Subsurface fault and colluvial wedge detection using resistivity, refraction tomography and seismic reflection

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Summary

Electric resistivity tomography (ERT), seismic refraction tomography, and seismic reflection are widely used in shallow geological applications such as fault detection. In this work we use the three methods to find and trace a shallow subsurface fault. A low velocity-low resistivity anomaly is shown on the velocity tomogram and the ERT, respectively. This anomaly is interpreted as a colluvial wedge located at the downthrown side of the fault. Comparing the results from the three methods show a very good match in the fault location, colluvial wedge location, thickness and width, as well as the different subsurface geological units.

Introduction

The goal in paleoseismology is to estimate the sizes and recurrence intervals of ancient earthquakes (McCalpin 1996). This information is usually retrieved by trenching across a fault and examines the geological cross-section for signs of ancient faulting activity. A Colluvial wedge is a geological feature associated with normal faults; it is a wedge-shaped deposit that accumulates at the base of a scarp following a surface rupturing event (McCalpin 1966). It is the geological signature of an ancient dip-slip earthquake that ruptured the ground surface (McCalpin 1966). Larger earthquakes produce greater displacement along the fault; so, wedge thickness is proportional to earthquake magnitude, while the depth interval between contiguous wedges is proportional to the recurrence interval between the corresponding earthquakes. Sediments that accumulate at the wedge are usually of lower velocity than surrounding sediments. However, colluvial wedges should show higher resistivity values than surrounding sediments if dry and lower resistivity if it is saturated with water.

Trenching studies of colluvial wedges are expensive, environmentally intensive, typically limited to depths less than 10 m, and reveals only a 2D section of the geological record. Geophysical methods can be used to overcome the disadvantages of the trenching approach. Seismic refraction, resistivity, and reflection are examples of the geophysical methods that can be used in shallow geological applications such as locating colluvial wedges, faults, or boundaries between subsurface layers. These methods 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).

Recently, electric resistivity tomography (ERT) (Guinea et al. 2010; Ostrowski et al. 2010), refraction tomography (Piatti and Socco 2010; Nolan et al. 2011), and reflection (Baker 1999; Frary et al. 2011) are used in near-surface applications of geophysics such as fault and void detections, geological mapping, environmental applications, etc. In this work we use ERT, refraction tomography, and seismic reflection to find and map a normal fault and its associated colluvial wedge.

Study Area

The study area is located at the western coast of Saudi Arabia (Figure 1a). Alongside the Red Sea in this area there is 40 km wide coastal gravel plain, which is underlain by a listric set of normal fault system (Roobol and Kadi 2008). The faults are very poorly exposed as they cut unconsolidated Tertiary and Cenozoic sediments of the coastal plain, so that fault scarps are often eroded or represented by low gravel banks. One fault of this system is called the Qademah fault, which can be traced along a north-south distance of 25 km. The importance of this fault is that it cuts across a newly developed area in Saudi Arabia where a new city and a new university are established. In this study we used seismic and resistivity to first verify the existence of the fault and second to trace and map it.

Data Acquisition

Seismic refraction tomography (SRT), seismic reflection, and electric resistivity tomography (ERT) data are recorded at two locations toward the northern end of the fault (Figure 1b).

One 2D resistivity imaging section is collected at each site. We used 64 electrodes with 5 m electrode spacing. The Syscal R2 instrument is used for the data collection and Res2DInv software is used to invert the collected data. Figures 2a and 2c show the raw resistivity data collected at sites 1 and 2, respectively

One seismic data set is collected at site 1. It has 109 common shot gather (CSG) with 109 receiver/CSG, where the shot/receiver interval is 3 m.

