"Geophysical Imaging of Fault Structures Over the Qadimah Fault, Saudi Arabia"

Thesis by
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ABSTRACT

“Geophysical Imaging of Fault Structures Over the Qadimah Fault, Saudi Arabia”,
Feras Adnan Al’Tawash

The purpose of this study is to use geophysical imaging methods to identify the conjectured location of the ‘Qadimah fault’ near the ‘King Abdullah Economic City’, Saudi Arabia. Towards this goal, 2-D resistivity and seismic surveys were conducted at two different locations, site 1 and site 2, along the proposed trace of the ‘Qadimah fault’. Three processing techniques were used to validate the fault (i) 2-D travel time tomography, (ii) resistivity imaging, and (iii) reflection trim stacking. The refraction traveltime tomograms at site 1 and site 2 both show low-velocity zones (LVZ’s) next to the conjectured fault trace. These LVZ’s are interpreted as colluvial wedges that are often observed on the downthrown side of normal faults. The resistivity tomograms are consistent with this interpretation in that there is a significant change in resistivity values along the conjectured fault trace. Processing the reflection data did not clearly reveal the existence of a fault, and is partly due to the sub-optimal design of the reflection experiment. Overall, the results of this study strongly, but not definitively, suggest the existence of the Qadimah fault in the ‘King Abdullah Economic City’ region of Saudi Arabia.
ACKNOWLEDGEMENTS

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<th>Description</th>
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<tbody>
<tr>
<td>2-D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>CMG</td>
<td>common midpoint gather</td>
</tr>
<tr>
<td>CMP</td>
<td>common midpoint</td>
</tr>
<tr>
<td>CSG</td>
<td>common shot gather</td>
</tr>
<tr>
<td>ERT</td>
<td>Electrical Resistivity Tomography</td>
</tr>
<tr>
<td>FD</td>
<td>Finite-difference</td>
</tr>
<tr>
<td>KAEC</td>
<td>King Abdullah Economic City</td>
</tr>
<tr>
<td>KAUST</td>
<td>King Abdullah University of Science and Technology</td>
</tr>
<tr>
<td>LVZ</td>
<td>low velocity zone</td>
</tr>
<tr>
<td>NMO</td>
<td>Normal move out</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>SGS</td>
<td>Saudi Geological Survey</td>
</tr>
<tr>
<td>SIRT</td>
<td>Simultaneous Iterative Reconstrucive Technique</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
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CHAPTER 1
INTRODUCTION

The western coastline of Saudi Arabia is undergoing a large increase in industrial development and population expansion, especially areas north of Jeddah such as the ‘King Abdullah Economic City’ (KAEC). In order to detect the area’s susceptibility to earthquakes, it is important to identify the actual location of major Saudi Arabian faults near the Red Sea that will also help design proper building codes and reduce earthquake risk.

1.1 Purpose and scope of work

The objective of this study is to geophysically identify or refute the conjectured location of the Qadimah fault [Roobol and Kadi, 2008], by conducting resistivity and seismic experiments at the main study area shown in Figure 1.1, and more specifically the two sites shown in Figure 1.2. It is expected that for this normal fault, the downthrown side will be characterized by soil with different resistivity and seismic velocity values compared to the upthrown side [Morey and Schuster, 1999]. Thus, the fault locations are to be identified by monitoring large lateral changes in the resistivity and the seismic velocity of the soil.

Colluvial wedges are formed by the collapse of normal fault scarps or steep sloping planes after a surface-rupture earthquake. A sketch that shows the formation history of a colluvial wedge is shown in Figure 1.3, where the accumulated alluvium (loose and unconsolidated) is deposited at the location of the surface rupture. Geophysically delineating the hidden fault structures and colluvial
wedges will likely identify the location of the Qadimah fault and subsequent studies regarding the fault’s activity will help in the assessment of earthquake hazard in this region of Saudi Arabia. This will enable engineers to design appropriate building codes and earthquake-safe buildings.

1.2 Site geological background

The ‘Qadimah fault’ is located on the western coast line of Saudi Arabia near the Rabigh area, and belongs to a set of listric normal faults that formed after the opening of the Red Sea around 30 million years ago. These normal faults are formed due to the gravity collapse of the Arabian tectonic plate margin into the newly formed Red Sea graben [Roobol and Kadi, 2008]. The Qadimah fault extends from ‘Sabkhat Adh Dhinaybh’ (50 km north of Thuwal) towards ‘KAEC’ and ‘KAUST’ in the south (shown in Figure 1.2) and was traced for a distance of 25 km from the north to the south with the help of an eroded fault scarp that makes up the first 10 km of that distance with a scarp height of 4 meters. The fault scarp is topped with Quaternary raised reef material that is mostly limestone and is believed to be younger than 1.8 million years old. The fault’s age is considered relatively younger than that (tens of thousands of years or younger), which is partly validated by sea shells in the fault scarp location that still had traces of their original color [Roobol and Kadi, 2008].

