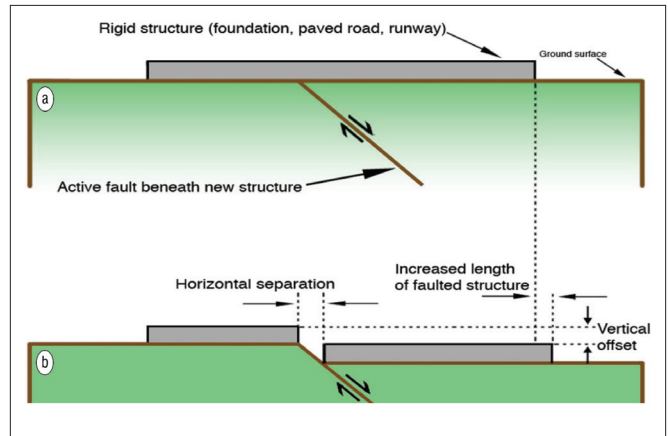


# Geophysical mapping of the Hockley growth fault in northwest Houston, USA, and recent surface observations

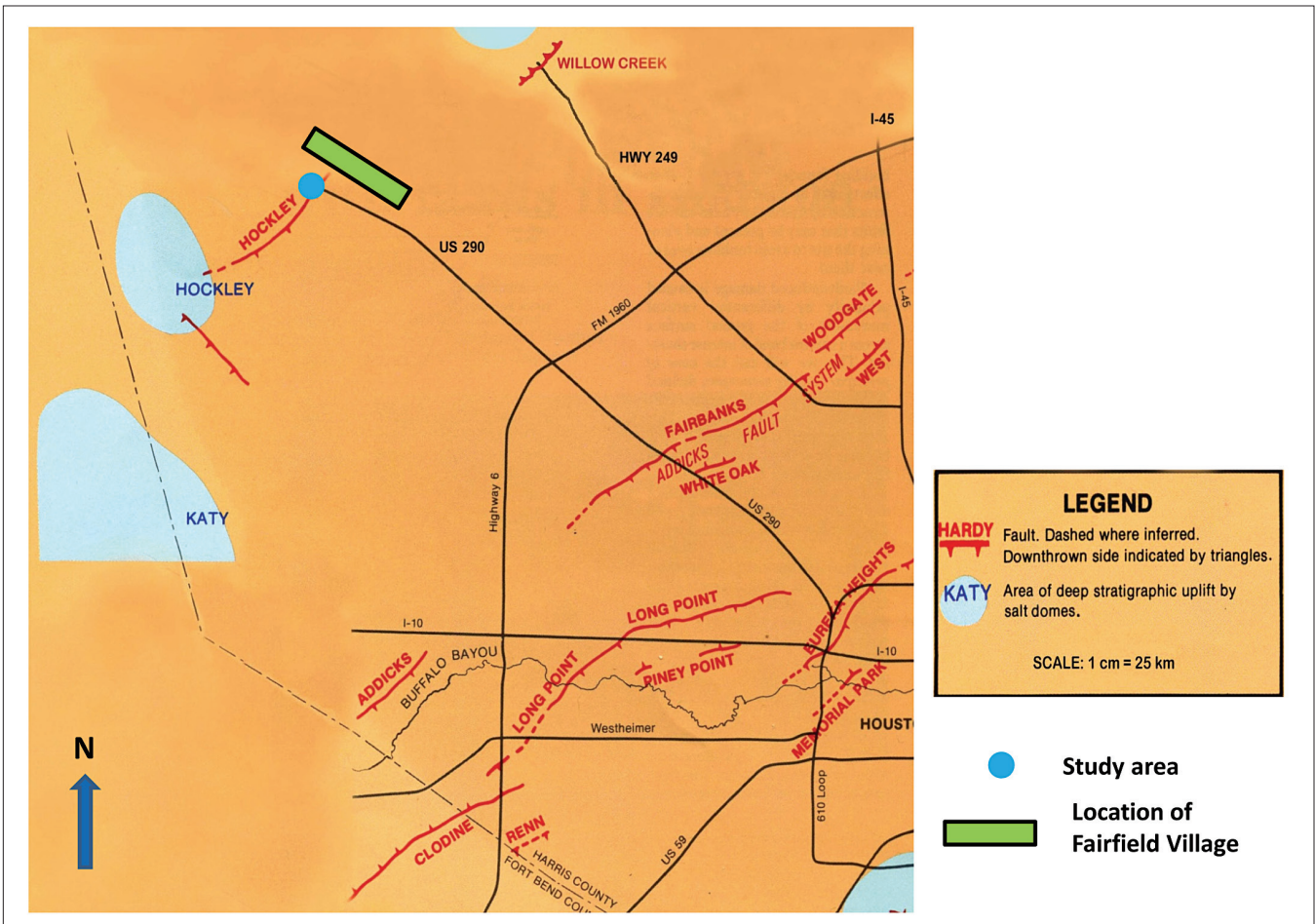
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Active growth faults cutting the land surface around the coast of the Gulf of Mexico represent a serious geohazard. Considering the average movement of these faults is a few inches per decade, the potential is high for structural damage to highways, industrial buildings, residential houses, and railroads that cross these features.

