

**MIGRATION AND TOMOGRAPHIC IMAGING
OF COLLUVIAL WEDGES AND FAULTS OVER
THE WASHINGTON FAULT, ARIZONA**

by

Shengdong Liu

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THE UNIVERSITY OF UTAH GRADUATE SCHOOL

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Shengdong Liu

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Chair: Gerard T. Schuster

Richard D. Jarrard

Sherif M. Hanafy

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Date

Gerard T. Schuster
Chair: Supervisory Committee

Approved for the Major Department

Marjorie A. Chan
Chair/Director

Approved for the Graduate Council

David S. Chapman
Dean of The Graduate School

ABSTRACT

Two-dimensional (2-D) and three-dimensional (3-D) seismic surveys are conducted across the Washington fault zone, of northern Arizona, with the purpose of imaging the fault related structures to a depth of 30 m by 3-D traveltimes tomography and 2-D poststack migration. The scientific objective is to use the seismic methods instead of a trenching log to deduce the paleoseismic characters of this fault zone, and to guide paleoseismologists in the optimal placement of a future trenching survey. The first-arrival traveltimes of the data are picked and inverted for the P-wave velocity distribution. Tomographic results delineates two large low-velocity zones (LVZ), which are interpreted as two colluvial wedge packages. To detect the fault structures, the 2-D seismic data are migrated, which have more observable reflection energy than the 3-D data. Four faults are recovered in the migration image, including the main fault, and possible antithetic fault. The fault location is identical to that in the tomogram and raypath density image. The main fault in the tomogram is also consistent with the results from the geomorphology survey. These results demonstrate that seismic imaging methods (3-D traveltimes tomography and 2-D reflection imaging) can delineate the shape and depth of LVZs associated with colluvial wedges. Although these LVZ images cannot unambiguously delineate different rupture events in a colluvial package, they can be used to optimally design a follow-on trenching survey. Combining the paleoseismic data with the fault slip inferred by tomography, the age of the fault is speculatively estimated to be younger than 16 kyr. Future work should compare my interpreted tomogram with the trench log soon to be excavated by UGS personnel, and analyze the validity of my geological interpretation. This trench was designed using the results of this survey, which is partial justification for seismic surveys over normal fault scarps.

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CHAPTER 1

INTRODUCTION

1.1 Purpose and Scope

A colluvial wedge is geophysically characterized as a low-velocity zone (LVZ) surrounded by alluvial deposits, where colluvial material is deposited by the collapse of the scarp-free face after a surface earthquake rupture (Morey and Schuster, 1999). Various properties of buried colluvial wedges, such as their location, size, and organic content, can record the rupture history of a fault. To study the subsurface structures over a fault zone with seismic methods, several seismic surveys over the Wasatch and Oquirrh fault zones were carried out by University of Utah personnel, and the seismic data were processed with a travelttime tomography method to detect the LVZs; in addition, reflection processing was used to delineate the fault locations. Their results showed that seismic imaging techniques can provide deeper and wider, but less resolved images of faults and colluvial wedges than the standard excavation and logging of trenches across faults (Morey and Schuster, 1999; Sheley et al., 2003; Buddenseik et al., 2007). The purpose of this thesis research is to reconstruct the shallow fault structures and colluvial wedges ($0 < Z < 30$ m) along a portion of the Washington fault zone, northern Arizona, with 2-D and 3-D seismic imaging techniques. These results are now used to guide the optimal placement of a soon-to-be excavated paleoseismic trench along the Washington fault.

1.2 Site Geology

The Washington fault zone lies along the western margin of the Colorado Plateau, extending northward from the Shivwits Plateau in Arizona into the St. George basin

of southwestern Utah. Southwestern Utah and northwestern Arizona are within the intermountain seismic belt of North America, a tectonically active area with several faults that could generate large earthquakes. The Washington fault is a relatively active normal fault in this region, although it has not experienced any earthquakes of magnitude larger than 6.5. However, geological studies indicate that faults in the region could produce earthquakes of magnitude 7 to 7.5 (Arabasz et al., 1992), which is of strong concern to the residents of the rapidly growing population center of St. George, Utah. The most recent large earthquake was a magnitude 5.8 event on September 1992, with the epicenter located in the Washington Dome quadrangle (Pechmann et al., 1995). The Washington fault is estimated to be 10,000 -25,000 years old based on evidence from soil profiles exposed in trenches in the area west of Warner Ridge (Earth Science Associates, 1982), and the dip of the Washington fault varies from 80 degrees west to nearly vertical (Higgins. 1998).

1.3 Organization of the Thesis

This thesis, is organized into five sections. Section 1 is the introduction and Section 2 provides details about data acquisition and processing. The third and fourth sections present the results of synthetic tests and field data processing, respectively. The final section contains the conclusions.

CHAPTER 2

SEISMIC SURVEYS AND PROCESSING METHODS

This section describes the acquisition parameters and geometry of the 2-D and 3-D seismic experiments conducted across the Washington fault scarp in northern Arizona. The data processing methods (traveltime tomography, reflection stacking and poststack migration) are briefly explained.

2.1 Seismic Surveys

2.1.1 2-D Seismic Survey

In March 2008, UTAM researchers carried out a 2-D high resolution seismic survey perpendicular to the Washington fault scarp near the Arizona-Utah border. Figure 2.1 shows the seismic survey site and the proposed trench site. The 2-D seismic data were collected using 96 vertical-component geophones spaced 1 m apart for a total line length of 95 m. Figure 2.2 shows the source and receiver lines, and the fault strike direction. Seismic sources, using a 16-lb sledgehammer striking a small metal plate, were initiated at every second geophone and stacked five times for each hammer (i.e., shot) position to improve the signal-to-noise ratio of each record. Recording of traces was carried out with a 120-channel Bison data recorder. Table 2.1 summarizes the acquisition and source-receiver parameters of the 2-D and 3-D seismic surveys.

2.1.2 3-D Seismic Survey

A 3-D seismic survey was carried out at the same location as the 2-D survey in October 2008 in order to obtain higher resolution images of the subsurface. The

Table 2.1. Parameters for the 2-D and 3-D seismic surveys.

Survey	2-D	3-D
Source	16-lb sledgehammer	10-lb sledgehammer
Recording instruments	one 120-channel BISON	two 120-channel BISONs
No. of shots	48	40/line (6 lines)
No. of receivers	96	80/line (6 lines)
Shot spacing	2 m	(Figure 2.3)
Receiver spacing	1 m	(Figure 2.3)
Survey length	95 m	119 m
No. of traces	4,608	115,200
Sampling interval	0.25 ms	0.25 ms
Record length	1.0 sec	1.0 sec

3-D acquisition geometry consisted of six parallel lines, where there were 80 in-line receivers with a 1 m spacing near the fault scarp and a 2 m spacing far away from the fault scarp. The cross-line spacing was 1.5 m. Shots were also activated at every other geophone, and the experiment geometry is shown in Figure 2.3.

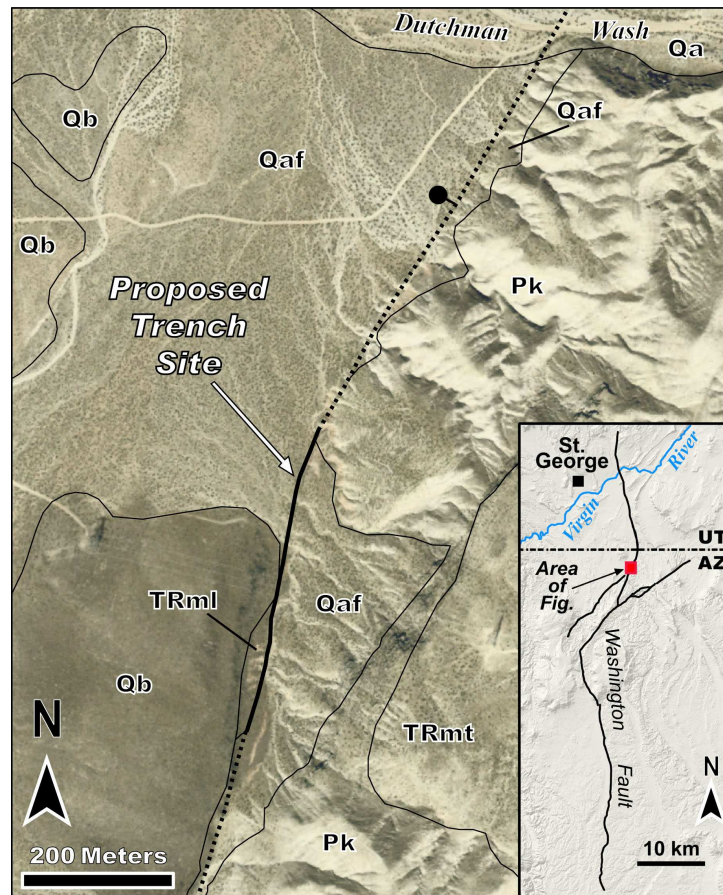


Figure 2.1. The map of the Washington fault and the survey site. The location of the survey site is 5 km south of the Utah-Arizona border. A trench will be excavated by UGS personnel in the same location, marked on the map, sometime in the late spring of 2009.