One of the key geologic indicators of the fault location is the area of surface washed sand and gravel or the flood deposits in the area of study. These deposits are located between the eastern most point of ‘Sabkhat Adh Dhinaybh’, (A ‘Sabkha’
material that consists of black mud with gypsum crystals observed on its surface) extending all the way to the western most point of the Quaternary reef material indicated in Figure 1.4.

**Figure 1.1:** Location of the study area on the Arabian Peninsula map.

**Figure 1.2:** Location of the ‘Qadimah fault’ and the locations (black solid lines) of the two geophysical survey profiles, [Roobol and Kadi, 2008].

<table>
<thead>
<tr>
<th>Profile locations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start point</strong></td>
</tr>
<tr>
<td>Profile 1</td>
</tr>
<tr>
<td>Profile 2</td>
</tr>
</tbody>
</table>

**STRATIGRAPHY**

**QTt** - Terrace deposit, gullied, cobbles to 20 cm diameter
Figure 1.3: The sequence of earthquake events that form colluvial wedges a) Cross section of earth before an earthquake event. b) Earthquake event forms a normal fault and loose unconsolidated material fills the downthrown side of the fault. c) After some time, another layer is formed that overlies the colluvial wedge [Morey and Schuster, 1999]. Colluvial wedges are made up of unconsolidated coarse-grained alluvium, which should have a slower P-wave velocity than the surrounding fine-grained sediments.
Figure 1.4: A view from the first survey location indicating the expected location of the ‘Qadimah fault’ in red, i.e. between the border of the ‘Sabkha’ indicated by the green dashed line and the Quaternary reef material indicated by the blue dashed line. The black dashed line indicates the actual survey line which is perpendicular to the fault line.
CHAPTER 2

FIELD SURVEYS AND PROCESSING METHODS

2.1 Field surveys

For each of the two profiles shown in Figure 1.2, two different types of geophysical surveys were conducted: a seismic survey and a resistivity survey. The seismic survey was used to delineate the detailed subsurface geological features near the fault whereas the resistivity survey was used to detect the sharp location of the fault contact.

2.1.1 Seismic surveys

In March and April 2011, a research group from KAUST and crew from Thuwal, Saudi Arabia conducted two 2-D seismic surveys perpendicular to the suspected location of the Qadimah fault scarp (shown in Figures 1.2 and 1.4). The objective of these surveys was to seismically image the proposed Qadimah fault and the associated colluvial wedges up to a depth of 30 meters.

For the first survey, seismic data were collected using 109 vertical component geophones (frequency of 40 Hz) at a 3 m spacing to form a total line length of 324 m. Similarly, for the second profile, 120 similar geophones were used with a 2 m spacing to form a profile of 238 m in length. The seismic source for both profiles was a 7 kg sledge hammer striking a small metal plate at each geophone location; each shot was stacked a number of times (indicated in Table 2.1a) at the same shot position to improve the signal-to-noise ratio (SNR) of each recorded
trace. Seismic traces were recorded using a 120-channel Geometrics data recorder, and the acquisition and source/receiver parameters are summarized in Table 2.1a.

**Table 2.1a**: 2-D Seismic survey acquisition parameters.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Profile 1</th>
<th>Profile 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source</strong></td>
<td>7 kg sledgehammer</td>
<td>7 kg sledgehammer</td>
</tr>
<tr>
<td><strong>Recording instruments</strong></td>
<td>120-channel Geometrics recorder</td>
<td>120-channel Geometrics recorder</td>
</tr>
<tr>
<td><strong>No. of shots</strong></td>
<td>109</td>
<td>120</td>
</tr>
<tr>
<td><strong>No. of receivers</strong></td>
<td>109</td>
<td>120</td>
</tr>
<tr>
<td><strong>Shot spacing</strong></td>
<td>3 m</td>
<td>2 m</td>
</tr>
<tr>
<td><strong>Receiver spacing</strong></td>
<td>3 m</td>
<td>2 m</td>
</tr>
<tr>
<td><strong>Survey length</strong></td>
<td>324 m</td>
<td>238 m</td>
</tr>
<tr>
<td><strong>No. of stacks</strong></td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td><strong>No. of traces</strong></td>
<td>11,881</td>
<td>14,400</td>
</tr>
<tr>
<td><strong>Sampling interval</strong></td>
<td>0.25 ms</td>
<td>0.25 ms</td>
</tr>
<tr>
<td><strong>Record length</strong></td>
<td>1.0 s</td>
<td>1.0 s</td>
</tr>
</tbody>
</table>

**2.1.2 Electrical resistivity surveys**

Two electrical soil resistivity surveys were also conducted at the same location of the 2-D seismic surveys to image the subsurface variation in the soil resistivity. The resistivity survey for a standard system configuration is carried out by passing alternating current from an external power source and measuring the potential difference between different points along the profile of investigation. Both of the resistivity surveys were conducted using 64 metal electrodes spaced at 5 m intervals, to form a total line length of 315 m. The Wenner electrode configuration was used for both profiles as it maintains consistent spacing between the potential electrodes and the current electrodes throughout the profile. Figure 2.1 presents a
sample Wenner electrode setup, where ‘P’ indicates the potential electrodes and ‘C’ indicates the current electrodes. All the electrodes in this configuration are separated by the same equal distance ‘a’.

