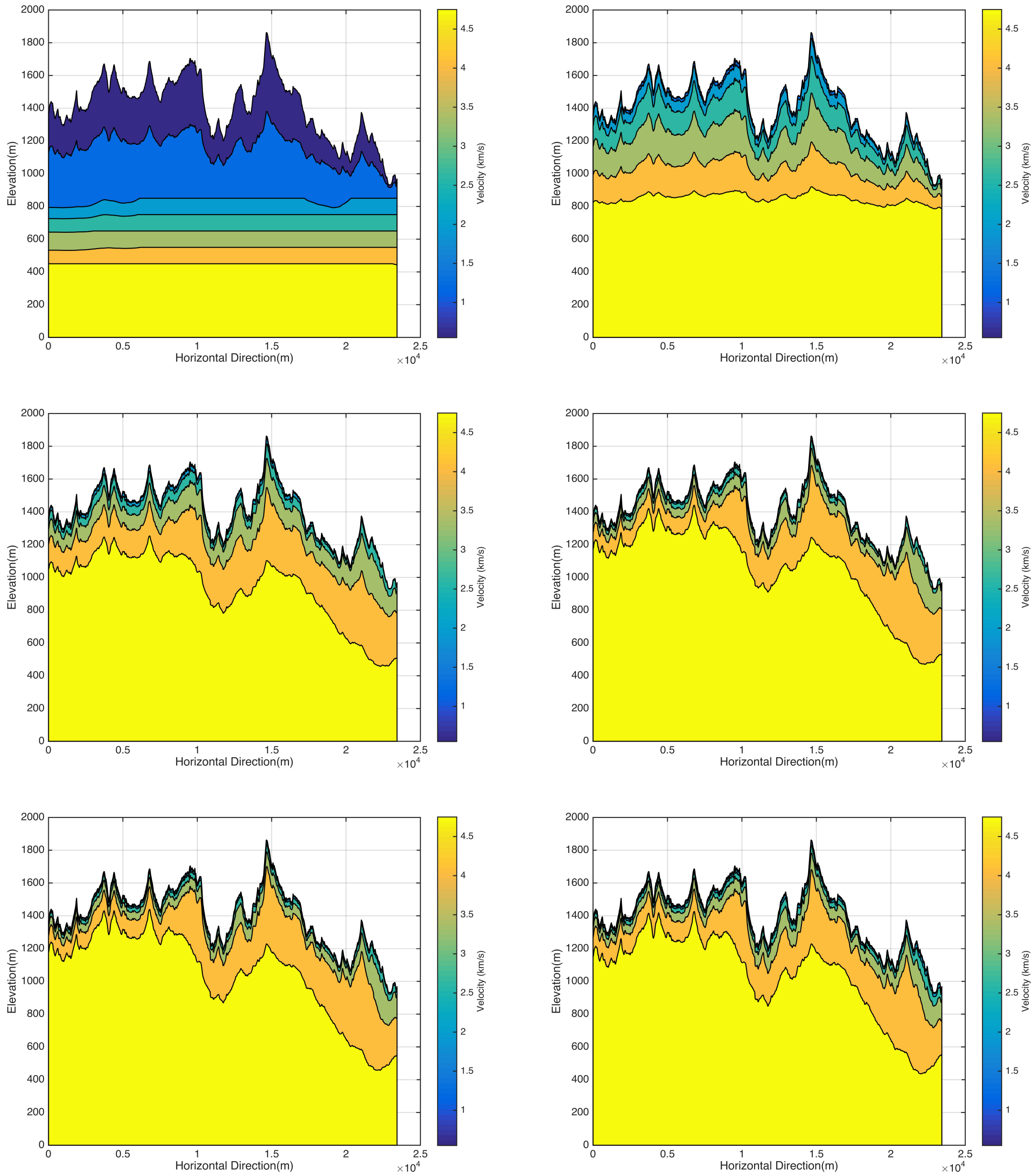

Figure 3.3: From left to right, top to bottom, inverted model after iteration 1, 8, 13, 17, 22, 29.