Figure 2.2. View of the Washington fault scarp and 2-D seismic survey line. The yellow line represents the fault strike direction, and the green line represents the 2-D seismic survey line.

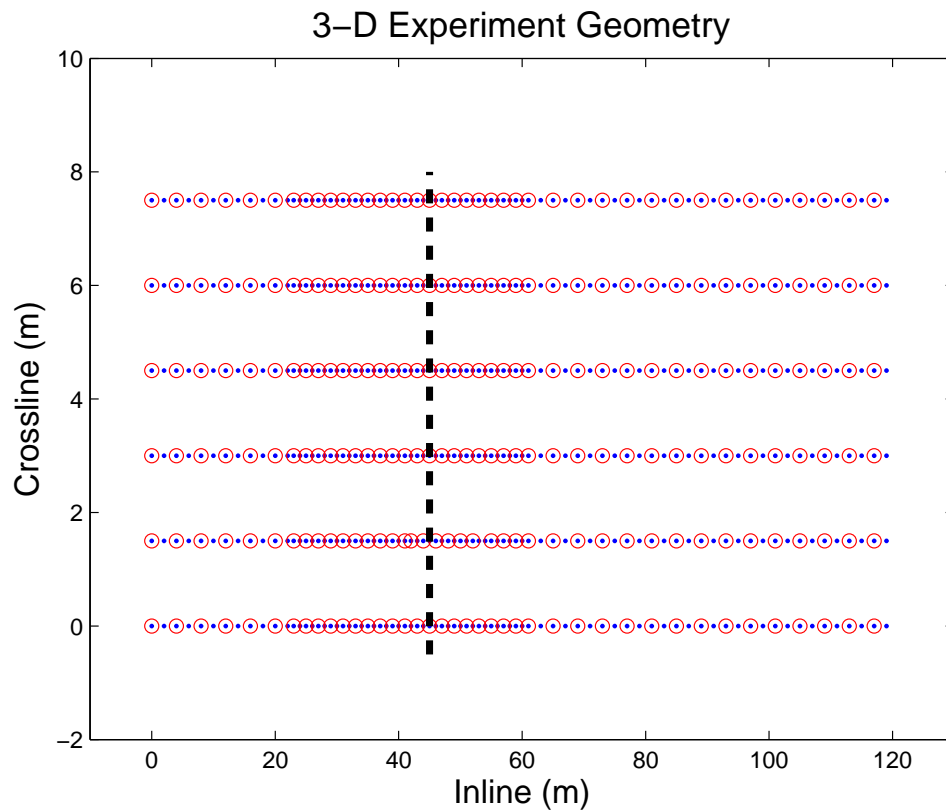


Figure 2.3. Survey geometry for the 3-D experiment. The open circles denote the locations of sources, the solid dots denote the locations of receivers, and the dashed black line denotes the location of the fault scarp. The crossline spacing is 1.5 m, the inline spacing of coarsely spaced receivers (far from the fault scarp) is 2 m, and that of finely spaced receivers (near the fault scarp) is 1 m. The sources are activated at every other receiver.

2.2 Traveltime Tomography

2.2.1 Methodology

Traveltime tomography is a standard methodology for reconstructing the subsurface velocity distribution from first-arrival traveltimes (Nolet, 1987; Lutter et al., 1990; Aldridge and Oldenburg, 1993; Ammon and Vidale, 1993; Nemeth et al., 1997 and many others), where velocities are updated by an iterative method such as the SIRT technique (Gilbert, 1972). The tomography method consists of a number of steps. First, an initial velocity model is estimated from the x-t slope of the first-arrival in the seismograms. The traveltimes are then computed from the starting model by a finite-difference solution to the eikonal equation (Qin et al., 1992). In this case, the data misfit function can be defined as:

$$\epsilon = \frac{1}{2} \sum_i (t_i^{obs} - t_i^{cal})^2, \quad (2.1)$$

where the summation is over the i_{th} raypaths, t_i^{obs} is the associated first-arrival traveltime pick, and t_i^{cal} is the calculated traveltime. The j_{th} gradient γ_j of the misfit function is defined as:

$$\gamma_j = \frac{\delta\epsilon}{\delta s_j} = \sum_i \delta t_i \frac{\delta t_i}{\delta s_j} = \sum_i \delta t_i l_{ij}, \quad (2.2)$$

where δt_i is the traveltime residual, δs_j is the slowness in the j_{th} cell and l_{ij} is the segment length of the i_{th} ray that visits the j_{th} cell. The slowness model is iteratively updated by a gradient optimization method (e.g., steepest descent).

2.2.2 Traveltime Picking and Quality Control

The first step in tomography processing is to pick first-arrival traveltimes. Approximately 4,608 and 115,200 traveltimes are picked, respectively, from the original 2-D and 3-D Washington fault data using ProMAX software. A shot gather of the 2-D data with the picked first-arrival traveltime is shown in Figure 2.4.

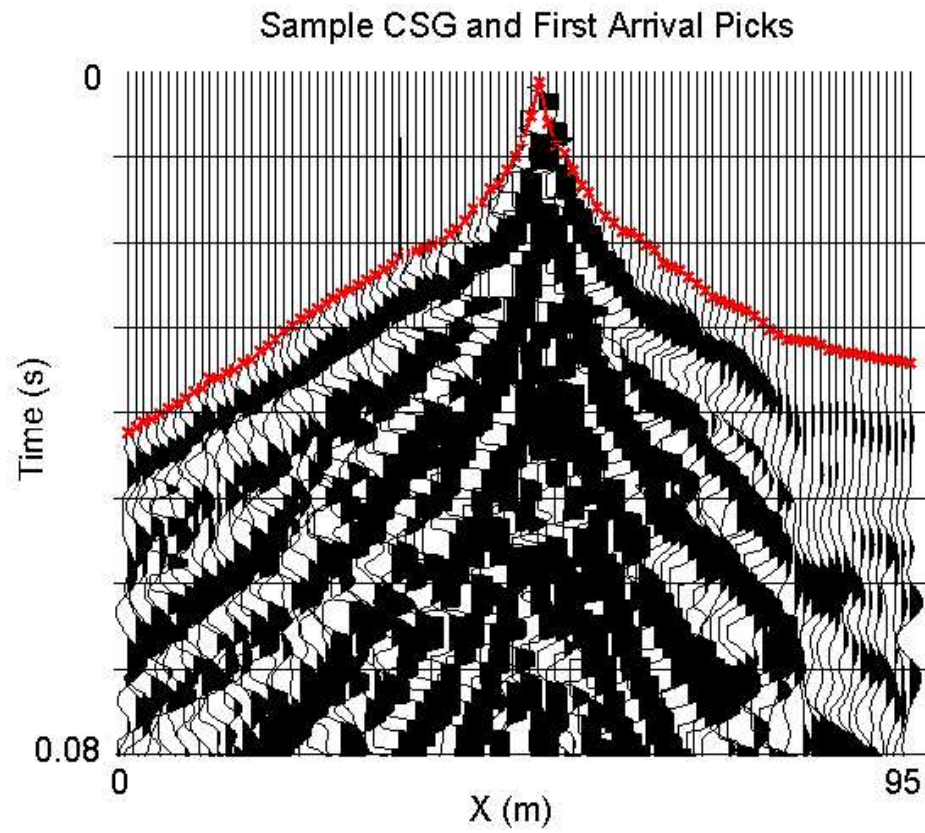


Figure 2.4. A common shot gather from 2-D Washington fault data set and first-arrival traveltimes are denoted by the red star.

Before computing the traveltime tomogram, a quality control of the traveltime picks is required for a reliable inversion. An important method for the quality control of traveltime picks is a reciprocity test. For traveltime pairs t_{ij} and t_{ji} , where t_{ij} represents the first-arrival traveltime pick for a source at the i th position and a receiver at the j th position, and t_{ji} represents the reciprocal traveltime pick of t_{ij} , if the reciprocity condition $t_{ij} = t_{ji}$ is not satisfied to within a tolerance of 3 milliseconds, the traveltime pairs are rejected. For the 3-D data, 29,750 traveltime picks are rejected by failing the reciprocity test. The remaining traveltimes are inverted using the SIRT algorithm described in 2.2.1.

2.2.3 Smoothing Filter

Due to irregular raypath coverage in some parts of the velocity model, a rectangular smoothing filter is applied after each iteration in the inversion process (Nemeth et al., 1997). Table 2.2 gives a listing of smoothing schedules for the synthetic data and field data in this paper. The reconstructed velocity model is initially smoothed with a 10 m x 5 m x 5 m smoothing filter. After six iterations the smoothing filter size is halved, which results in a better spatial resolution. The final smoothing filter is iteratively reduced to a volume of 2 m x 1 m x 1 m.

Table 2.2. Smoothing schedule for synthetic and field data. The smoothing sizes are given in number of cells. The iteration number is 6 for each schedule.