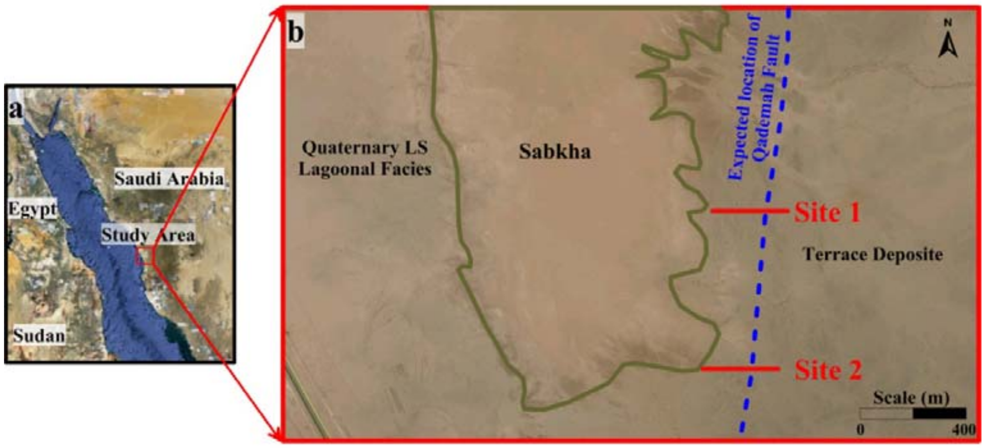

Figure 1 *A map shows the location of the study area and the two sites where we collected data.*

Data Processing and Interpretation

Electric resistivity tomograms (Figures. 2b and 2d) show the existence of 5 different subsurface units:

1. A low resistivity layer (5 to 30 Ω.m) is shown at an offset x=211-252 m and depth z=5.2-23 m from ground surface. This low resistivity zone is interpreted as the colluvial wedge (CW) associated with the Qademah fault which is partially to fully saturated with saline water coming from the sea (2 km west of the site).

2. A high resistivity layer (> 600 Ω.m) is shown to the east of the colluvial wedge at offset x > 255 m, this is associated with dryer loose sediments (sand, silt, and gravel (SG)).

3. A very low resistivity layer that has a thickness of 1 - 2 m and resistivity < 10 Ω.m. It is corresponding to Sabkha (S) deposits

4. Below the Sabkha layer there is a layer with thickness of 2 - 5 m and resistivity 100-200 Ω.m. It corresponds to fan (F) deposits and consists of fine grained sand and gravel.

5. The lowermost layer has high resistivity values (> 1000 Ω.m) which is corresponding to limestone (LS) deposits.

The Qademah fault appears at offset x=211 and 195 m at sites 1 and 2, respectively, while the antithetic faults appears at offset x=250 and 240 m at sites 1 and 2, respectively.

First arrival travel times of the 109 CSGs are picked and then inverted to get the refraction tomogram shown on Figure 3a. Three units are shown in this tomogram:

1. The upper layer has a thickness of 7 - 9 m from ground surface and velocity < 800 m/s. This layer corresponds to the Sabkha-fan deposits (S and F). The seismic tomogram does not show the Sabkha-fan deposits contact, because their velocities are nearly the same.

2. The lower layer shows velocities ranging between 1800 to 2000 m/s, which corresponds to the limestone (LS) layer.

3. A low velocity zone (LVZ) is shown at offset x=200-248. This LVZ corresponds to the colluvial wedge (CW) associated with the Qademah fault. Its horizontal offset matches well with that shown on the ERT from site 1.