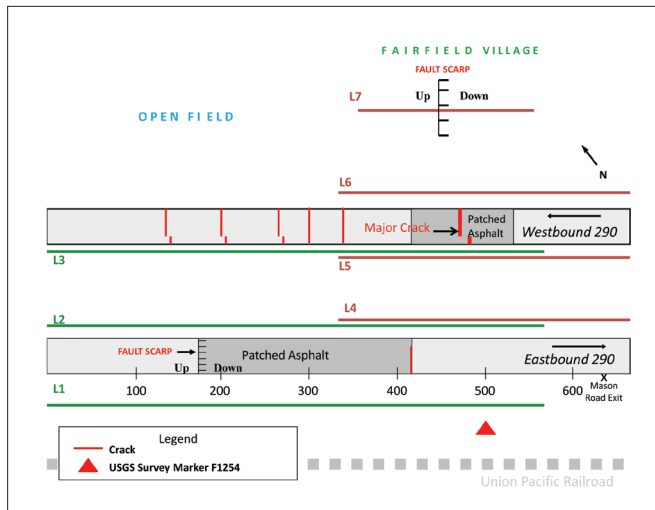
Common methods used to identify these faults include analysis of aerial photographs and field mapping; borehole data on both the down- and upthrown sides of the faults; core data; and familiar geophysical methods such as resistivity, gravity, magnetic, conductivity and ground penetrating radar and gravity. Pioneering resistivity work was performed over some of the Houston faults by Kreitler and McKalips in 1978. Field mapping and analysis of aerial photographs are the most frequently used methods for locating faults in the Gulf Coast area. Geophysical methods are sporadically used to estimate the locations and parameters of these faults. Opinions concerning the effectiveness of these geophysical



**Figure 1.** Effect of fault movement on a rigid structure built on an active fault. (a) Original construction; (b) structure damaged by fault movement. Both vertical offset and horizontal separation are necessary consequences of displacement. Rigid structures may literally be pulled apart as faulting proceeds (modified from Elsbury et al. 1980).



**Figure 2.** Location of Hockley fault in NW Houston (modified after Elsbury et al., 1981).



**Figure 3.** Schematic map of Hockley fault at Highway 290 and Fairfield Village. The thinner red lines show fracture locations. Resistivity data were collected along Lines L1, L2, L3, L4, L5, L6, and L7. GPR data were collected only along Line 1 (L1). Not to scale.

surveys are mixed, and geophysical techniques are not generally recognized as primary tools in engineering-scale fault studies.

However, remarkable advances in the manufacturing of geophysical instruments over the last ten years have made geophysics a viable tool for engineering studies of these faults. Data quality has been increased by the advent of continuous data collection. The data are better processed and interpreted by new and improved software packages, which results in improved subsurface imaging and mapping. This article describes an integrated geophysical survey using ground-penetrating radar (GPR) and resistivity imaging methods over the Hockley fault in the northwest part of Houston, USA. Results indicate that both methods successfully imaged significant anomalies across the known fault location.

## Introduction

The coastal plain of the Gulf of Mexico is underlain by a thick sequence of largely unconsolidated, lenticular deposits of clays and sands. Growth faults are common throughout these unconsolidated sediments. Based on a study of borehole logs and seismic reflection data, faults have been delineated to depths of 12,000 ft below surface (Kasmarek and Strom, 2002). Most of these faults are associated with natural geologic processes such as differential compaction and salt movement and have been active since the Cretaceous. Some faults are currently active and disturb the surface in areas throughout the coastal plain of the Gulf of Mexico (Clanton and Verbeek, 1981). The Houston area has an active shallow fault system as evidenced by active surface movement and measurable localized subsidence (Verbeek and Clanton, 1981).

Evidence of faulting is visible from structural damage such as fractures and/or displacement. Fault movement is predominantly normal, dip-slip down to the south, and listric; but some growth faults are antithetic and down to the



**Figure 4.** A picture showing a significant crack on the westbound lane of Highway 290 prior to the construction of a shopping mall. The picture was taken facing north. Approximate locations of resistivity profiles L5, L6, and L7 are shown.

north. Some active faults are clearly indicated by surface damage such as scarps that cut across lots, fields and streets. The dip on the near-surface faults is generally between 60 and 75°, with vertical exceeding horizontal displacement (Figure 1).

Today, active faults can be the source of considerable damage to pavements, utilities, homes, businesses, and other manmade structures in the Gulf Coast region. In the Houston area alone (Harris County), there are more than 300 active or potentially active faults that combined total more than 300 miles in length. These active faults are usually not discrete rupture planes, but zones of sheared ground tens of meters wide (Clanton and Verbeek).

The NE-SW Hockley fault is more than five miles long, extending from the Hockley salt dome, across Highway 290 to its terminus in Fairfield Village (Figure 2). The fault is downthrown toward the coast, and is considered to be the near-surface expression of slow gravity creep of more plastic materials (rock salt and shale) at greater depths toward the Sigsbee deep of the Gulf of Mexico (Elsbury et al., 1981).

The study area was evaluated in 1991 in a report for the construction of Fairfield Village that describes the Hockley fault passing through the site with a fault scarp 40 ft in height.

This paper presents and evaluates the use of two non-invasive geophysical methods for investigating the Hockley growth fault across Highway 290.

## Geophysical instruments

Resistivity imaging has been widely used in mapping contaminant plumes, karst features (voids), and subsurface structures, such as faults and fractures. In this study, the Advanced Geosciences (AGI) Super R1 Sting/Swift resistivity meter with the dipole-dipole resistivity technique is used. This technique is more sensitive to horizontal changes in the subsurface, and provides a 2D electrical image of the near-surface geology. Electrode spacing was held to 6 m along all profiles. The depth of the investigation was approximately 135 ft (~41 m).