The external power source used was a 12DCV battery along with a 12DCV to 800DCV direct current booster to provide the required high voltage for the system. The data were recorded using the Syscal-R2 system. To relate the geophysical measurements to lithology, Table 2.1b lists the range of electrical resistivity values with respect to rock/soil type.

![Diagram of Wenner electrode setup]

**Figure 2.1:** The Wenner electrode configuration [Reynolds, 1997].

**Table 2.1b:** Electrical resistivity values for different materials [Lowrie, 2007].

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity values (Ω m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>10 – 10,000</td>
</tr>
<tr>
<td>Alluvium</td>
<td>1 – 1000</td>
</tr>
<tr>
<td>Gravel</td>
<td>100 – 10,000</td>
</tr>
</tbody>
</table>
2.2 Traveltime tomography

Traveltime tomography is used to reconstruct the earth’s subsurface velocity model from the picked first arrival travel times [Aldridge and Oldenburg, 1993]; [Ammon and Vidale, 1993]; [Nolet, 1987]; [Nemeth et al., 1997]; [Lutter et al., 1990]. The procedure requires a finite difference (FD) solution to the eikonal equation [Qin et al., 1992], and an iterative reconstruction method such as the Simultaneous Iterative Reconstructive Technique (SIRT) algorithm [Gilbert, 1972]. The first step is to estimate an initial velocity model for the data using the offset-time (x-t) slope from the first arrivals in the seismograms. The initial velocity is iteratively readjusted until the computed traveltimes match the observed traveltimes to achieve a specified accuracy in predicted traveltimes. A FD solution to the eikonal equation [Qin et al., 1992] is used to compute the predicted traveltimes used for calculating the traveltime residual, i.e., the difference between the observed and predicted traveltimes: These residuals are squared and summed together to get the data misfit function.

\[ \epsilon = \frac{1}{2} \sum_i (t_i^{obs} - t_i^{cal})^2 \]  \hspace{1cm} [2.1]

where the summation is over all the \( i_{th} \) raypaths in the velocity model, \( t_i^{obs} \) is the picked first arrival traveltime from the seismograms, and \( t_i^{cal} \) is the traveltime calculated from the eikonal equation.

The \( j_{th} \) gradient of the misfit function \( \epsilon \) is given by:

\[ \gamma_j = \frac{\delta \epsilon}{\delta s_j} = \sum_i \delta t_i \frac{\delta t_i}{\delta s_j} \quad \text{where} \quad \frac{\delta t_i}{\delta s_j} = l_{ij} \quad \therefore \gamma_j = \sum_i \delta t_i l_{ij} \]  \hspace{1cm} [2.2]
where $\delta t_i$ is the traveltime residual of the original misfit function, $\delta s_j$ is the slowness perturbation in the $j_{th}$ cell and $l_{ij}$ is the length of the $i_{th}$ ray that visits the $j_{th}$ cell. Finally, the slowness model is updated iteratively by optimizing the gradient of the misfit function (using the steepest descent method etc.) and the slowness model update formula is given by:

$$s_j^{k+1} = s_j^k - \alpha \gamma_j$$

where $\alpha$ is the step length and $s_j^k$ is the slowness at the $k_{th}$ iteration.

### 2.2.1 First arrival picking and quality control

To apply traveltime tomography to the ‘Qadimah fault’ data, the first arrival traveltimes are picked for 11,881 traces in the first 2-D seismic profile and 14,400 traces in the second profile. A sample shot gather from the second 2-D seismic profile along with the first arrival traveltime picks (indicated by the green line) are shown in Figure 2.2. The shot gather indicated in Figure 2.2 includes direct waves, refracted waves and reflected waves.

After picking the first arrival traveltimes for the two seismic data sets, a quality control check on the picked data sets was performed. The reciprocity test is used for the quality control of the picked traveltimes, where the picked traveltimes are used if the traveltime pair $t_{ij} = t_{ji} < \frac{T}{4}$, where the source is at the $i_{th}$ position, the receiver is at the $j_{th}$ position, and the dominant period of the source wavelet is $T = 0.025$ s. Otherwise the traveltime pairs $t_{ij}$ and $t_{ji}$ are rejected and are not incorporated in the traveltime tomography process that was performed with a
MATLAB code courtesy of the University of Utah Tomography Modeling/Migration Consortium (UTAM) group (http://utam.gg.utah.edu).

The elevation values for both profiles were used in the traveltime tomography method to account for topography changes along the profile. This correction assumes that the data were collected on a straight datum line.