Experiment	2-D synthetic test	3-D synthetic test	2-D actual data	3-D actual data
Grid size	0.5 m	0.5 m	0.5 m	0.5 m
No. of effective unknowns	4,800	72,000	4,800	72,000
No. of traveltimes	3,200	115,200	2,687	85,450
Smoothing size 1	20 x 10	20 x 10 x 10	20 x 10	20 x 10 x 10
Smoothing size 2	12 x 6	12 x 6 x 6	12 x 6	12 x 6 x 6
Smoothing size 3	8 x 4	8 x 4 x 4	8 x 4	8 x 4 x 4
Smoothing size 4	4 x 2	4 x 2 x 2	4 x 2	4 x 2 x 2

2.3 2-D CDP Reflection Processing

The goal of common depth point (CDP) reflection processing is to transform the seismic reflection data into an approximate reflectivity image of the subsurface. Because near-surface scattering, statics, and surface waves are dominant in the shallow seismic data, the following processing flow (Figure 2.5) is required to obtain reflectivity images (Yilmaz, 1987).

2.3.1 Data Sorting and Geometry Defining

The first step in CDP data processing is to convert the data format from Bison seismograph format to SEG-Y format so processing can be performed with Pro-MAX. Then the survey geometry is defined according to the field survey, including the shot and receiver locations, shot and receiver offsets, CDP locations, and other known parameters that affect the data processing.

2.3.2 Elevation Statics

The statics problem is defined to be static time shifts introduced into the traces by, e.g., near-surface velocity anomalies and/or topography. These time shifts distort the true geometry of deep reflectors. For the Washington experiment, large static time shifts are introduced by the large elevation changes in the topography. Thus, an elevation statics correction is applied to the data, so that the data appear to have been collected on a flat datum plane. The final datum elevation is the same as the highest topographic point, and the replacement velocity is 500 m/s for correcting the traces to the new datum.

2.3.3 Bandpass Filter

To remove the low-frequency noise (such as surface waves), 40-200 Hz bandpass filtering was applied to the traces. The low frequency surface waves are mostly suppressed by this filter.

2.3.4 NMO and Stacked Section

The seismic data are sort into 190 common midpoint gathers (CMG) with 0.5 meter spacing. Two or three near zero-offset traces of each CMG were selected for stacking.

2.3.5 Poststack Migration

In order to move dipping reflectors into their correct positions and collapse diffractions, poststack migration was applied to the stacked data, where the maximum dip angle is limited to be no more than 30 degrees. The migration method selected was Kirchhoff migration.

Processing Flow

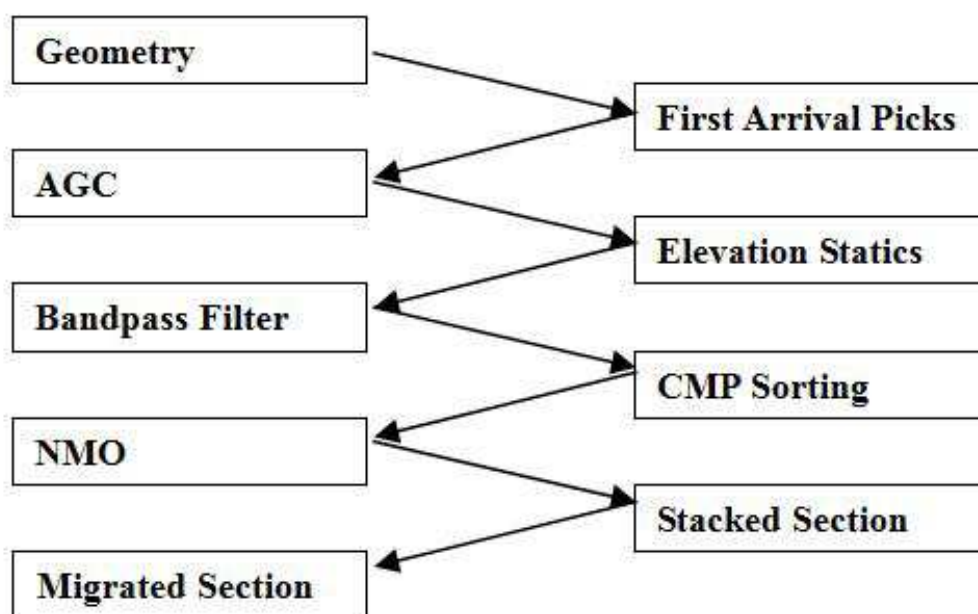


Figure 2.5. Chart for reflection processing of the 2-D Washington fault data set. Here, AGC = automatic gain control, NMO = normal moveout correction, CMP = common midpoint.

CHAPTER 3

NUMERICAL RESULTS FOR SYNTHETIC DATA

The migration and tomographic images for synthetic data are presented. The results suggest that the faults and LVZs can be clearly imaged by seismic methods, and 3-D tomograms are more accurate and have fewer artifacts than 2-D tomograms in delineating fault structures.

3.1 Traveltime Tomography of the Synthetic Data

To understand the sensitivity of the tomography method in delineating fault structures, both 2-D and 3-D synthetic tests are carried out. The input model is a 3-D fault model, and has the same dimension as the area investigated with the 3-D Washington fault experiment. The model was constructed by defining the background velocity to be similar to that of the actual 3-D Washington fault tomogram. The velocity at the ground surface is defined to be 500 m/s and the vertical velocity gradient is assigned as 110 m/s/m, and the depth of bedrock is about 15 m below the surface with the velocity 2400 m/s. There is no variation of velocity in the Y direction. An X-Z velocity slice of the fault model is shown in Figure 3.1a. The source and receiver geometry for the synthetic test are identical to that of the 3-D Washington fault experiment, shown in Figure 2.3. Approximately 115,200 first-arrival traveltimes are generated by solving the 3-D eikonal equation with a finite-difference method (Qin et al. 1992), and the traveltimes taken from the 1st source line and receiver line ($Y=0$ m) are used for 2-D traveltime inversion. Table 2.1 summarizes the model and acquisition parameters for the synthetic tests.

Table 3.1. Model and acquisition parameters for the synthetic tests.

Survey	2-D	3-D
Model size	117 m x 30 m	117 m x 7.5 m x 30 m
Grid size	0.5 m	0.5 m
No. of shots	40	40 x 6
No. of receivers	80	80 x 6
Shot/receiver spacing	(Figure 2.3)	(Figure 2.3)
Survey length	117 m	117 m
No. of traveltimes	3,200	115,200

The first-arrival traveltimes are inverted to obtain the P-wave velocity distribution, and a gradient model with velocities ranging from 500 m/s at shallow depths to 2,400 m/s at depth are used for the initial model. The reconstructed velocity model is initially smoothed with a 10 m x 5 m x 5 m smoothing filter, and the smoothing filter is iteratively reduced to a volume of 2 m x 1 m x 1 m. Table 2.2 gives the inversion and smoothing filter parameters (Nemeth et al., 1997).

A comparison between the 2-D and 3-D tomograms is shown in Figures 3.1b and 3.1c. Both of the tomograms are along the 1st receiver line ($Y=0$ m), and the images obtained from 2-D and 3-D tomography are comparable at low wavenumbers. The fault surfaces in the model are characterized by a smooth down drop of the velocity contours in both of the tomograms. This is not surprising since previous studies (Buddenseik, et al., 2007) empirically showed that the tomogram is a smoothed version of the actual velocity, where faults are characterized by a smooth downdrop in tomographic velocities. Another observation is that the 3-D tomogram seems to have fewer artifacts than the 2-D tomogram. This should not be too surprising because rays in the the 3-D survey are characterized by a greater diversity of ray angles, which leads to better model resolution. In addition, the ratio of unknowns to traveltime equations (see Table 2.2) is smaller for the 3-D tomogram and suggests a more stable and overdetermined solution. In Figure 3.2, the velocity and gradient profiles at $X=26$ m (Fault 1), $X=48$ m (Fault 2) and $X=74$ m (Fault 3) are compared. The faults are identified as large positive gradient values of velocity,

and the fault structures delineated in the 3-D tomogram are more accurate than those in the 2-D tomograms. Figure 3.1d depicts the 2-D raypath density image, which displays the number of rays visiting each cell of the tomogram. For the normal-slip fault (F1, F2 and F3), the rays focus near the fault plane, which results in fewer raypaths visiting the hanging wall side, and the LVZ ($48 \text{ m} < X < 75 \text{ m}$) has lower raypath coverage than other regions.

To assess the convergence of the iterative solution, a plot of RMS traveltimes residual vs. iteration number is shown in Figure 3.3. It demonstrates that the iterative solutions converge within ten iterations. The final traveltimes residual is about 0.3 ms, which is close to 0, since no picking errors are added.