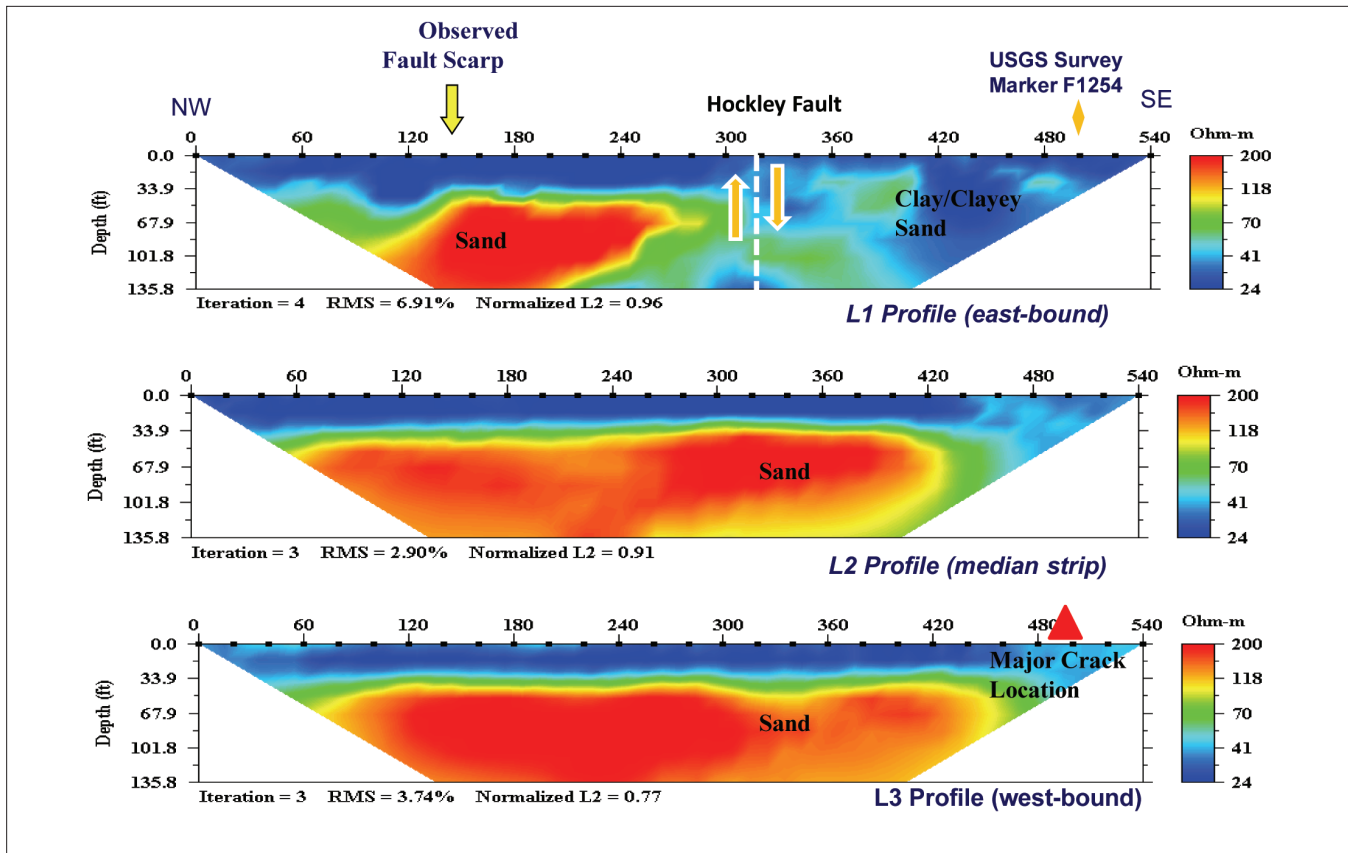


Figure 5. Resistivity imaging data along profiles L1, L2, and L3 (see Figure 3 for locations).