**Figure 2.2:** A sample shot gather from the second 2-D seismic data set collected for the ‘Qadimah fault’, where the first arrival traveltime picks are indicated by the green line.
2.2.2 Smoothing filter

The travel times that pass the reciprocity test are tomographically inverted using multiscale rectangular smoothing filters applied after each iteration in the inversion algorithm [Nemeth et al., 1997]. Smoothing filters are applied to the slowness model and iteratively decreased in size to increase the spatial resolution of the resulting tomogram. Different degrees of smoothing were used in this study, although the following filter sizes were deemed acceptable to solve the spatial resolution problem. A summary of the smoothing schedules used in this thesis for the field data and synthetic data are shown in Table 2.2.

Table 2.2: Smoothing schedules for the field and synthetic data, all smoothing sizes are in number of cells and size in meters and are applied to six iterations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Actual data (Profile 1)</th>
<th>Actual data (Profile 2)</th>
<th>Synthetic data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Size</td>
<td>2.5 m</td>
<td>2 m</td>
<td>1 m</td>
</tr>
<tr>
<td>No. of unknowns</td>
<td>3110</td>
<td>3570</td>
<td>21420</td>
</tr>
<tr>
<td>No. of travel times</td>
<td>10422</td>
<td>10198</td>
<td>14400</td>
</tr>
<tr>
<td>Smoothing filter 1</td>
<td>20 x 10 cells, 50 x 25 m</td>
<td>20 x 10 cells, 40 x 20 m</td>
<td>20 x 10 cells, 20 x 10 m</td>
</tr>
<tr>
<td>Smoothing filter 2</td>
<td>12 x 6 cells, 30 x 15 m</td>
<td>12 x 6 cells, 24 x 12 m</td>
<td>12 x 6 cells, 12 x 6 m</td>
</tr>
<tr>
<td>Smoothing filter 3</td>
<td>8 x 4 cells, 20 x 10 m</td>
<td>8 x 4 cells, 16 x 8 m</td>
<td>8 x 4 cells, 8 x 4 m</td>
</tr>
<tr>
<td>Smoothing filter 4</td>
<td>4 x 2 cells, 10 x 5 m</td>
<td>4 x 2 cells, 8 x 4 m</td>
<td>4 x 2 cells, 4 x 2 m</td>
</tr>
</tbody>
</table>

Note: For each inversion, the ratio of the number of travel times to the number of unknowns was maintained to be 3:1 or more for the actual data. The distance between the grid points in the model is also the grid size indicated for each experiment in the table above.
2.3 Electrical Resistivity Tomography (ERT)

The electrical resistance of any homogenous material is proportional to its length divided by the cross sectional area. That is \( R \propto \frac{L}{A} \) which can be written as \( R = \frac{\rho L}{A} \), where \( \rho \) is the true resistivity. Using Ohm’s law: \( R = \frac{V}{I} \), where \( V \) is the potential difference across a resistor and \( I \) is the current passing through the resistor, Resistivity \( \rho \) can be re-written as \( \rho = \frac{VA}{IL} \) [Reynolds, 1997].

In a resistivity survey a controlled electric current is passed into the ground through a pair of electrodes. The current flows into the ground and adapts in a pattern according to the geometry of the subsurface resistivity array, where the potential difference between two equipotential surfaces is measured at their point of intersection at the ground surface using another pair of electrodes [Lowrie, 2007]. Using the system of electrodes that includes a current pair and a potential pair of electrodes is known as the four electrode method. This method can have special geometries or configurations for the two pairs of electrodes that include Wenner, Schlumberger, dipole-dipole etc. where some may be simpler to use compared to one another for a certain investigation.

The subsurface around the ‘Qadimah’ field site is usually not homogeneous, so it is important to note that the measured resistivity values are not the true resistivity values anymore but the apparent resistivity values. The apparent resistivity is the true resistivity value multiplied by a geometric factor \( K \) (meters) that accounts for the specific type of electrode configuration or geometry of the electrode array [Telford et al., 1990].
Depending on the size of the survey a multi-electrode investigation may be performed in which both the current electrode pair and the potential electrode pair are interchangeable. This is because the direct current, as the source of electric current, may cause spurious signals due to the accumulated charge on the potential electrodes. This problem is solved by using a low-frequency alternating current which rapidly commutates or reverses the direction of the direct current.

2.3.1 Resistivity data quality control and processing

The resistivity field data are processed through the resistivity data management software ‘Prosys II’ (ver 02.36.00, IRIS instruments). Initial quality control and processing tasks like filtering out high resistivity values from the dataset, topography correction etc. are performed and the file is saved into the format of the inversion software ‘RES2DINV’ (ver 3.58, Geotomo software).

Similar to seismic tomography, where the first arrival traveltimes are inverted to determine the subsurface velocity structure, ERT is used to invert the measured potential values along current flow lines using a least squares inversion method. This is generally an iterative procedure that is controlled by the convergence of the relative absolute error that compares the measured apparent resistivity values collected in the field with the calculated apparent resistivity values. The results of the inversion process estimate the true resistivity distribution in the shallow subsurface to a depth of tens of meters.