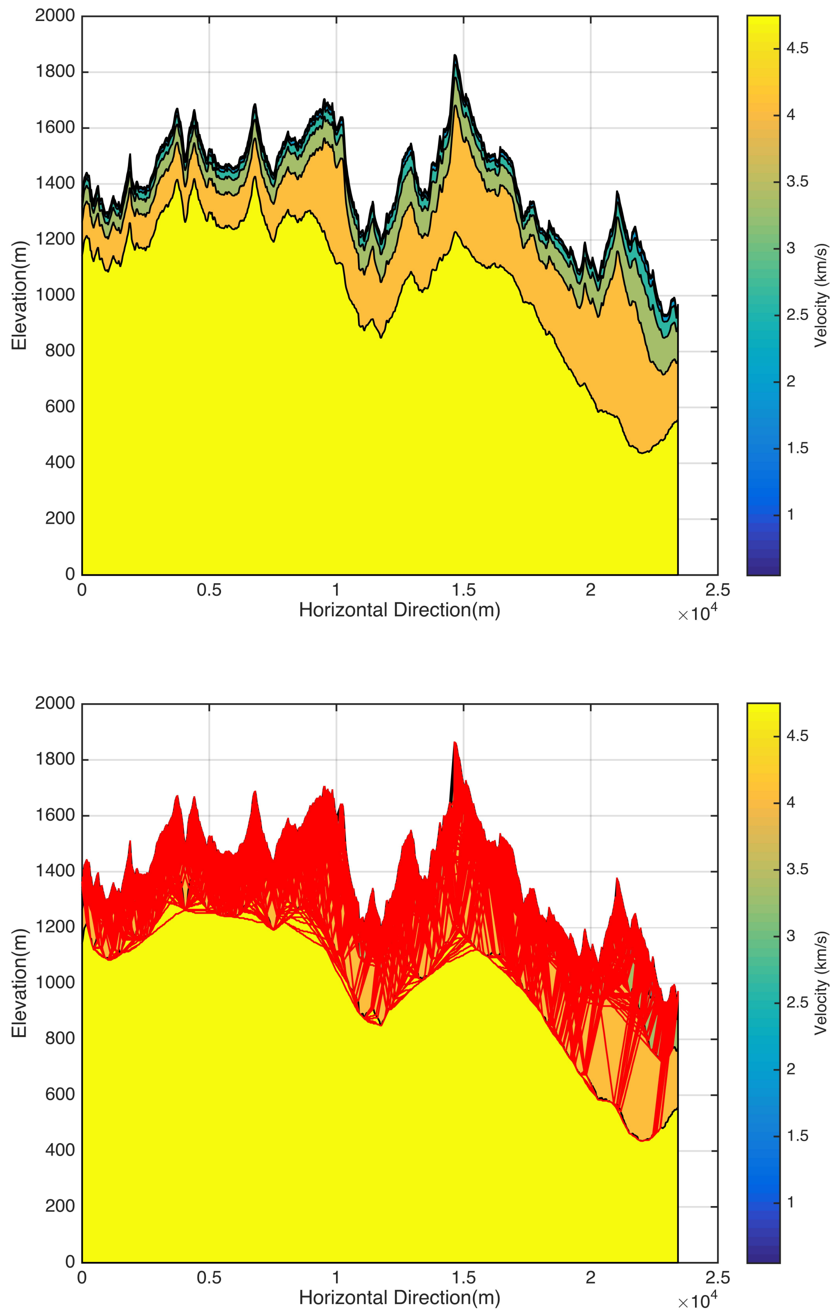

Figure 3.4: Final model (upper picture) and its ray coverage (red curves) plot (lower picture, ray coverage of every 30 shots).