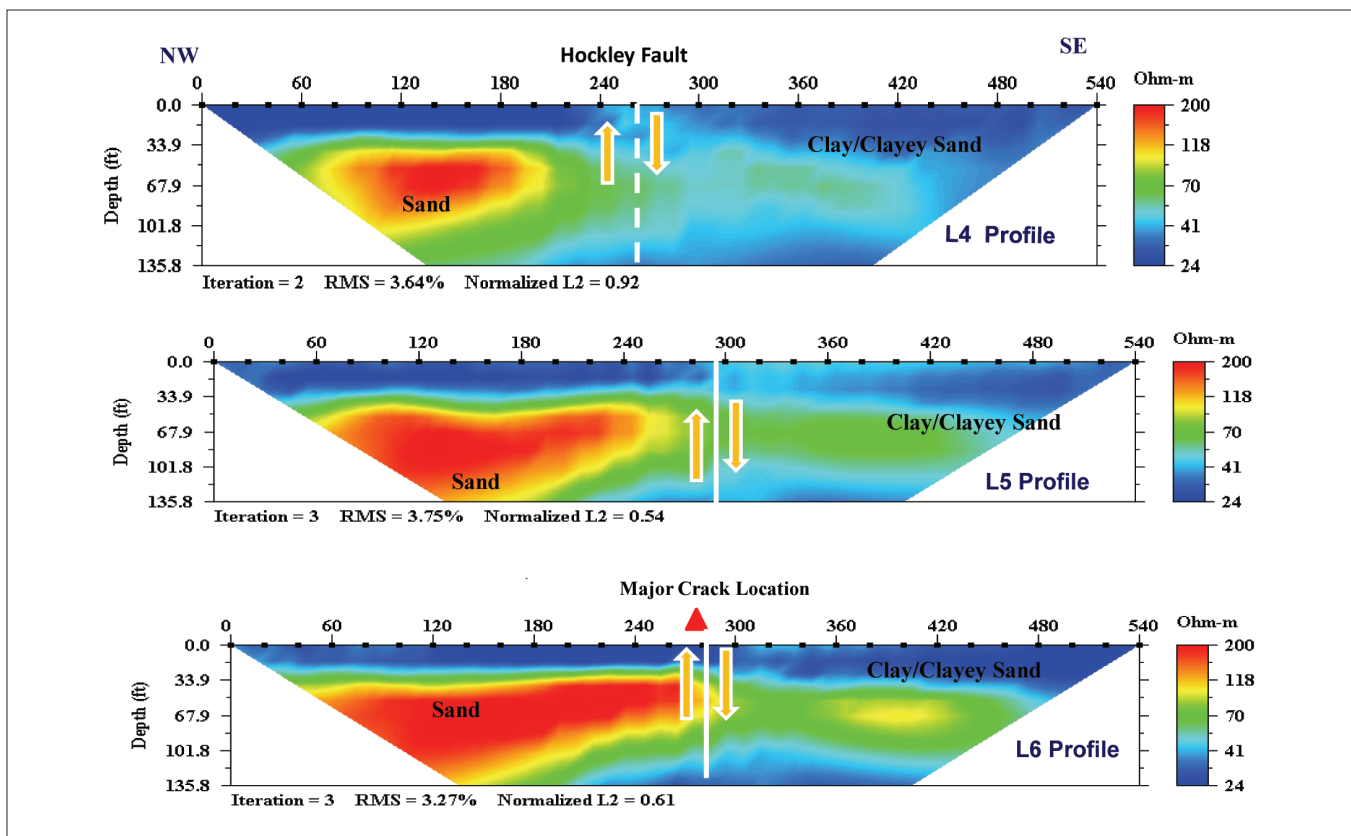
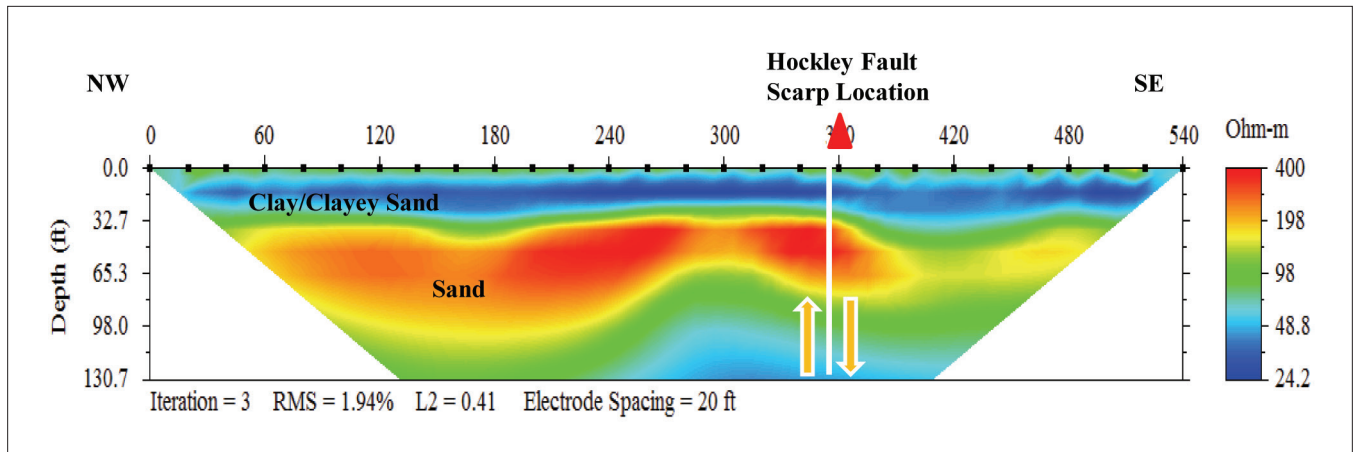


Figure 6. Resistivity imaging data along profiles L4, L5, and L6 (see Figure 3 for locations).





**Figure 7.** Resistivity imaging data along profile 7. Note the correlation of the resistivity anomaly and observed fault scarp in the field. Note also the increased thickness of the clay/clayey sand (blue) in the downthrown side of the fault (see Figures 3 and 4 for location).