The resistivity inversion procedure for various combinations of current electrode pairs and potential electrode pairs is performed with the inversion
software ‘RES2DINV’, where unlike traveltime tomography no smoothing filters were applied. The output resistivity tomogram is a vertical cross section of the apparent resistivity values in the subsurface below the electrode array, and the maximum depth reached is estimated to be one-fifth the length of the profile that is around 60 meters in this experiment. Certain features of this cross section such as its resolution and the maximum depth of investigation differ with a different spacing and geometry of the electrodes.

Figure 2.3 shows a sample apparent resistivity cross section produced after six iterations using the inversion program ‘RES2DINV’, it also includes the topography values measured in the field.

**Figure 2.3**: The vertical resistivity cross section produced by the inversion program ‘RES2DINV’ (ver 3.58, Geotomo software) after six iterations using the least-squares inversion method which includes the topography of the ground surface at the site of investigation.
2.4 2-D Seismic reflection data processing

Shallow seismic reflection data is processed to describe the reflectivity features of the shallow subsurface. Processing the data includes the elimination of near-surface scattering, coherent noises, static shifts and surface waves [Baker, 1999; Yilmaz, 1987]. The sequence of the processing steps for producing a subsurface reflectivity image is shown in Figure 2.4.

2.4.1 Data formatting and geometry definition

Reflection data processing starts by defining the survey geometry parameters of the field experiment and includes the source and receiver locations, their offsets from one another, the temporal and spatial sampling intervals and the trace length.

2.4.2 Elevation and refraction statics

The elevation statics correction is introduced to correct for topography changes in the field that result in static time shifts in the recorded traces. These time shifts result from the distorted geometry for the reflector at that location, and the correction assumes that the data were collected on a straight datum line. Similarly, the refraction statics correction is applied to the data to correct for the time shifts in the traces caused by velocity anomalies located in the near surface. These time shifts are calculated by the time picks of the first arriving refraction event, which are affected by the variations above the refracting interface.
2.4.3 Frequency filtering

Bandpass filtering of the recorded traces is used to attenuate noise at certain frequencies other than the dominant frequency of the signal. A commonly used filter is the bandpass filter that is applied to shallow reflection data in order to suppress or filter low-frequency noises such as surface waves etc. Another type of filter used in processing shallow reflection data is the frequency-wave number (f-k) filter that is used to remove linear coherent noise as long as the signal has a different slope compared to the noise.

2.4.4 Normal move out (NMO) and stacking

The NMO correction is usually applied to reflection traces in a common midpoint gather (CMG). This correction shifts the travel times to the zero-offset position, and the shifted traces are stacked or summed together to produce the stacked seismic section.

2.4.5 Post stack migration

Post stack migration is applied to the stacked seismic section, to relocate dipping reflectors to their original positions and collapse diffraction energies back to their original positions. In this case, the migration method used is Kirchhoff migration.
Figure 2.4: Seismic reflection processing flow
2.5 Super virtual refraction interferometry

As mentioned in section 2.2, the subsurface P-wave velocity distribution is estimated using traveltime tomography after inverting for the picked first arrival traveltimes. This procedure relies on the accuracy of picking the first arrival traveltimes in the seismic surveys. An important issue that could affect the reliable picking of first arrival traveltimes is that the trace’s SNR decreases with increasing offset from the source position.

This is where super virtual refraction interferometry is used to enhance the SNR of the far offset traces in the seismic data. This method enables the reliable picking of the first arrival traveltimes used for tomographically inverting the subsurface velocity distribution. The theory behind this technique can be summarized in two main steps:

1) Cross correlation and summation of traces from the raw data that are responsible for generating the head wave arrivals at a certain source position, in order to generate traces with similar head wave arrivals at virtual sources.

2) Convolution of these virtual source traces with the original raw data to produce enhanced super virtual traces at long offsets that have reduced noise and clean first arrivals.

The methodology of this technique is explained briefly in Figure 2.5 [Mallinson et al., 2011].
Figure 2.5: The procedure of generating super virtual refraction traces [Mallinson et al., 2011].

a) Cross correlation of the trace recorded at location A with that at location B for a source position at x, to generate a trace with a virtual head wave arrival at source position A'.

b) Convolve and stack over A to generate super-virtual refractions.

Cross correlation

Convolution
CHAPTER 3

SYNTHETIC DATA RESULTS

In this chapter, a synthetic data model that resembles the actual field fault model in terms of geology and seismic velocity values is introduced and the 2-D traveltime tomography results for the synthetic model are presented. The results indicate that the fault can be imaged by traveltime tomography which can help locate the fault structures and features.