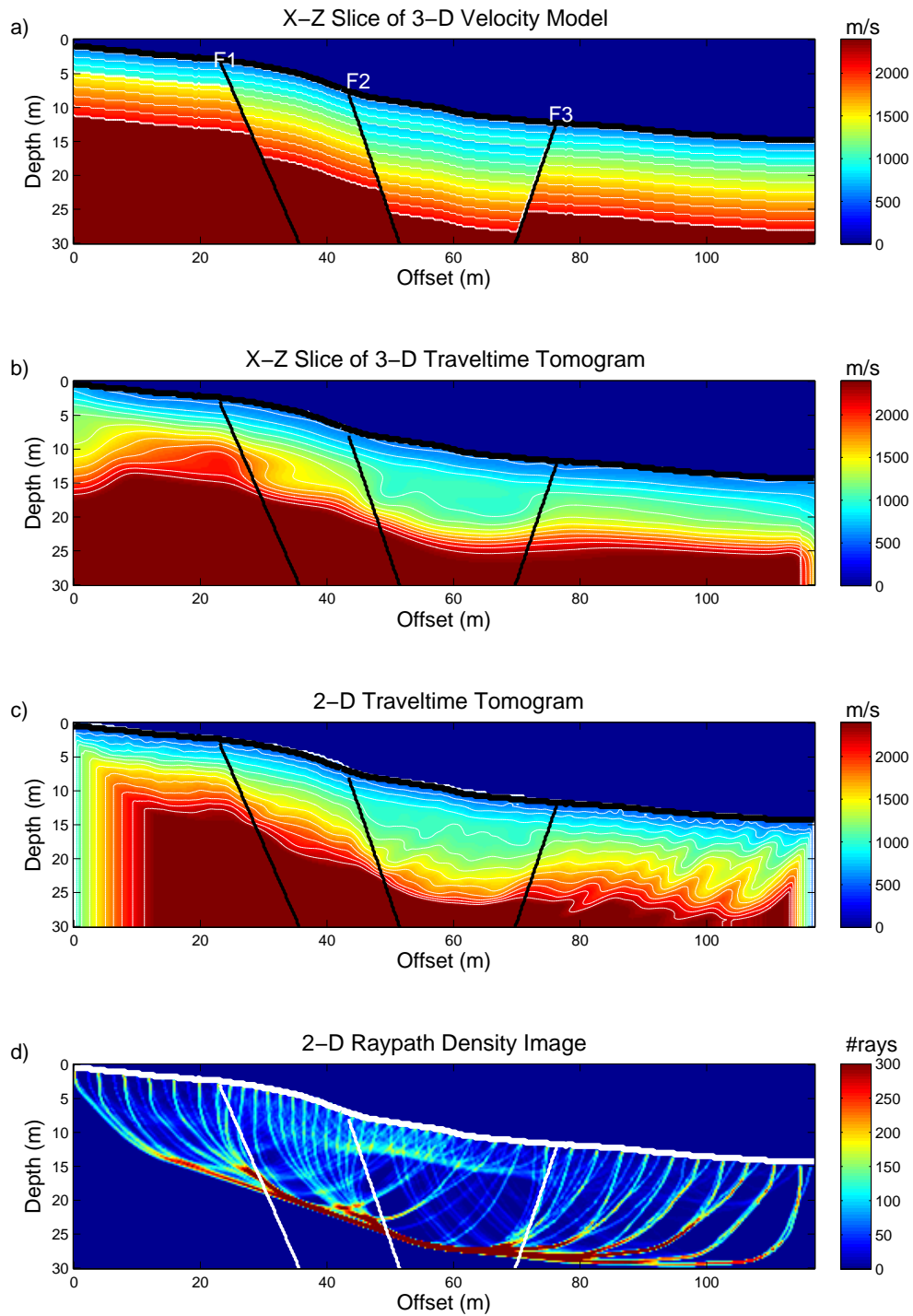


Figure 3.1. Results of 2-D and 3-D traveltimes tomography test. a): an X-Z slice of the linear gradient velocity model with 3 normal faults. b): an X-Z slice of the 3-D tomogram along the first receiver line ($Y = 0$ m). c): 2-D traveltimes tomogram along the first receiver line ($Y = 0$ m). d): raypath density image obtained from 2-D traveltimes inversion.

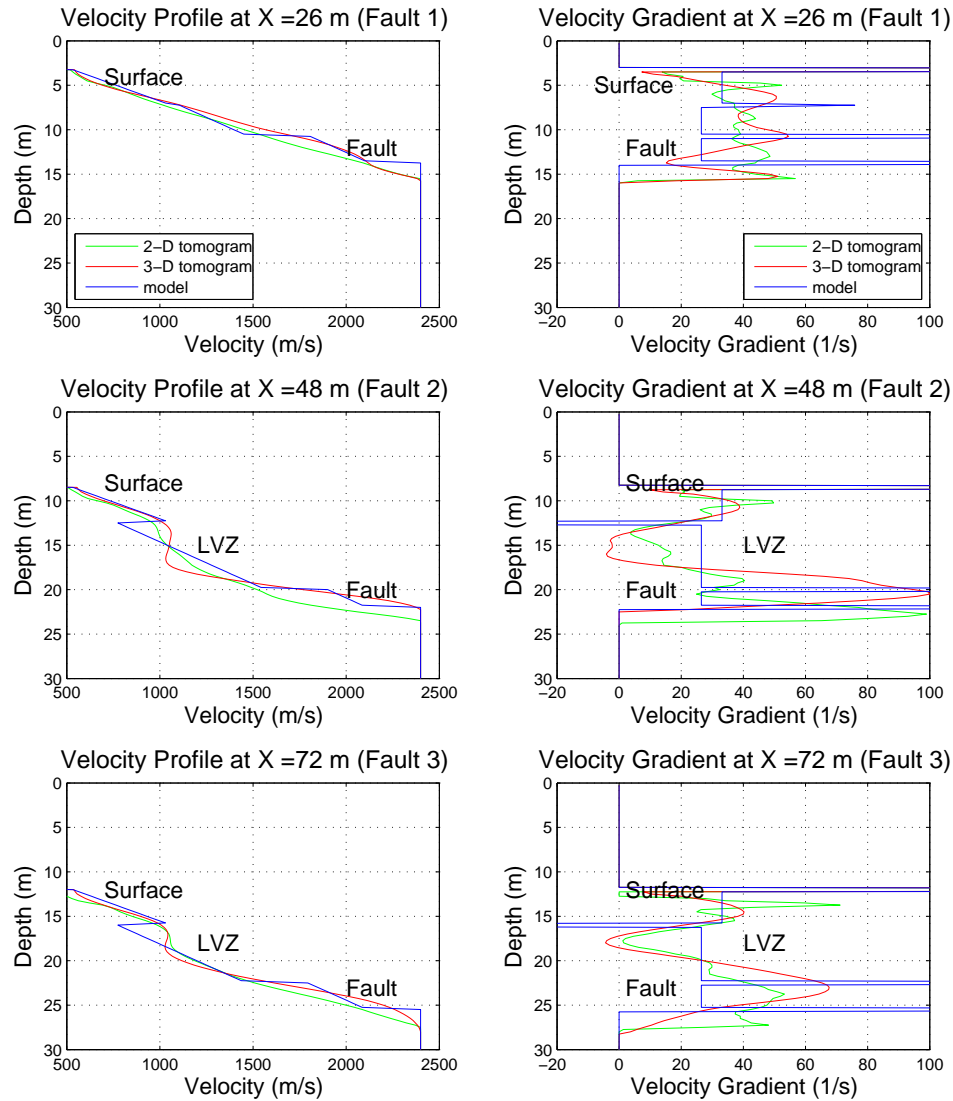


Figure 3.2. Velocity and gradient profile comparison at 3 different locations for the synthetic test. Left panels are the velocity profiles, and right panels are the velocity gradient profiles. In the velocity gradient profiles, the faults are identified by large positive gradient values and LVZs are identified by large negative gradient values.

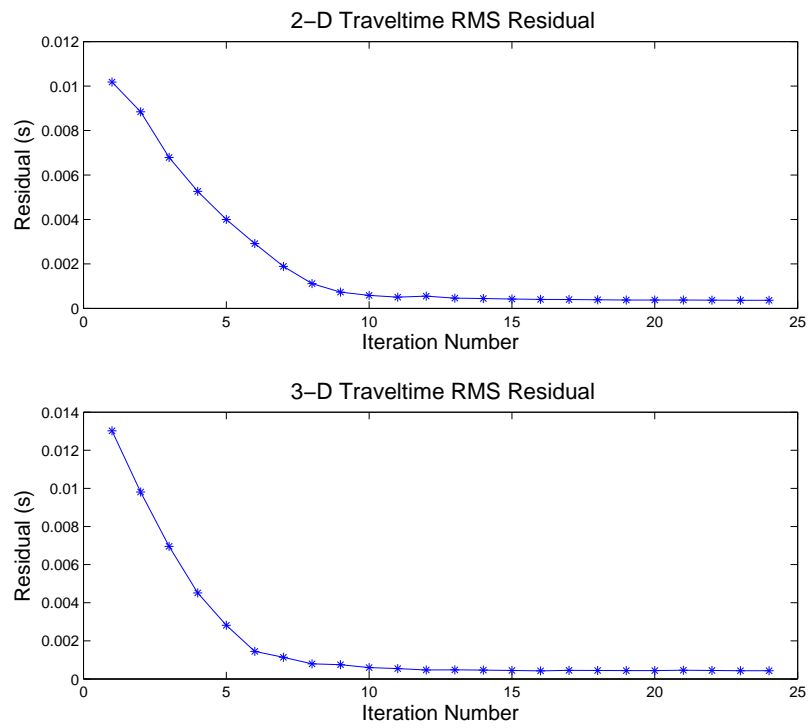


Figure 3.3. 2-D and 3-D RMS traveltime residual vs. iteration number. The iterative solutions converge after about ten iterations. The final traveltime residual is about 0.3 ms, which is close to 0, since no picking errors are added.