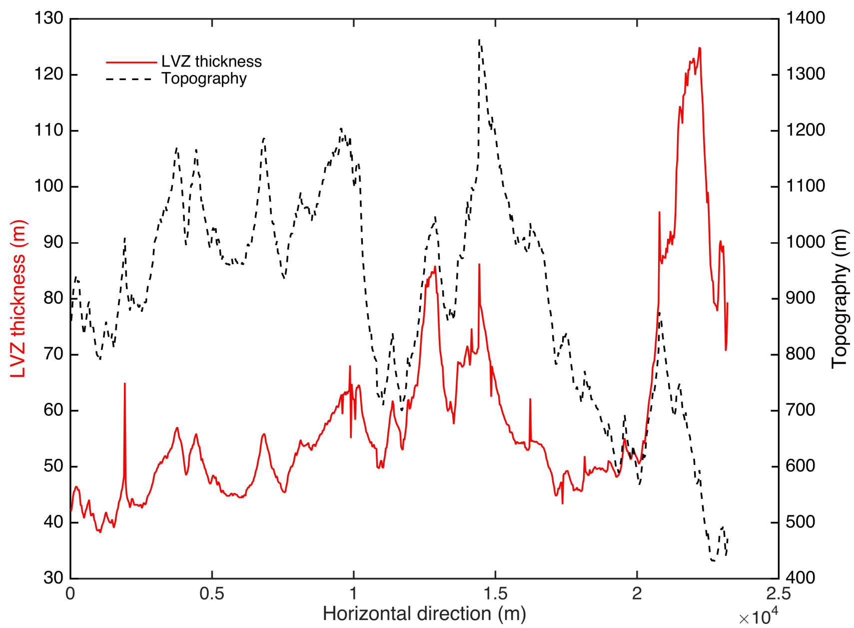

Figure 3.5: Thickness above high-velocity interface versus topography.

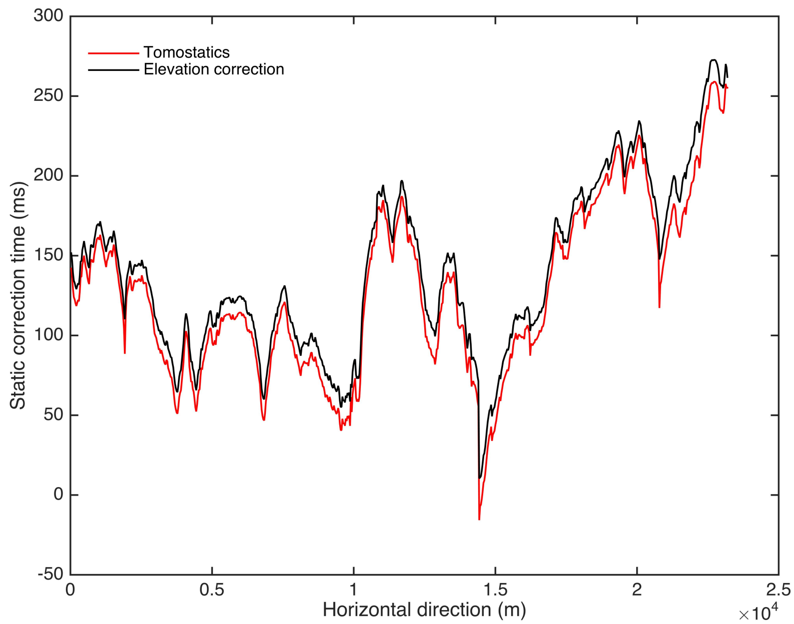

Figure 3.6: Tomostatics and elevation correction results.

a flat datum at the elevation of 1400 m and the replacement velocity is 3.55 km/s. Static correction results are compared by shot gathers as well as stacked sections.

1. Static correction calculation

   The static correction value is calculated using Equation 3.1 and 3.2. Figure 3.6 is the corrected value of tomostatics and elevation correction. Since LVZ is relatively shallow in mountainous areas, these two curves are almost of the same shape, only with some minor differences caused by LVZ.

2. Static correction comparison on common shot gathers

   Static correction is applied to all the shot gathers along this 2D profile. Figure

3.7 is a typical comparison between raw shot gather, shot gather after elevation correction and shot gather after deformable-layer tomostatics.

On the raw data, the first arrivals exhibit zigzag behaviors and are not smooth. After elevation correction, the first arrivals are more smoothed (red arrows). After tomostatics the level of reflection coherence is improved (circled area).

3. Static correction comparison on stack section

   Static correction results are also compared on stack section. Velocity profile for normal moveout (NMO) is picked after elevation correction. In order to keep consistency, same velocity profile is used.

   Figure 3.8 is the stack section after elevation correction and Figure 3.9 is the stack section after deformable-layer tomostatics. Generally speaking, the tomostatics offers a result with much higher level of reflection coherency (circled part). This improvement support DLT's fidelity on near-surface velocity model building.