3.1 Traveltime tomography Results

Synthetic data was generated for the Qadimah fault experiment with a total of 120 shots and receivers at 3 m intervals. This is similar to the second seismic profile surveyed in this research project. The main purpose of the synthetic test is to evaluate the accuracy of the traveltime tomography method that was applied to the actual field data collected, where the input velocity model was generated to have a range of velocities similar to those of the actual field data. At the ground surface, the initial velocity model was set to be 600 m/s and the depth to the bedrock is 10 m below the ground surface with a velocity value of 2500 m/s. The velocity of the colluvial wedge in the model was set to 900 m/s, surrounded by a layer with a velocity of 1500 m/s. The velocity model does not vary in the Y direction and an Offset (X)–Depth (Z) section of the velocity model is presented in Figure 3.1a. Table 3.1 displays the parameters for the synthetic 2-D velocity model.
Table 3.1 2-D Synthetic velocity model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Size</td>
<td>357 m x 60 m</td>
</tr>
<tr>
<td>No. of Shots</td>
<td>120</td>
</tr>
<tr>
<td>No. of Receivers</td>
<td>120</td>
</tr>
<tr>
<td>Shot spacing</td>
<td>3 m</td>
</tr>
<tr>
<td>Receiver spacing</td>
<td>3 m</td>
</tr>
<tr>
<td>Length of Profile</td>
<td>357 m</td>
</tr>
<tr>
<td>No. of traces</td>
<td>14,400</td>
</tr>
</tbody>
</table>

In this case, 14400 traveltimes are generated by solving for the 2-D eikonal equation using a FD solution [Qin et al., 1992]. The first arrival traveltimes for the synthetic velocity model are inverted to estimate the P-wave velocity distribution using traveltime tomography. The updated velocity model is smoothed with different smoothing filters that diminish in size as the number of iterations increase. The smoothing and inversion parameters for the synthetic data are given by Table 2.2 and the resulting 2-D velocity tomogram is presented in Figure 3.1 b.

Figure 3.1 c. shows the 2-D raypath density image that reveals the raypath coverage or the number of rays passing through each cell of the tomogram. From the raypath density image, it is noticed that the rays start to focus at the fault location. This decreases the number of rays passing through the hanging wall section of the fault and at the LVZ location (120 m < X <160 m).
An important feature for identifying the fault structures is the sudden drop in the velocity contour lines of the 2-D velocity tomogram (Figure 3.1 b). Another fault-finding tool is to plot the velocity profile and velocity gradient profile against depth at different offset (X) i.e. X = 50 m and at X = 120 m (fault location in this case) in Figure 3.2. From these plots, the fault is indicated by a high-velocity gradient value and similarly the LVZ is identified by a large velocity gradient value at the offset location X=120 m. This is expected as the velocity tomogram is typically a smoothed version of the original velocity model [Buddensiek et al., 2008].

The iterative inversion algorithm converges when the root mean square (RMS) traveltime residual does not significantly change. To evaluate its convergence, the RMS traveltime residual is plotted against the number of iterations as shown in Figure 3.3. The plot indicates convergence to an acceptable traveltime residual is achieved after 15 iterations with a final averaged residual value of 1 ms, which is still much smaller than the picking error value of 6 ms.
Figure 3.1  2-D travel time tomography results for the synthetic data. a) 2-D synthetic velocity model, indicating a normal fault along with a LVZ. b) 2-D velocity tomogram, resulting from the travel time inversion of the synthetic data. c) raypath density image.
Figure 3.2  Velocity profiles and velocity gradient profiles at two different offset locations for the synthetic data. (Left column) Velocity profiles at different offset locations. (Right column) Velocity gradients at different offset locations. The velocity gradient profiles indicate the fault by high positive gradient values and LVZs are identified by negative gradient values.
Figure 3.3 2-D travel time residual plotted against the number of iterations for the synthetic data. The iterative process converges after 15 iterations with a final travel time residual of 1 ms, which is still much smaller than the picking error value of 6 ms.
CHAPTER 4
FIELD DATA RESULTS

In this chapter, 2-D travelt ime tomography results and the 2-D resistivity images are presented for the Qadimah fault data. The tomograms are computed and analyzed for both the seismic and resistivity profiles. The trim stacked seismic section produced from reflection trim stacking of the first seismic profile is also presented.

4.1 Traveltime tomography Results

The tomography results for the two seismic surveys are presented in this section, and include the velocity tomograms, the raypath density images, and the RMS residual vs. the number of iterations relation for both profiles.

4.1.1 First 2-D seismic profile

For the first seismic survey line, the total number of traces collected is 11,881 traces out of which 10,506 first arrival traveltimes were picked using the super virtual refraction data. The reciprocity test rejected 84 picked traveltimes as they did not comply with the reciprocity condition for a tolerance limit of 6 milliseconds. The remaining picked traveltimes that passed the reciprocity test were used to invert for the P-wave velocity distribution. The resulting velocity tomogram is displayed in Figure 4.1a, where values of seismic velocity are indicated in the form of contour lines with increasing depth along the investigated profile, the maximum depth reached was 45 m. Figure 4.1b represents the raypath coverage or ray density through each cell of the tomogram.
Figure 4.2 represents the RMS traveltime residual along with the number of iterations. The plot indicates that the RMS traveltime residual value alternates between 3.5 ms and 4 ms, which is still smaller than the estimated picking error value of 6 ms.