3.2 CDP Reflection Processing of the Synthetic Data

To locate the fault positions, CDP reflection processing is carried out. The velocity model is the same as the 2-D model in Section 3.1, and Figure 3.4a shows the reflectivity image computed from the velocity model. To make the processing simple, the sources and receivers are distributed evenly at 1 m spacing for a total line length of 117 m. A 2-4 finite-difference solution to the acoustic wave equation is used to generate the zero-offset seismograms, and Table 3.2 gives the model and acquisition parameters for the synthetic tests. Figure 3.4b shows the stacked seismic section with the horizontal axis in offset and the vertical axis in time. Figures 3.4c and 3.4d show the migration images using the true velocity and the velocity obtained from the tomogram, respectively. Although there are some artifacts in the migration image using the tomographic velocity, where the layers around $X < 15$ m are tilted and the layers around $X > 90$ m undulate, the fault locations are clearly identified with the correct dip angles.

Table 3.2. Model and acquisition parameters for the synthetic tests.

Model size	117 m x 30 m
Grid size	0.25 m
No. of shots	118
No. of receivers	118
Shot/receiver spacing	1 m
Source	100 Hz Ricker wavelet
Recording length	0.2 s
Sampling interval	0.02 ms

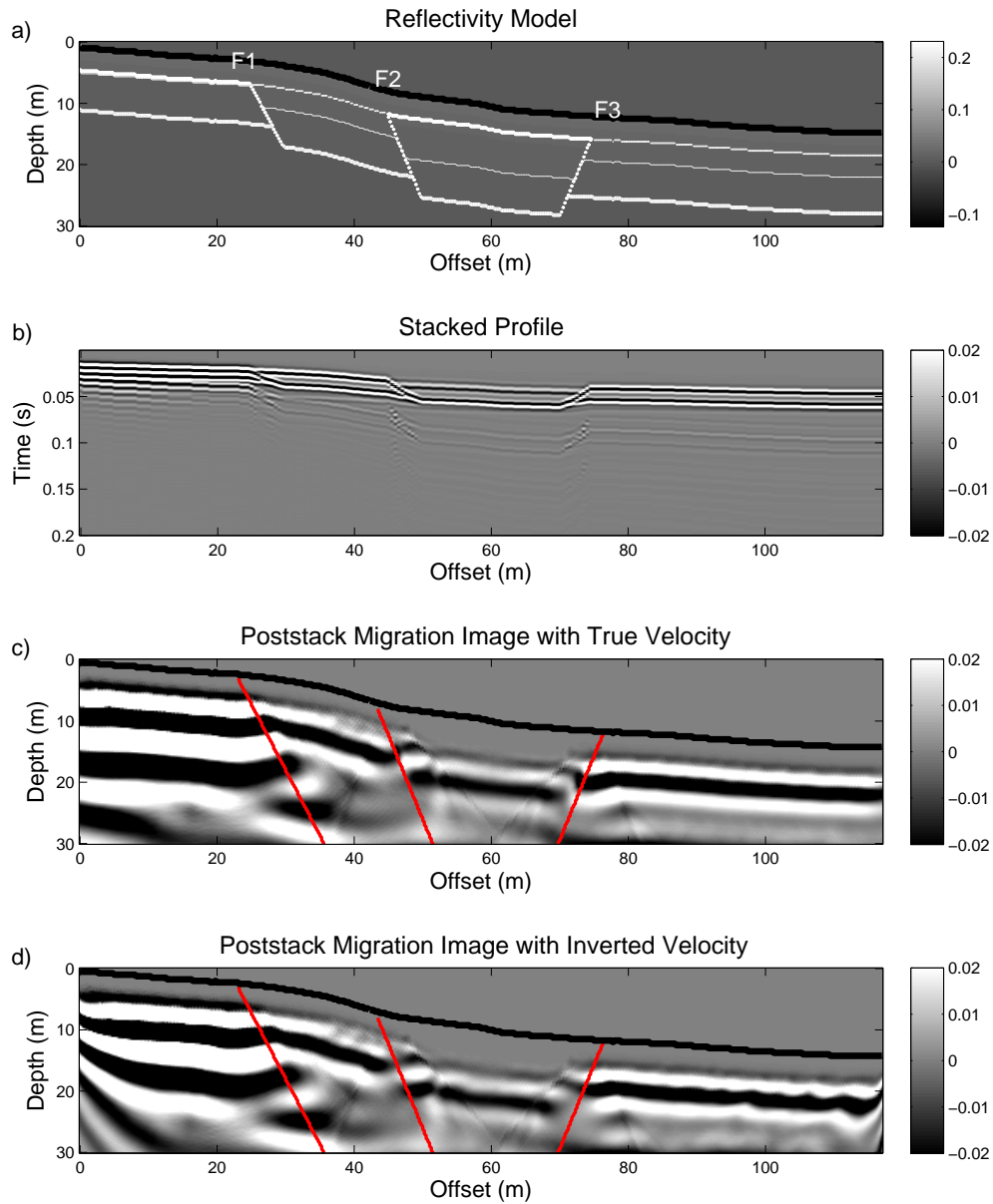


Figure 3.4. Stack and migration images. (a): the reflectivity image computed from the velocity model. (b): the stacked seismic section with the horizontal axis in offset and the vertical axis in time. (c): the migration images using the true velocity. (d): the migration images using the inverted velocity from tomography.

CHAPTER 4

NUMERICAL RESULTS FOR FIELD DATA

The 2-D and 3-D tomographic results and the 2-D migration images are computed for data recorded from the Washington fault experiment and analyzed in this section. My interpretation suggests that there are four faults and two large LVZs. These LVZs are likely to be colluvial wedge packages, as they appear to be associated with the faulting.

4.1 Tomographic Results

4.1.1 2-D Tomographic Results

One 2-D survey line is taken from the original 3-D data. The first-arrival traveltimes are picked from 3,200 traces, where 513 traveltime picks were rejected because they did not satisfy the reciprocity condition within a tolerance of 3 milliseconds. The remaining traveltimes are inverted to obtain the P-wave velocity distribution. Figure 4.1a depicts the velocity tomogram presented as contours of seismic velocity in depth along the profile, and Figure 4.1b displays the raypath density through each cell in the tomogram. Based on the synthetic tests in section 3.1, two criteria are used to identify a fault in the tomogram: (1) Focusing of rays in the raypath density image (the fault is not exactly located at the greatest raypath density area, but is located at the low-density side near the plane, (see Figure 3.1). (2) a sharp change in the velocity gradient (see Figure 3.2). Combining the tomogram, velocity gradient profile, raypath density distribution and migration image (discussed in Section 4.2) together, four faults are interpreted, numbered from F1 to F4. Four LVZs are outlined with ellipses in the traveltime tomogram. In the raypath density, the LVZs correspond to the zones of low raypath density,

marked with ellipses as well. A plot of RMS traveltimes residual vs. iteration number is shown in Figure 4.2. The final RMS traveltimes residual is about 2.4 ms, which is slightly smaller than the estimated picking error of 3 ms.

4.1.2 3-D Tomographic Results

The first-arrival traveltimes are picked from 115200 traces in the original data set, where 29750 traveltimes picks are rejected because they failed the reciprocity test or were deemed unpickable. The 3-D velocity tomogram is inverted from these picks and is shown in Figure 4.3. Four X-Z slices spaced every 2 m along the Y direction are shown in Figure 4.4. This tomogram clearly delineates three large LVZs. The one denoted as LVZ1 is located at X=20-35 m, LVZ2 is located at about X=50-65 m, and LVZ3 is located along the near surface at X= 35-65 m. All of the LVZs are parallel to the fault scarp. The main fault (F3, see Figure 4.8) interpreted from the migration image and the raypath density image, is located at the offset of 45 m, and suggests that LVZ2 is possibly the colluvial wedge generated by surface rupture events on the Washington fault. The LVZ 3 is possibly another colluvial wedge package and is the youngest of the LVZs. Comparing the 2-D tomogram with the 3-D tomogram, both have similar structures at low wavenumbers; but, the 3-D tomogram has fewer artifacts than the 2-D tomogram. To assess the accuracy of the predicted traveltimes, a plot of RMS traveltimes residual vs. iteration number is shown in Figure 4.5. The final RMS traveltimes residual is about 3.2 ms, which is almost the same as the estimated picking error of 3 ms.