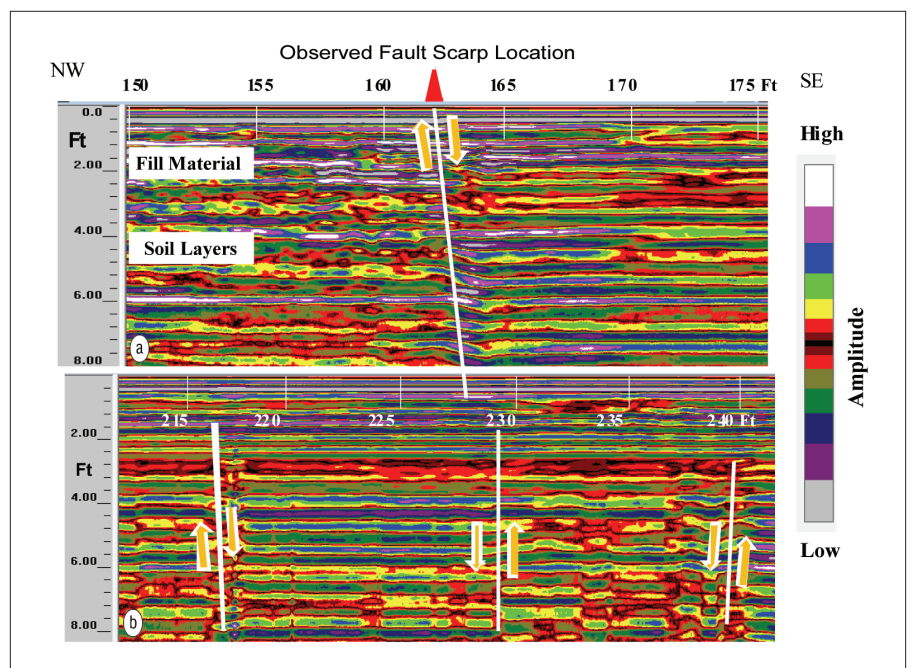
The 400-MHz antenna was used with a cart system to collect GPR data. The ability of a GPR system to work successfully depends upon two electrical properties of the subsurface, electrical conductivity and relative dielectric permittivity (i.e., dielectric constant). The value of dielectric constant ranges between 1 (for air) and 81 (for water). The dielectric constant for sandy clayey soils varies between 10 and 15. A dielectric constant of 12 was chosen for the study area, and the depth exploration with the GPR unit was approximately 8 ft.

**Survey design and data processing**

In 2004 and 2005, I performed GPR and resistivity surveys along line 1 on the eastbound side of Highway 290 (Figure 3). I also obtained resistivity profiles on both sides of Highway 290, and along a line between Fairfield Village and Highway 290. In November 2009, I collected GPR data along the eastbound and westbound profiles (Figure 3). In all, seven resistivity surveys and one GPR profile were performed.

During the surveys in 2004, I sketched the locations of the cracks and patched pavement locations on both sides of the highway and mapped a discrete fault scarp on the south side of the highway (Figure 3). Another fault scarp was also mapped along one of the resistivity profiles, in an open field between the highway and Fairfield Village (Figure 3). In addition, a major crack is observed crossing the highway on the north side (Figure 3 and 4). Resistivity profiles L4, L5, and L6 crossed over this significant crack.

Resistivity data were processed and inverted using AGI Earth Imager software. The resistivity values obtained in this study varied between 24 and 400 ohm-m. Resistivity values, in general, of 30 ohm-m and greater correspond to sand units;



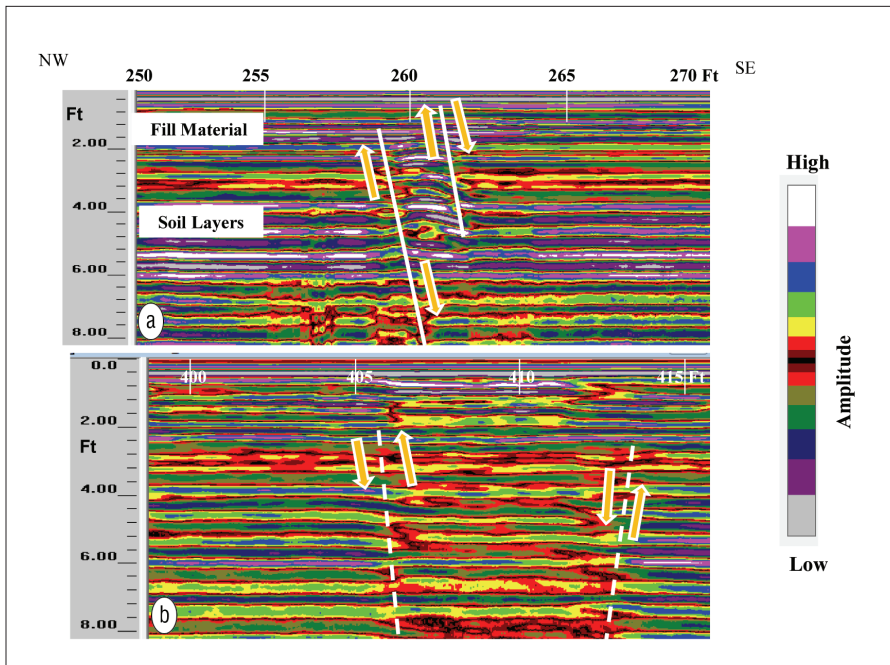
**Figure 8.** GPR data along line 1 between stations 150 and 175 ft (a) and stations 215 and 240 ft (b). Note the fault offset of GPR data over the scarp location. There are small-scale faults downthrown to the southeast as well as to northwest.

whereas resistivity values less than 30 ohm-m correspond to clayey sand, sandy clay, and silty sand.