### 4.1.2 Second 2-D seismic profile

Similarly, for the second seismic survey line the total number of traces collected is 14,400 traces out of which all first arrival traveltimes were picked using the super virtual refraction data. The reciprocity test rejected 4202 picked traveltimes as they did not comply with the reciprocity condition for the same tolerance limit of 6 milliseconds. The remaining picked traveltimes that passed the reciprocity test were used in the inversion for the P-wave velocity distribution of this profile. The resulting velocity tomogram is displayed in Figure 4.3a, where the maximum depth reached was 25 m and Figure 4.3b represents the raypath coverage or ray density through each cell of the tomogram.

Figure 4.4 represents the RMS traveltime residual along with the number of iterations. The plot indicates that the final RMS traveltime residual value is about 3 ms, which is half the estimated picking error value of 6 ms.
4.2 2-D Resistivity results

A single 2-D resistivity survey line for the Wenner configuration used in the Qadimah fault experiment results in 650 data points of apparent resistivity values. These values contain some outlier points that clearly do not fit in the collected dataset and are filtered out of the original dataset in preparation for the inversion process. This is because these outliers can influence the inversion result and can produce a distorted resistivity image of the subsurface.

For the first profile, the measured apparent resistivity values were reduced to 619 values where 31 values were eliminated because of their relatively high values that could have affected the inversion results. The remaining apparent resistivity values ranging from (25 – 3600 ohm m) were inverted to obtain the true resistivity distribution of the subsurface. The logarithmic values of the final resistivity distribution are computed and displayed in the tomogram that is shown in Figure 4.5a. The logarithmic resistivity values were displayed instead of the true resistivity values because the inversion process produces a result with a wide variation of resistivity values, and the logarithmic plot compresses the range of resistivity values in the model.

Similarly, for the second profile the measured apparent resistivity values were reduced to 623 values. The remaining apparent resistivity values ranging from (20 – 4500 ohm m) were similarly inverted to obtain the true resistivity model of the subsurface. The logarithmic values of the final resistivity distribution are displayed in the tomogram shown in Figure 4.5b.
4.3 Reflection trim stacking results

The 2-D seismic data collected from the first profile are used for reflection trim stacking, whose purpose is to identify the reflectors below the ground surface in order to produce a trim stacked seismic section. The trim stacked section is an image of the reflecting surfaces that helps to identify the fault structures.

The stacking procedure starts by sorting out the common shot gathers (CSG) into 217 CMPs with 1.5 m spacing. In each CMG, the 8\textsuperscript{th} trace before the zero-offset trace was selected as the reference trace to help re-datum the reflection data. The reason for selecting the 8\textsuperscript{th} trace as the datum and not any other trace was that it was present and repeated in most CMPs. After re-datuming the traces that resemble the reflection data in each CMP to the reference trace position, the shifted traces are summed together to represent a stacked trace for each CMP. The stacked traces for the 217 CMGs are displayed in the trim stacked section presented in Figure 4.6.

The trim stacked section in Figure 4.6 shows four reflecting horizons, with a shallow and continuous first reflector that does not show any signs of faulting. Similarly, the remaining three deeper reflectors are continuous and do not show any features or structures that could be related to the fault.
Figure 4.1 2-D traveltime tomography results for the first seismic profile. a) 2-D velocity tomogram. b) raypath density image.
**Figure 4.2** 2-D traveltime residual plotted against the number of iterations for the first seismic profile. The RMS traveltime residual alternates between 3.5 ms and 4 ms, which is still smaller than the estimated picking error value of 6 ms.
Figure 4.3 2-D traveltime tomography results for the second seismic profile. a) 2-D velocity tomogram. b) raypath density image.
Figure 4.4  2-D traveltime residual plotted against the number of iterations for the second seismic profile. The final RMS traveltime residual is around 3 ms, which is half the estimated picking error value of 6 ms.
Figure 4.5 2-D electrical resistivity tomograms (a): First profile (b): Second profile.
Figure 4.6 Trim stacked seismic section, displaying the reflecting surfaces with depth.
4.4 Summary of results

The interpreted velocity and resistivity tomograms for the first profile are presented in Figure 4.7. The following is a geologic interpretation of these results:

1) The fault F1 imaged by both 2-D traveltime tomography and resistivity tomography is indicated by the slanted black line at X = 210 m in both the velocity and resistivity tomograms. The abrupt change in resistivity marks this fault boundary. The lower resistivity values on the upthrown side of this fault might be due to a salty brine channel just west of the reef complex to the far right. The lower velocity just to the west of F1 is consistent with a colluvial wedge [Morey and Schuster, 1999].

2) The fault F2 imaged by resistivity tomography that is indicated at X = 255 m, is another possible fault. The lower resistivity value is consistent with a channel of brine parallel to the reef complex.