4.2 Reflection Results

The 3-D Washington fault data has less observable reflection energy seen in the seismogram. This is because only a 10-lb sledgehammer was used in the 3-D experiment compared to the 16-lb sledgehammer in the 2-D experiment; and the 2-D experiment had a shorter survey length. Here, only the 2-D seismic data are used for reflection stacking. The common shot gathers (CSG) are sorted into 190 common midpoint gathers (CMG) with 0.5 meter spacing, and two or three

near zero-offset traces of each CMG were selected for stacking. Figure 4.6 shows the stacked seismic section with the horizontal axis in offset and the vertical axis in time. It shows more than two shallow horizons, which are mostly continuous, except for the region around $X = 14$ m. From the stacked profile, it is difficult to determine the locations of the fault planes. To delineate the fault structures clearly, the stacked data are migrated. Figure 4.7 shows the final migration image, and using the migration images of the synthetic data as a guide, the layered horizons are discontinuous at the fault plane. Here, four faults (F1-F4) are interpreted, combined with the tomogram and raypath density image, where F3 is possibly the main fault, and F4 is the antithetic fault. The dip angles of the four faults are estimated from the migration image to be about 80 ± 10 degree. This is consistent with the description of the Washington fault by Higgins, 1998.

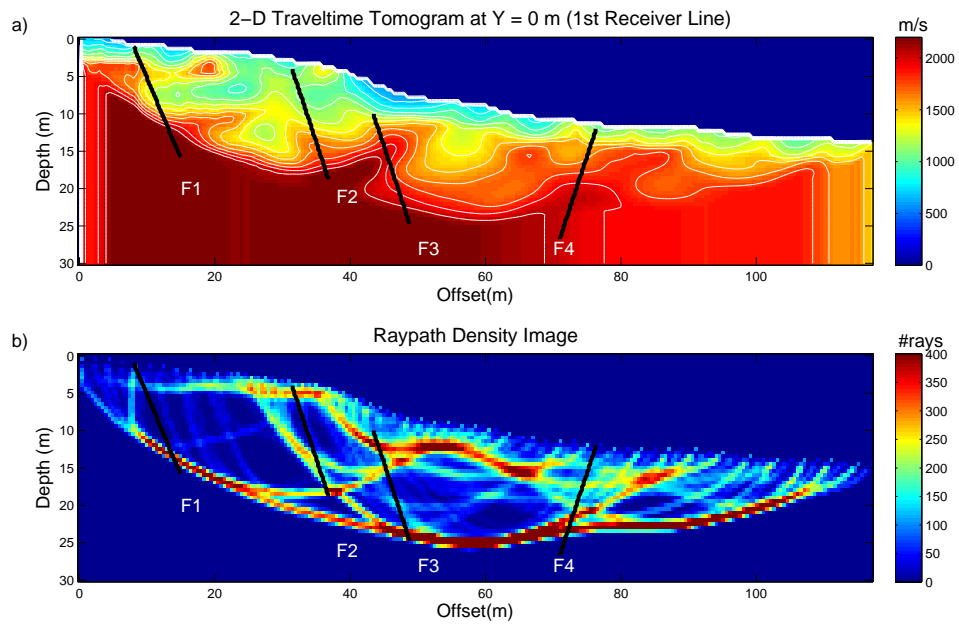


Figure 4.1. 2-D traveltime tomogram and raypath density image. (a): the 2-D traveltime tomogram with the fault interpretation. (b): the raypath density image.

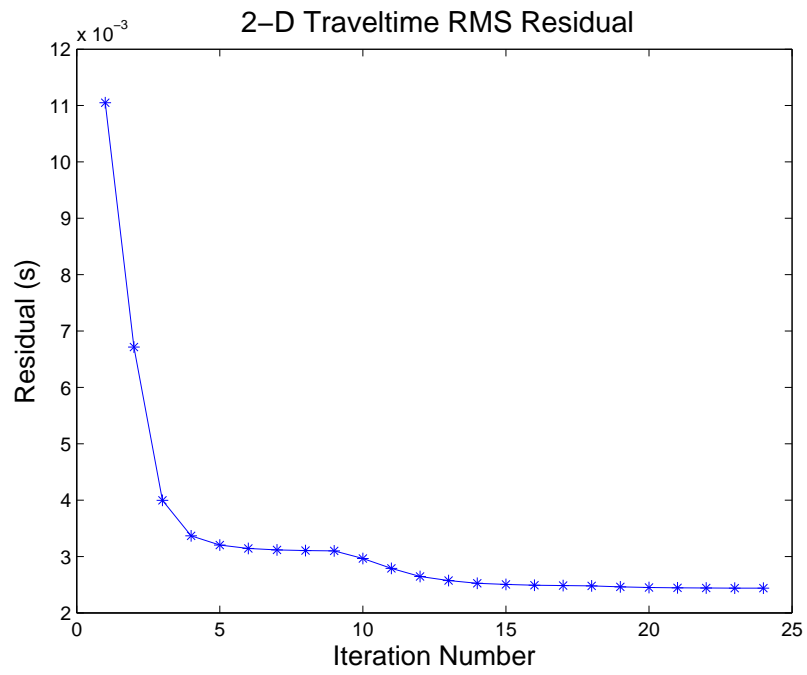


Figure 4.2. RMS traveltime residual vs. iteration number. The solution converges after about twenty iterations, and final RMS traveltime residual is about 2.4 ms.

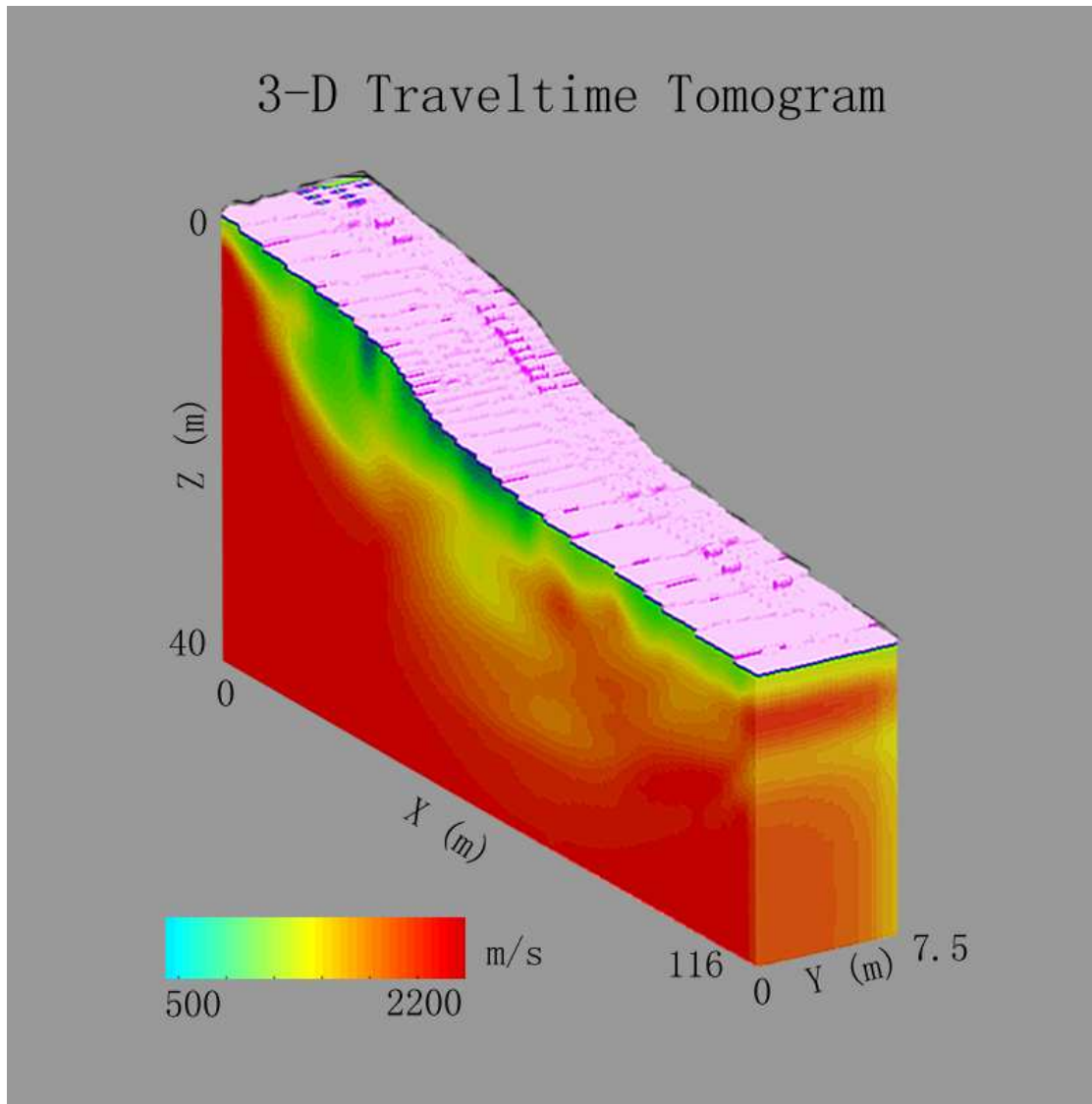


Figure 4.3. The volume of the 3-D velocity tomogram. Two large LVZs are clearly delineated in the tomogram.