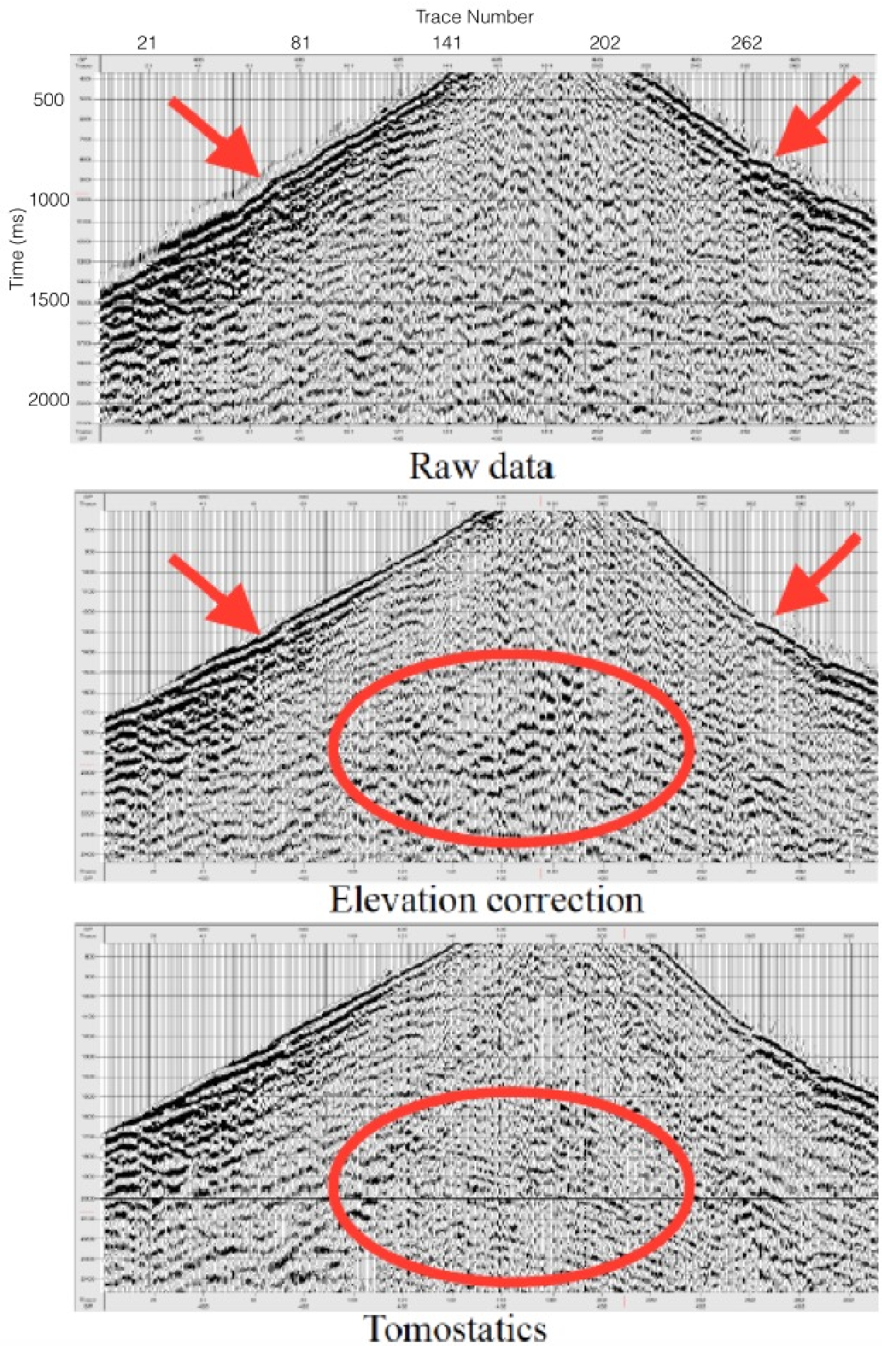

Figure 3.7: Raw data, data after elevation correction, data after deformable-layer tomostatics.