3) A low velocity zone LVZ1 is identified in the velocity tomogram at (170 m < X < 200 m) as a colluvial wedge [Morey and Schuster, 1999].

Similarly, Figure 4.8 presents a summary of the interpreted tomograms for the second profile and the main observations are below:

1) The interpreted fault F1 imaged by both the velocity and resistivity tomograms is located at X = 250 m in both tomograms and is likely to be the main fault.

2) The fault F2 imaged by both the velocity and resistivity tomograms is indicated at X = 210 m and is a possible antithetic fault to the main fault F1.
3) A low velocity zone LVZ2 is identified in the velocity tomogram at 
\[(215 \text{ m} < X < 235 \text{ m})\], but it is not as thick as the one shown in Figure 4.7. This 
is due to the smaller source-receiver aperture.

The trim stacked seismic section shown in Figure 4.9 indicates the reflecting 
surfaces with depth. It is evident that the shallow reflectors are generally 
continuous and do not show any distinct faulting signatures away from F1. This 
applies to all the four reflecting horizons indicated by the red lines. Unfortunately 
the reflection results between F1 and F2 are too noisy to confirm or refute the 
existence of a fault at F1 and F2 \((180 \text{ m} < X < 220 \text{ m})\). The data in this offset range 
are related to the near offset traces in each of the CMPs that were picked to form the 
trim stacked section; these traces were deemed unpickable as they were interfered 
by the surface wave cone in each of the CMGs.
Figure 4.7 Summary of traveltome tomography tomograms and resistivity tomogram for the first profile, with interpretation.
Figure 4.8 Summary of travel time tomography tomograms and resistivity tomogram for the second profile, with interpretation.
Figure 4.9 Trim stacked seismic section with red lines, indicating the reflecting surfaces interpretation. The drop in elevation between the shallowest red line on the left with respect to the shallowest one to the right is 6 meters (estimated from velocity tomogram).
CHAPTER 5

CONCLUSIONS

The 2-D seismic and resistivity tomograms show respectively, low-velocity zones and abrupt changes in resistivity values that are consistent with a faulted subsurface. The following observations could be made from the results:

1) The interpreted fault F1 that is imaged consistently in both profiles with the 2-D velocity tomogram and the resistivity tomogram and is likely to be the main fault.

2) The interpreted fault F2 that is imaged in the first profile with the resistivity tomogram is a possible fault boundary if the proposed brine channel exists, although in the second profile it is likely to be an antithetic fault to the main fault F1 as it has been imaged in both the velocity and resistivity tomograms until further evidence is acquired.

3) Low-velocity zones are identified in the velocity tomogram of the first profile at $(170 \, \text{m} < X < 200 \, \text{m})$ and at $(215 \, \text{m} < X < 235 \, \text{m})$ of the second profile respectively. They can be interpreted as colluvial wedges on the downthrown side of a normal fault.

4) There is no clear evidence of any distinct faulting signatures in the trim stacked seismic section due to the missing reflection data in the offset range $(180 \, \text{m} < X < 220 \, \text{m})$.

5) The apparent resistivity values from both profiles relate to the theoretical values of resistivity that depend on the lithology, shown in Table 2.1b.
6) The apparent resistivity values from both profiles are consistent with saturation and salinity, as in the dry consolidated material such as the reef deposits indicated by high resistivity values in the resistivity tomograms. Similarly, poorly consolidated material that is also highly saline similar to the ‘Sabkha’ indicated by low resistivity values in the resistivity tomograms.

Therefore, the resistivity and velocity tomograms reveal a fault-like structure (F1) and two LVZs (LVZ1 and LVZ2) related to the downthrown portions of a normal fault. However, a wider reflection profile is required to give a more accurate tomogram of the fault features.

In summary, the resistivity and seismic velocity tomograms strongly suggest the presence of a normal fault near the ‘King Abdullah Economic City’ region. A geological map that represents the summary of the interpreted faults F1 and F2 is shown in Figure 5.1.

Future geophysical work should include a wider seismic survey over nearby locations that would enhance the reflection events and evaluate the validity of the current interpretation. I would also recommend that the LVZs be drilled and the core samples interpreted and dated to confirm the existence of a colluvial wedge. This information can also be used to estimate earthquake magnitude and recurrence intervals. This approach would validate the interpretation of this seismic and resistivity study.
Figure 5.1: Geological map indicating interpreted faults F1 (blue line) with the downthrown side and F2 (blue circle).

Profile locations

<table>
<thead>
<tr>
<th></th>
<th>Start point</th>
<th>End point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>22.56827 N, 39.13842 E</td>
<td>22.56975 N, 39.13574 E</td>
</tr>
<tr>
<td>Profile 2</td>
<td>22.56203 N, 39.13835 E</td>
<td>22.56236 N, 39.13605 E</td>
</tr>
</tbody>
</table>

STRATIGRAPHY

QTT - Terrace deposit, gullied, cobbles to 20 cm diameter
REFERENCES