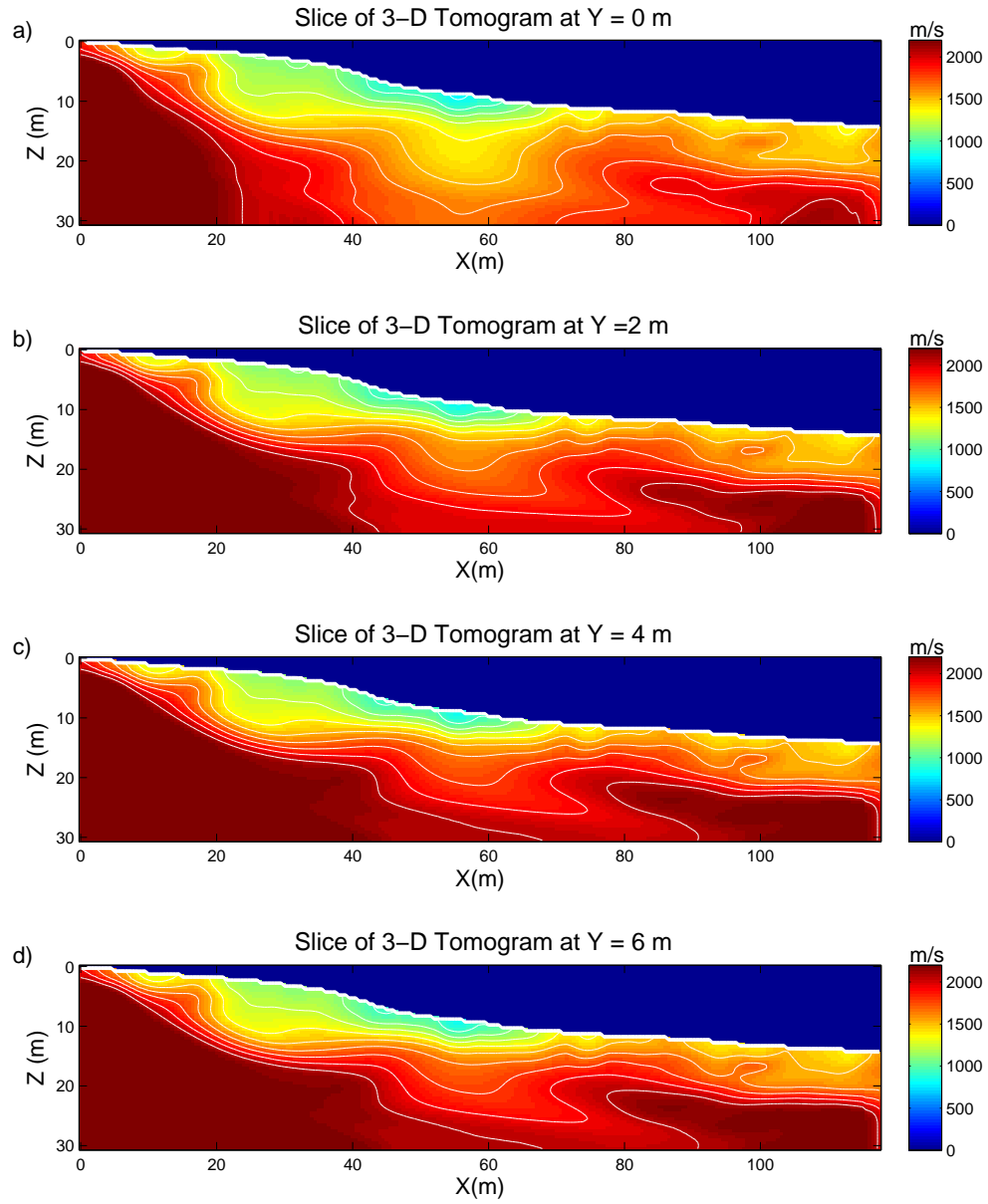


Figure 4.4. X-Z slice of 3-D velocity tomogram. (a): slice at $Y = 0$ m. (b): slice at $Y = 2$ m. (c): slice at $Y = 4$ m. (d): slice at $Y = 6$ m.

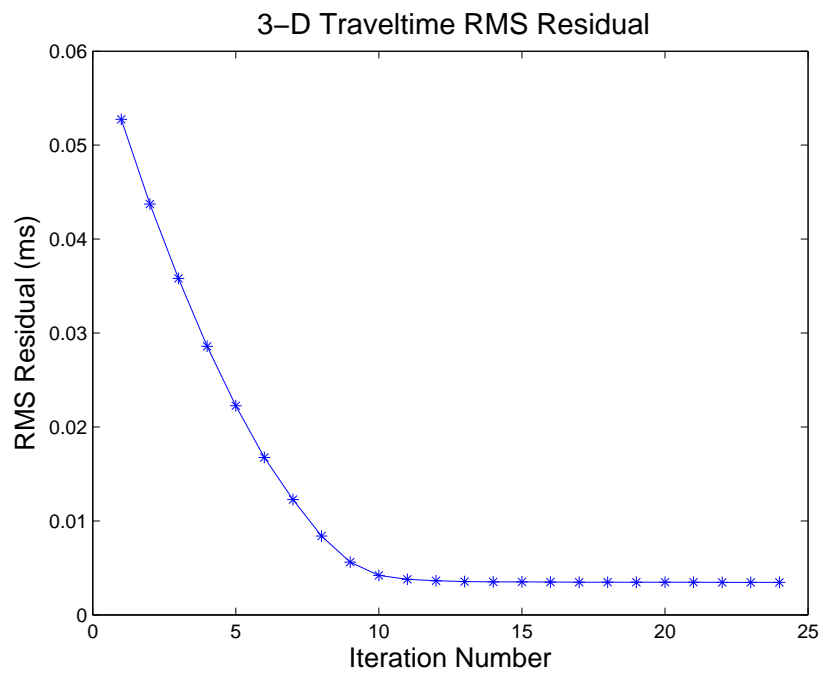


Figure 4.5. RMS traveltime residual vs. iteration number. The solution converges after about fifteen iterations, and the final traveltime residual is about 3.2 ms.

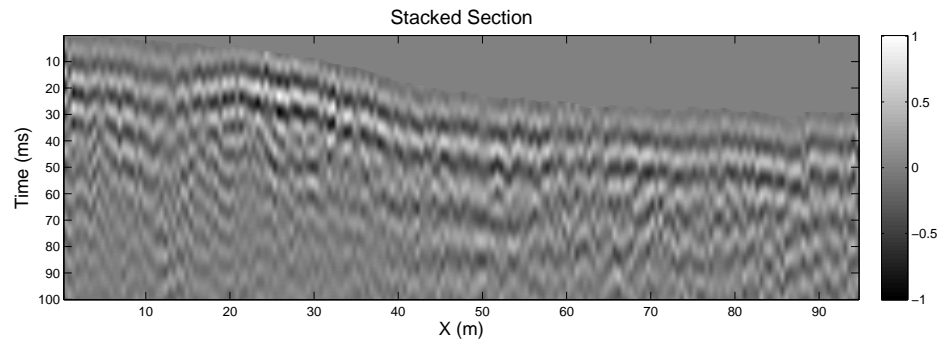


Figure 4.6. Stacked seismic section.

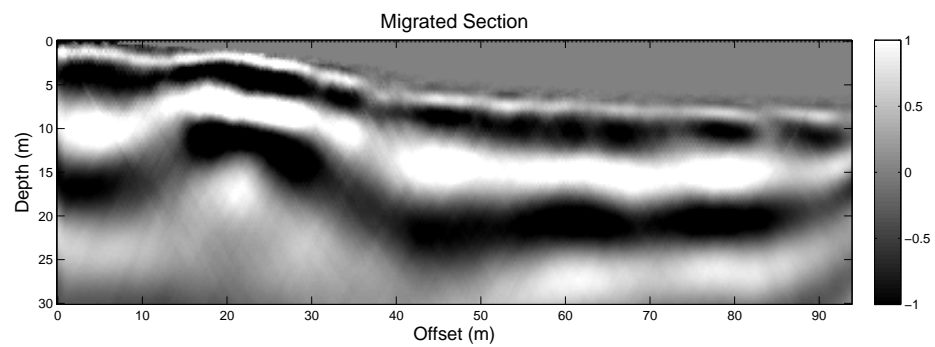


Figure 4.7. Migrated seismic section.