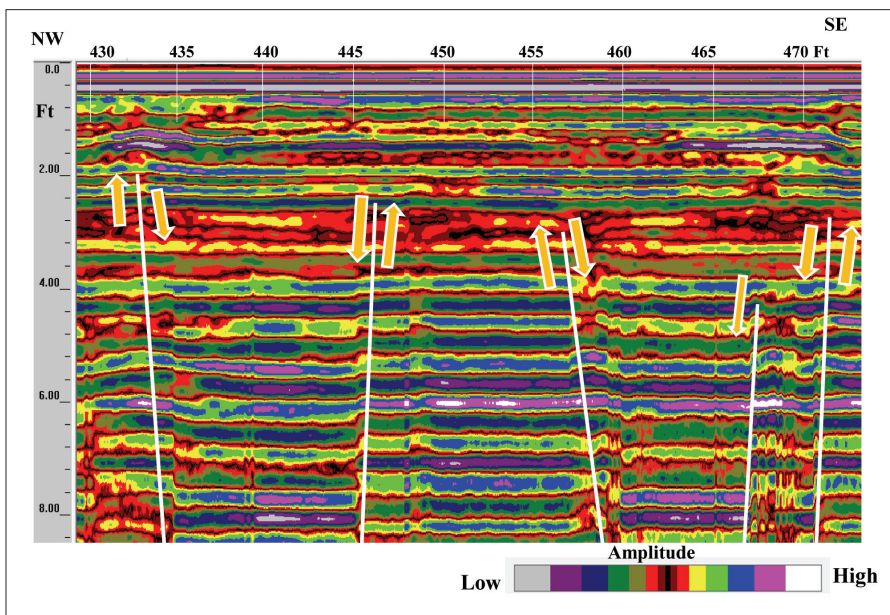
The 400-MHz GPR data is displayed in a color-amplitude format, and a color assigned to a specific positive or negative value of the recorded signal.

The resistivity profiles in Figures 5–7 indicate sandy clay and sand units. Spacing of resistivity profiles L1, L2, and L3 (Figure 5) is from 75 to 100 ft. Profile L1 does not indicate any fault offset visible in the soil layers over the fault scarp, which where present was several inches in height. Instead, a fault-like anomaly is observed at approximately 300 ft to the southeast. Resistivity profiles L2 and L3 do not indicate any fault offset along their entire lengths. However, there is an apparent resistivity contrast toward the end of the profiles between the sand and clay layers, although confidence in the





**Figure 9.** GPR data along line 1 between stations 150 and 175 ft (a) and stations 215 and 240 ft (b). There are small-scale faults downthrown to the southeast as well as to the northwest.



**Figure 10.** GPR data along line 1 between stations 430 and 470 ft. There are small-scale faults downthrown to the southeast as well as to the northwest. Note the graben-like structure between stations 430 and 445 ft and 455 and 470 ft.

resistivity data decreases toward the edges.

In order to map the resistivity contrast, three more resistivity profiles (L4, L5, and L6) were surveyed (Figure 6). A fault-like anomaly is present from 240 to 280 ft on all three data sets.

Figure 7 shows resistivity profile L7, which was taken in an open field between the westbound lane of Highway 290 and Fairfield Village. This area was covered with vegetations during acquisition. For reference purposes, the SE end of the

profile was next to the asphalt pavement. A distinctive fault scarp (several inches in height) was observed at this location, and profile L7 displays the resistivity data over the fault. The fault scarp was located at a station 360 ft on the resistivity profile and a fault-like anomaly is observed in the data at that same station.

Significant anomalies can be observed in the GPR data along the resistivity profile L1 between the fault scarp and the USGS survey marker F1254. The deformation is interpreted to consist of small faults and fractures in the fill materials beneath the pavement and sandy soil underlying the fill materials of the highway road. Location of GPR anomalies are identified according to their respective station coordinates, and shown in Figures 8–10. It should be noted that the horizontal scale for the GPR profile is exactly the same as for resistivity profile L1.

A vertical offset over the fault scarp can be observed at approximately 160 ft in Figure 7a. This offset includes the fill materials and the underlying soil layers. Figure 7b shows several small-scale faults between stations 215 and 240 ft. Figures 8a and 8b show small faults between stations 250 and 415 ft. Small faults between stations 430 and 470 ft are evident on Figure 10. Two micrograben-like structures, approximately 14 ft in length, are defined by the small-scale faulting.

I resurveyed line 1 on the south side and line 6 on the north side of the highway. The repeated GPR survey data on line 1 and line 6 did not show the anomalies (including the fault scarp) discussed in the previous paragraphs. The reason for this may be related to the removal of native soils during the construction of the highway and any maintenance due to road damage from ground movement. It should be noted

that since the initial geophysical surveys, Highway 290 was rebuilt and a Houston Primary Outlet Shopping Mall was constructed in the vicinity of Hockley fault. The original east and westbound lanes of the Highway 290 have been rebuilt and have become feeder roads.