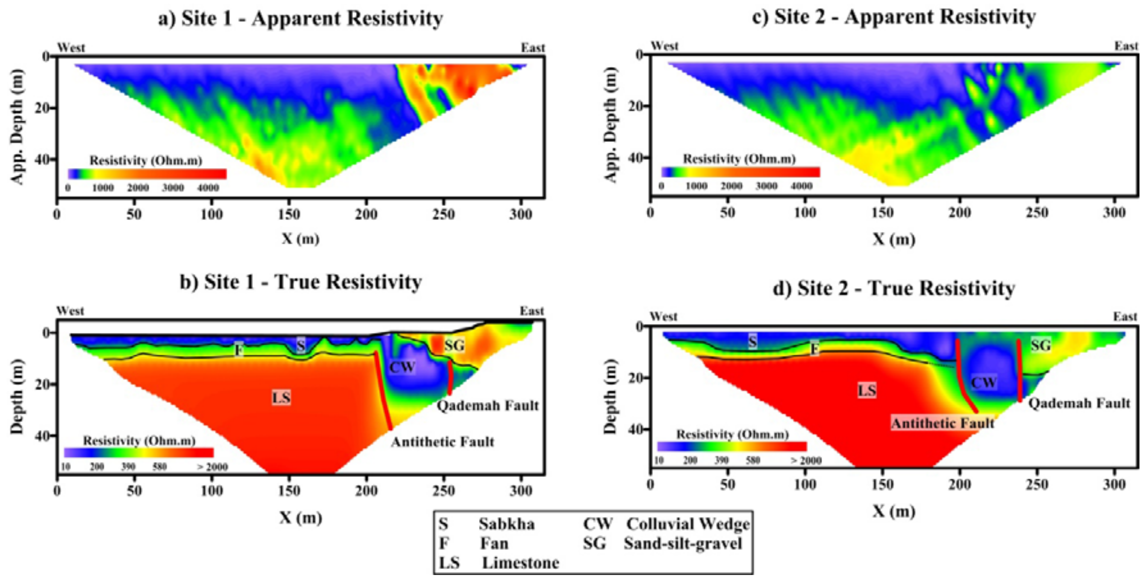

Figure 2 *The collected resistivity (raw) data and the inverted ERT. (a) and (b) are from site 1 while (c) and (d) are from site 2. Red lines represent the Qademah fault and the associated antithetic fault.*

The same seismic data set is used to generate the seismic stacked section shown on Figure 3b. To generate this stacked section we (1) applied AGC, (2) the CSGs are FK filtered to remove the surface waves, (3) deconvoultion, (4) bandpass filter, (5) convert the data to common midpoint gather to get the stacking velocity, and (6) and finally, apply NMO and stack (for more details on processing steps see Baker 1999). Figure 3c shows the stacked section with our interpretation. The Qademah fault and the antithetic fault appears at offset x=241 and x=202 m, respectively, which is similar to both the ERT and the refraction tomography results. However, another antithetic fault appears at offset x=150-160 m. The absence of this antithetic fault on both the ERT and refraction tomogram could be due to the absence of a colluvial wedge, i.e. no low resistivity or low velocity zone is associated with this fault.

Conclusions

Two electric resistivity, one seismic refraction, and one seismic reflection profiles are collected at the western coast of Saudi Arabia to first locate and second trace a subsurface fault. The fault has a poor exposure at the ground surface since it cuts unconsolidated Tertiary and Cenozoic sediments of the coastal plain. The fault, the colluvial wedge, and the antithetic fault are clearly revealed on the ERT, refraction tomogram, and reflection stacked section. The horizontal location of the fault and the thickness of the subsurface geological layers are consistent in the three images.
Future work includes migrating the stacked reflection section and collecting more seismic and resistivity profiles to trace the faults toward the southern direction. Several GPR profiles were collected at this site, but they didn't show useful information since the surface layer is partially saturated with saline water. Trenching is highly recommended to validate the existing results and use it to calibrate further geophysical readings.

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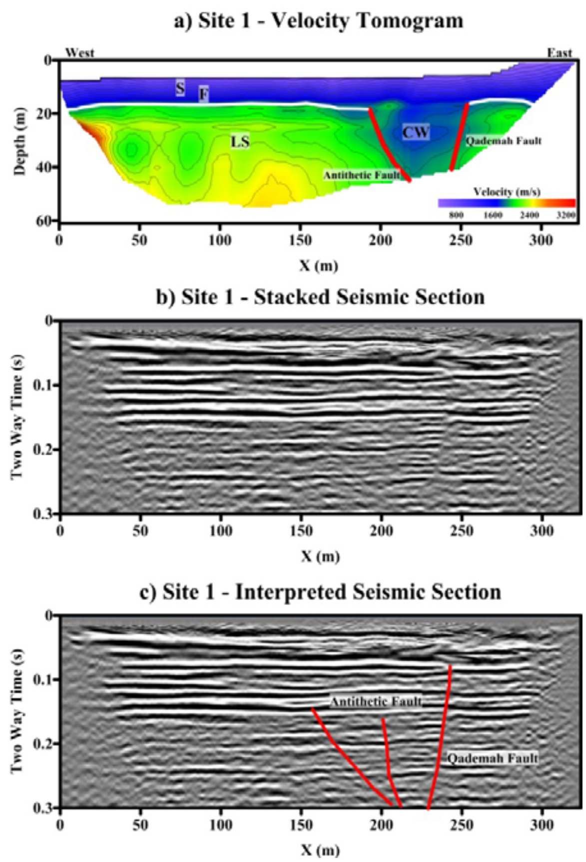

Figure 3 *(a) The inverted seismic refraction tomogram. (b) The seismic reflection stacked section. (c) The same stacked section as in (b) with the red lines represents the interpreted Qademah fault and the antithetic faults associated with it. In the seismic reflection results we can see two antithetic faults while in the refraction and resistivity tomograms only one antithetic fault is shown.*