4.3 Interpretations

Figure 4.8 presents a summary of the tomographic results and the migration image. From the 2-D and 3-D traveltimes tomogram and 2-D migration images, we can identify the following features:

(1) Three LVZs (LVZ1, LVZ2 and LVZ3) have been imaged with both 2-D and 3-D traveltimes tomography. To establish their identity, age, and the estimated frequency of past earthquake occurrence, a much cheaper alternative than trenching is to drill a well over the areas ($20 \text{ m} < X < 35 \text{ m}$ and $50 \text{ m} < X < 65 \text{ m}$).

(2) F3 is likely to be the main fault, which is consistent with geomorphology data, and F4 is a possible antithetic fault.

(3) The depth of the bedrock is estimated to be about 15 m with the velocity larger than 2200 m/s.

(4) The four faults have an apparent dip of approximately 70-80 degrees.

(5) From the 3-D tomogram, the thickness of the LVZ1 and LVZ2 is about 5 m, and the thickness of LVZ3 is about 2 m.

Four faults and three LVZs are interpreted in Figure 4.9, and Table 4.1 summarizes the features interpreted from Figures 4.8 and 4.9. The thickness of LVZs can be considered as an approximation of the fault vertical slip. Combining the fault slip rate from paleoseismic data with the fault slip inferred by tomography, the age of the fault can be speculatively estimated. Earth Sciences Associates (1982) state that the slip rates for the Washington fault are 0.003 mm/yr for the past 1.5 kyr, and a minimum slip rate of 0.03-0.12 mm/yr for the past 10 to 25 kyr. If these estimates are correct, then I estimate that the fault activity started later than 16 kyr.

Table 4.1. List of the features from the interpretation of Figure 4.8 and 4.9. The letters 'h', 'd', 'w' indicate the thickness, depth and width of the LVZs, respectively.

	Location	Features
F1	15 m	80 degrees
F2	35 m	80 degrees (possibly not exist)
F3	42 m	80 degrees (main fault)
F4	76 m	70 degrees (antithetic fault)
LVZ1	20-35 m	h= 5 m, d= 3 m, w= 15 m
LVZ2	50-65 m	h= 5 m, d= 7 m, w= 15 m
LVZ3	35-65 m	h= 2 m, d= 0 m, w= 30 m

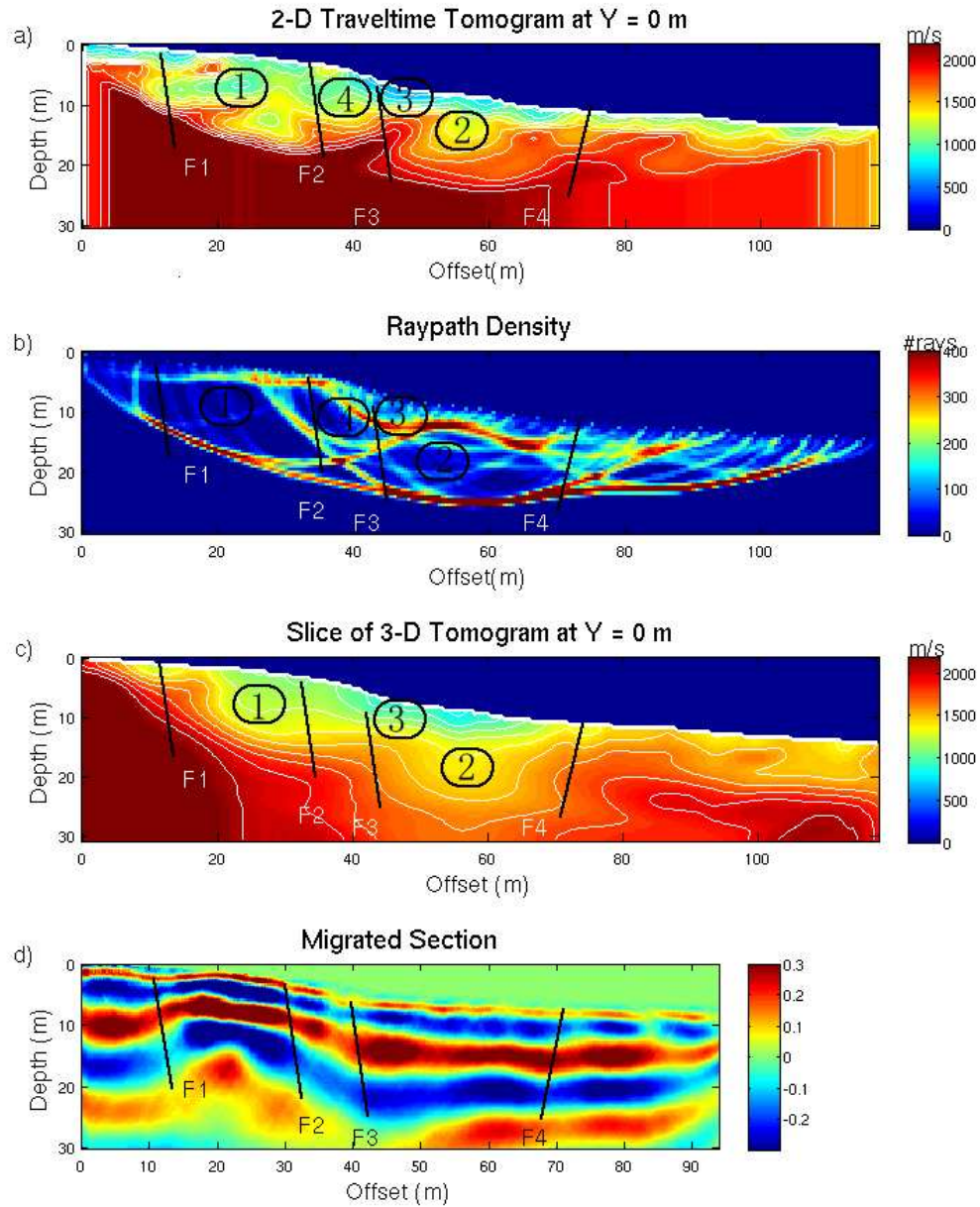


Figure 4.8. Summary of tomographic results and migration image, and interpretation.

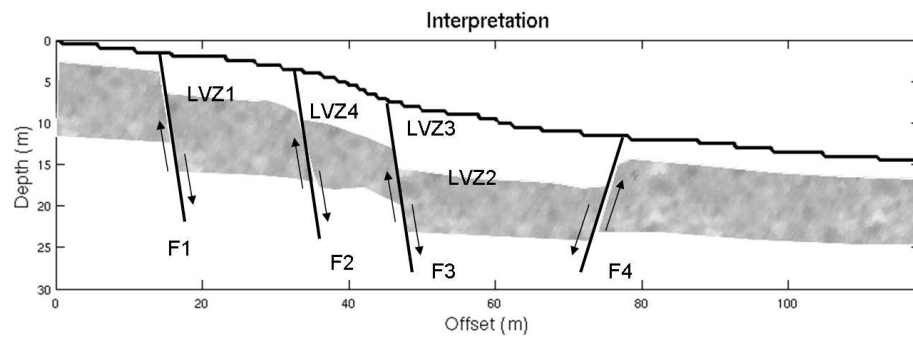


Figure 4.9. Final interpretation.

CHAPTER 5

CONCLUSIONS

Seismic experiments were conducted across the Washington fault with the goal of imaging the shape and location of colluvial wedges. The 3-D data consisted of 115,200 traces of which 85,450 traveltimes were picked and inverted to estimate the 3-D velocity structure of the Washington fault over a volume of 116 m x 7.5 m x 30 m. Reflectivity images from the 2-D seismic data provided information on the fault zone that was used, in conjunction with information from the 3-D tomogram, to estimate fault and colluvial wedge package locations associated with a prehistoric earthquake along the Washington fault.

The results of processing the 2-D and 3-D seismic surveys over the Washington fault show consistent images that appear to be faults and LVZs to a depth of about 30 m. From the 2-D and 3-D traveltime tomograms and the 2-D migration images, we can identify the following consistent features:

(1) Three LVZs (LVZ1, LVZ2 and LVZ3) are imaged with both 2-D and 3-D traveltime tomography.

(2) F3 is likely to be the main fault, which is consistent with geomorphology data, and F4 is the possible antithetic fault.

(3) The depth of the bedrock is estimated to be about 15 m, the velocity of which is larger than 2200 m/s.

(4) The four faults have an apparent dip of approximately 70-80 degrees.

(5) From the 3-D tomogram, the thickness of the LVZ1 and LVZ2 is about 5 m, and the thickness of LVZ3 is about 2 m.

(6) Combining the fault slip rate from paleoseismic data with the fault slip inferred by tomography, the age of the fault is estimated to be younger than 16 kyr.

I have demonstrated that seismic tomographic images can reveal the shape and depth of LVZs, which are possibly colluvial wedge packages associated with normal-fault earthquakes. This result is now used by UGS personnel to optimally design a trenching survey over this area. A much cheaper alternative is to drill into the LVZs to establish their identity, age, and the estimate the frequency of past earthquake occurrence. A future task is to compare the tomogram with the trench log (soon to be recorded by UGS in 2009), and analyze the accuracy of my interpretation.

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