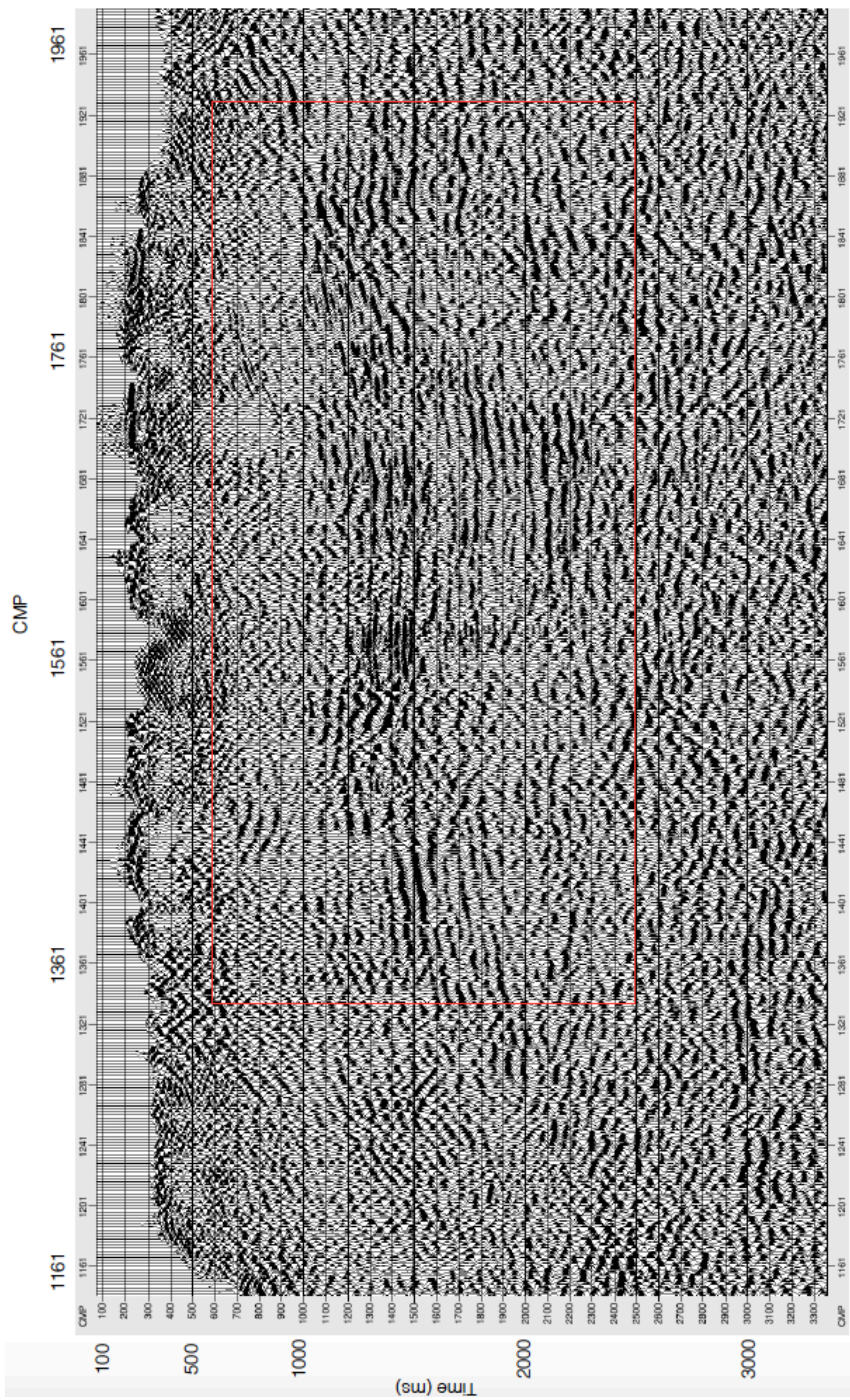

Figure 3.8: Stack section in time domain after elevation correction. CMP interval is 15 meters. Vertical axis is time in ms.