### Discussion and conclusions

The resistivity data from the four profiles (L4, L5, L6, and L7) are interpreted to have imaged a normal fault set that is

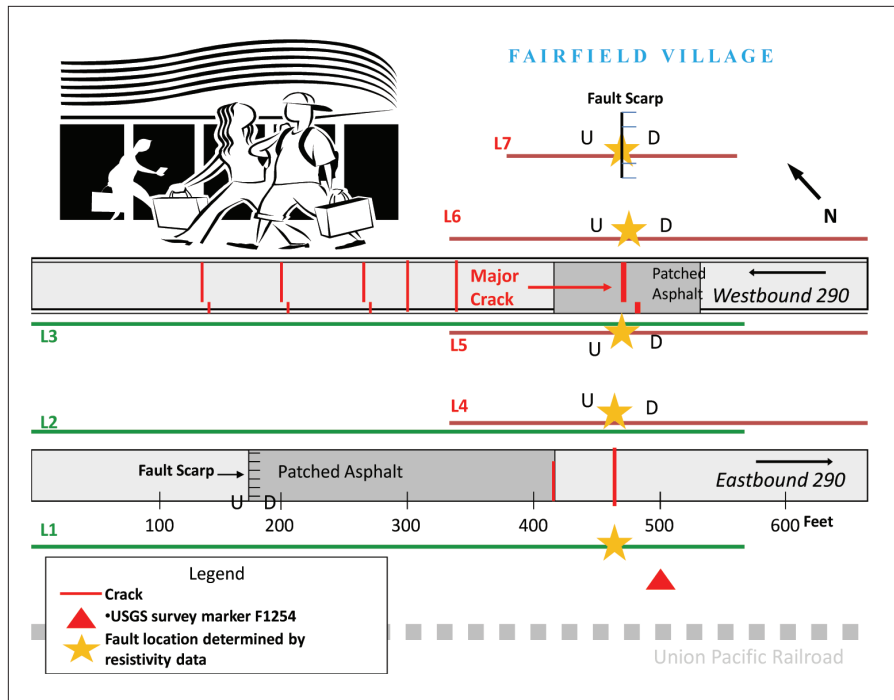


Figure 11. Approximate locations of Hockley fault determined by the geophysical data. A sketch of the shopping mall is shown in the NW section of the study area.



Figure 12. Map showing approximate extension of the Hockley fault zone in the vicinity of Houston Premium Outlet Shopping Mall.

downthrown to the southeast. The observed surface location of the fault scarp correlates well with the interpretation of resistivity Line 7. The combination of clayey sand with 24 ohm-m resistivity (shown in blue), and sand layers with 70 ohm-m resistivity (shown in green) is indicative of a dipping and curved fault plane. No fault like anomaly (no offset between the soil layers) is evident in the resistivity data from L2 and L3. Resistivity profile L1 possesses an anomaly at the approximate location of the fault but does not display the characteristic layer offset interpreted on the other profiles. The reason for this may be the presence of more clayey soil where

consistent anomalies with a known fault zone. It is clear that, as this study and a study of the Willow Creek Fault (Saribudak and Van Nieuwenhuise) suggest, these geophysical methods can be used to map Gulf Coast faults quickly and inexpensively. Further geophysical surveys of these faults will better define their development and geophysical signatures. Confidence to independently describe growth faults in the Houston metropolitan area in the future should increase as successful detection of fault-based anomalies becomes more routine. Depending on site conditions, future fault studies should include as many of the geophysical techniques described here as

the fault plane crosses the eastbound lane. Unpublished magnetic, gravity and conductivity data on Line 1 also indicate a fault anomaly where the resistivity data is interpreted to show the fault (Saribudak and Van Nieuwenhuise, 2005). The location of the fault as interpreted on the resistivity data appears to shift to the northwest from L7 through L1 (Figure 11). The fault scarp observed on the ground surface does not appear to be present on the resistivity data along line 1. The reason for the lack of evidence in the resistivity data for the fault scarp anomaly could be the fact that the scarp may be related to one of the minor shallow faults evident in the GPR data.

The GPR data along profile L1 indicate significant anomalies that are believed to be caused by small displacement faults in the near-surface. These small faults are likely normal with movement down to the southeast and consistent with the movement of the Hockley fault.

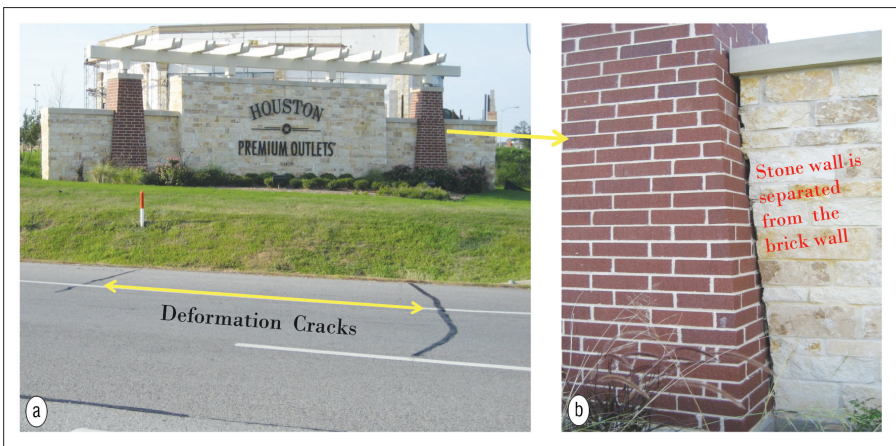
The resistivity and GPR data indicate a wide zone of deformation across the Hockley fault. Geophysical data presented here combined with the field observations indicate a deformation zone of approximately 400 ft that includes the east- and westbound lanes of Highway 290 (now access roads to the shopping mall). The principal fault plane and its associated shallow zone of deformation are in the vicinity of a newly built shopping mall. The zone of fault-induced deformation extends under the eastern part of the parking lot and the major entrance road to the mall (Figure 12).