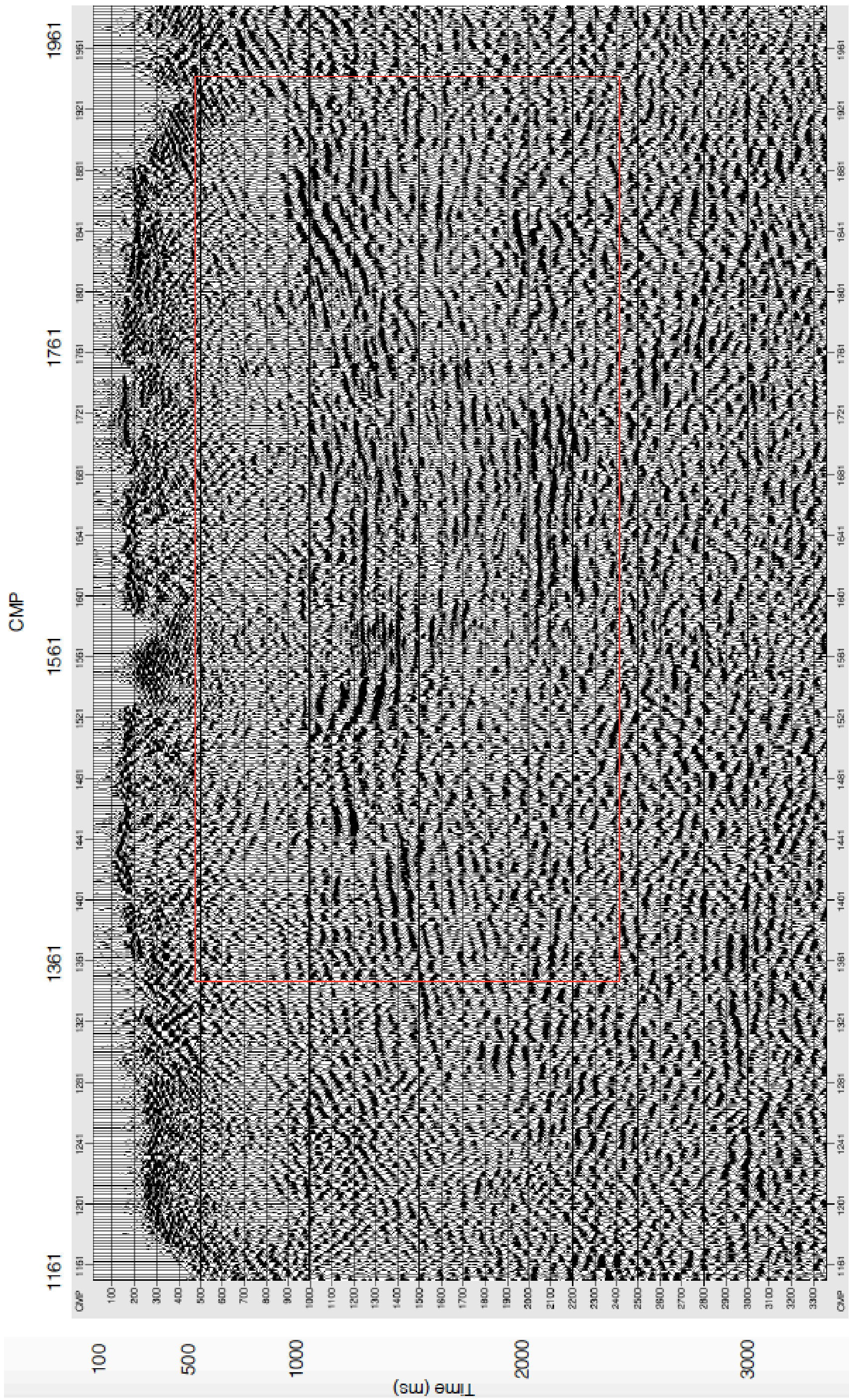

Figure 3.9: Stack section in time domain after applying deformable-layer tomostatics. CMP interval is 15 meters. Vertical axis is time in ms.

3.3 Discussions

In this section, the idea and algorithm of deformable-layer tomostatics are introduced. Then, the velocity model is built via DLT. The result of DLT is solid concerning not only the convergence of statistical measurements, but also the similarities when compared to uphole information and geological background. Static correction is thus calculated based on inverted model, and results show clear improvements both on shot gather and stack section.

The whole workflow of deformable-layer tomostatics is now complete. Several important issues need to be discussed and emphasized.

1. Bookkeeping and quality control (QC)

   Bookkeeping and QC are important throughout this process, especially for field data. In the workflow, there are several steps that requires re-number sources and receivers, or the corresponding first arrivals. It is common that these steps are followed by coordinates changes. Thus it is essential to keep consistency and QC results from time to time. Otherwise it would be extremely difficult to locate the error when dealing with field data, since most of the true information remains unknown.

2. Model parameterization of DLT

   In deformable-layer tomography, the first step is to determine the number of layers and interval velocities.

   As for interval velocities, it can be estimated from apparent velocities on shot gathers (Zhu et al., 1992), or from uphole information and so on. On top of that, some constraints may apply. For instance, Zhou et al. (2009) constrained the depth range of shallow reflectors during tomographic inversion, which shows good convergence and improved results. In this thesis, due to the low data quality which is affected by strong ground rolls, shallow reflectors are barely recognizable. Thus I determine the velocity based on apparent velocities and uphole information.