In conclusion, geophysical data acquired and used to detect growth faults in the NW Houston area allowed correlation and delineation of unique and





**Figure 13.** Recent pictures of Hockley fault at Highway 290 Frontage and Fairfield Falls Way roads: (a) taken in April 2010 and (b) taken in August 2010. Note the development of the tiny cracks in (a) into significant ones in (b).



**Figure 14.** Pictures of road (a) and wall deformation (b) to the immediate west of the Hockley fault was taken in August 2010.

practical to both improve fault characterization and correlate surface features with the subsurface structures. Results of this study show the benefit of a well rounded investigation that includes geophysical methods as well as the more commonly

used borehole logging techniques for mapping faults today.

the subject since the late 1970s. Verbeek and Clanton, in 1981, pointed out that there were 150 faults (now exceeding 300) in the Houston area. These faults damage road pavements, pipelines, bridges, rail-

used borehole logging techniques for mapping faults today.

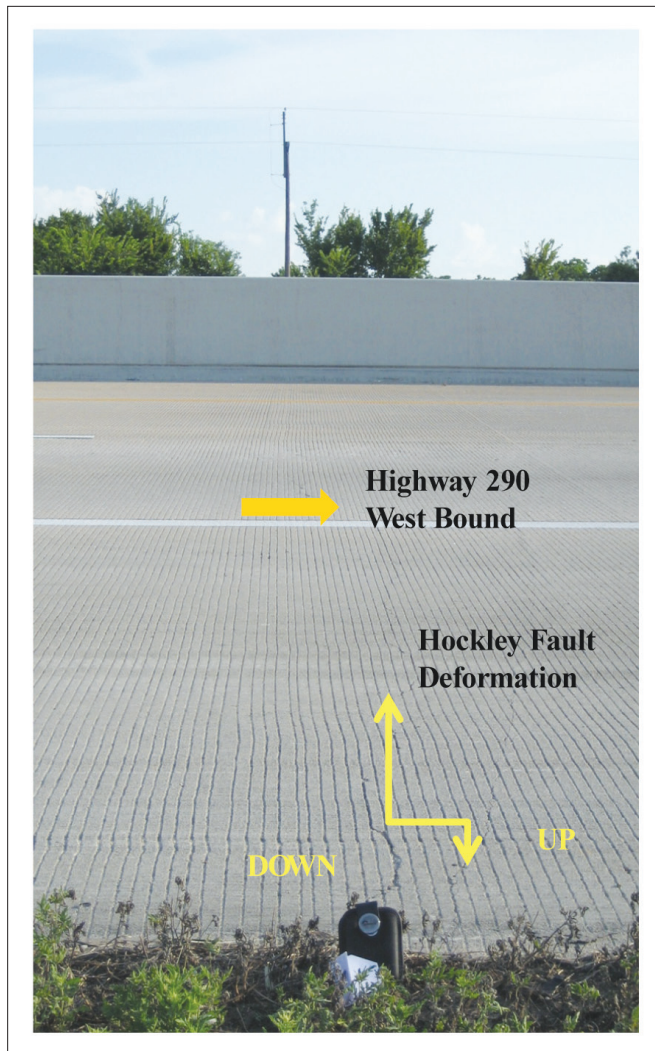
**Postscript**

Since the measurements discussed previously were taken, a shopping mall was built in the vicinity of the Hockley Fault zone (Figure 12), and Highway 290 was rebuilt and extended, covering the evidence for the fault. Site visits during April and August 2010 provide additional evidence in developing a fault growth past and predictions for the future (Figure 13). Small cracks in the pavement over the main fault trace photographed in April 2010 had extended and widened significantly by August. Note that the cracks in Figure 2b have been filled with asphalt.

Geophysical results previously discussed suggested correlations between several small faults and the cracks observed on Highway 290 frontage roads. Figure 14 shows two developing cracks to the west of the main Hockley fault plane. Mortar stone and brick walls in the background show evidence of unique fault deformation in Figure 14b. The brick wall appears to be separated from the stone wall due to combination of horizontal and vertical offsets expected from this type of growth fault (Figure 1). The original cement holding the brick and stone walls is no longer visible at this location due to the detachment. Although this type of deformation could also be due to local settling or erosion of fill materials beneath the brick wall, its apparent relationship to the cracks in the asphalt are strong evidence for this being fault related.

The Hockley Fault continues across Highway 290 (Figure 15) and the uneven highway surface caused by movement of the fault can be felt by an alert driver. This observation is consistent with the geophysical study and is strong evidence that the ground surface in the area is changing with active faulting being one of the drivers. The USGS has published many articles on





**Figure 15.** A recent picture (August 2010) showing revived cracks (main Hockley fault) on the westbound side of Highway 290. The fault deforms the newly built Highway 290 and the feeder roads. The picture was taken facing south.

road, tunnels, refineries, as well as private homes in the Houston area. In recent years, a public school in the NW part of the Houston (Tomball) was abandoned due to damage from an active fault. The fault hazard is real and needs to be miti-

gated by avoidance and application of good engineering design and land use practices. **TLE**

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*Acknowledgments: I thank Carl Norman for showing the Hockley fault in the field and a number of friends and colleagues who helped in the data acquisition. I am thankful to Bill Rizer for his instructive and critical editing of the manuscript. I also thank Esin Saribudak for her graphical contribution to this paper. This research project was funded by Environmental Geophysics Associates. Finally, I thank Rick Miller for his detailed and invaluable comments and revisions, which greatly improved the flow of this paper.*

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