As for the number of layers, it is difficult to be determined at beginning. Increasing number of layers may represent the subsurface better, but also increases the number of unknowns for inversion. In this thesis, I did several tests on models with different number of layers. Finally, I choose the 7-layer result because it matches the uphole information best. Also, the 7-layer initial model yields better result compared to other models. After all, as long as the velocity range of layer model is close to true velocity range, different layer models are likely to yield similar results.

3. Offset range of first arrivals for DLT

   For deformable-layer tomostatics, the range of offset is an important parameter which has to be taken into consideration. The offset of turning rays indicates the depth that the ray can reach. In this thesis, I compared the offset ranges of 2.5 km, 3.5 km, 4.5 km, and full offset. Among these results, 3.5 km offset gives the best result compared to others. Geologically speaking, LVZ is relatively shallow in mountainous regions, and 3.5 km offset is long enough to ensure that the turning rays reach the high-velocity interface.

Chapter 4

Conclusions

The purpose of this thesis is to solve the static problem in the field data acquired in western Sichuan, China. I choose tomostatics as the static correction method, and deformable-layer tomography (DLT) as the tomographic velocity model building method. The static correction is then calculated from inverted velocity model and is applied to field data. Both common shot gathers and stack sections show clear improvement after deformable-layer tomostatics. The purpose is achieved at the end of this thesis.

Seismic imaging in mountainous area has been, and very likely will be, a tough problem for geophysicists. On one hand, mountainous area usually comes with extremely complicated near-surface structures, which are adverse to many basic seismic imaging assumptions. On the other hand, the acquisition of seismic data in mountainous area is difficult and challenging, and the acquired data's quality is commonly poor (e.g., low SNR and strong ground rolls) in many cases.

The field data in this thesis has many typical features as seismic data acquired in western Sichuan, where subsurface structures are commonly complex. Previews of this dataset show severe static issues. As a data-driven problem, it is important to choose a method that is capable of dealing with this specific issue. Deformable-layer tomography (Zhou, 2006), based on geologically reasonable assumption that near surface tends to be a layered structure, has been applied to many cases and yields good results. Therefore, I apply DLT to this dataset and then determine static correction values.

Before DLT velocity model building, model parameters should be determined based on direct information interpreted from field dataset. For example, velocities within shallow layers should be consistent with near-surface survey's results (e.g., uphole surveys and refraction surveys). Higher velocity values in the model should agree with the apparent velocities estimated from seismic records. These restrictions on velocity determination are critical. As for DLT, even though velocities can be updated by inversion, only interface geometry is updated. Yet the velocities within each layer are set to be unchanged. This is due to the concern that invert both velocity and interface geometry may lead to untrue results since as long as velocities are close to true earth's values, the main concern is interface geometry. Thus, I would conclude that for DLT application in this case, prior information is critical to determine model parameters.

During DLT velocity model building, specific issues needs attention concerning the purpose of static correction. For instance, offset range of first arrivals should be determined according to the depth of target zone (e.g., LVZ in this thesis). When the offset range is too short, first arrivals can not reach the target zone, while when the offset range is too long, redundant information for inversion is brought in. Another issue is ray coverage verses model depth. For tomographic inversion, velocity model has to be deep enough to avoid rays traveling on the bottom, otherwise the model's fidelity is questionable.

After DLT velocity model building, it is essential to evaluate the inverted model before further application, either in data space (e.g., average misfit and standard deviation) or model space (e.g., compared to uphole surveys and check ray coverages). Static correction is then a straightforward procedure. It is known that static correction in many cases just helps geophysicists to have an approximate understanding of subsurface structure, and precise imaging requires other techniques such as migration. Nevertheless, the quality of migration afterwards is related to the near-surface velocity values used for static correction (Zhu et al., 2008) (Liu et al., 2010). Therefore, DLT, as the velocity model building technique, is the spirit in this thesis.

The current work has shown its limitations. At this stage, the velocities within each layer is set to be constant while only interface geometry is updated. This mainly solves the long-wavelength velocity variations along the survey area. A more challenging issue is how to invert those short-wavelength variations. Waveform method may work but would suffer from complex near-surface structure and poor quality dataset. Following the idea of Dr. Zhou in the blind test (Zelt et al., 2013), I propose to work on inverting short-wavelength velocity anomalies as future work. To be specific, I would convert current DLT model into a celled model with denser layers, then invert short-wavelength geometry changes, and finally invert velocities within each cell. This comprehensive approach is believed to overcome current work's limitations and further improve DLT's result.

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