Integrated geophysical studies over an active growth fault in Houston

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Active growth faults cutting the land surface in the Gulf Coast area 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 to identify these faults include aerial photographs and field mapping; subsurface borehole data on both the down and upthrown sides of the faults including geophysical logs and core data along with borehole data; and such familiar geophysical methods as resistivity, gravity, magnetics, and conductivity.

The first two of these investigation techniques are the most frequently used in the Gulf Coast area. Geophysical methods are sporadically used to estimate the locations and parameters of these faults. Opinion concerning the effectiveness of geophysical surveys is mixed, and therefore 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 10 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 result in highly detailed mapping or subsurface imaging.

We have conducted an integrated geophysical survey utilizing ground-penetrating radar (GPR), resistivity imaging, magnetics, and microgravity—over the Hockley and Willow Creek faults in the northwest part of Houston. Results of this investigation indicate that all methods have imaged significant anomalies across the known fault locations.

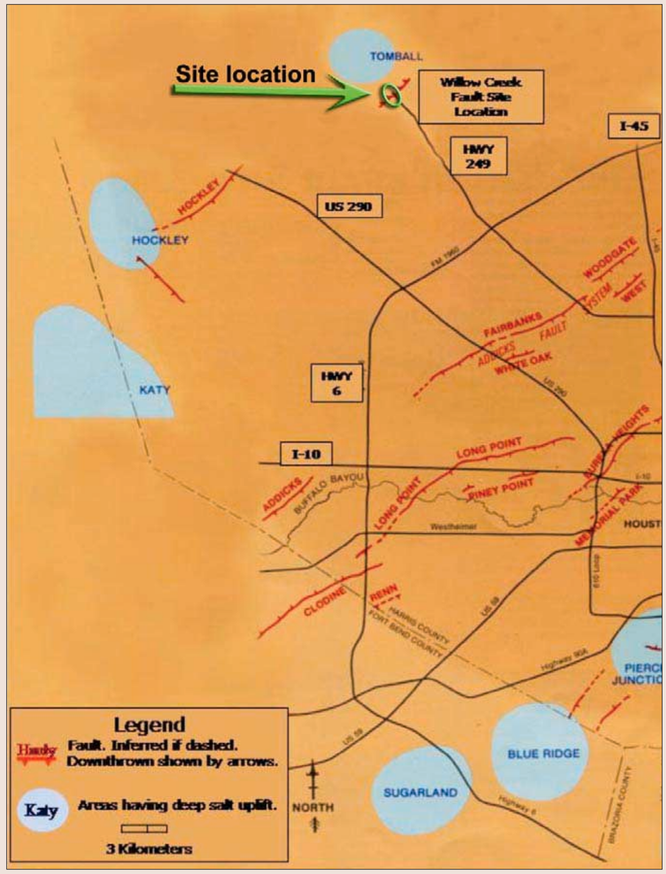

Figure 1. Willow Creek fault site location, annotated as a green ellipse (after Elsbury et al.).

Background. 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, these faults have been delineated to depths of 1000-4000 m below surface. Most of these faults are associated with natural geologic processes such as differential compaction and salt movement and have been active since the Cretaceous. As a result, some faults are currently active and disturbed throughout the coastal plain of the Gulf of Mexico.

The Houston area has a very active shallow fault system as evidenced by active surface movement and measurable localized subsidence.

Evidence of faulting is visible from structural damage such as fractures and/or displacement. Fault movement is predominantly normal, dip-slip listric type with some growth faults being antithetic (north-dipping), but most are synthetic (south-dipping). Some active faults are clearly evident in surface damage such as scarps across lots, fields, and streets.

Today, active faults are the source of heavy 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 with a total length exceeding 300 miles. These active faults are not discrete ruptures. Rather, they are zones of intensely sheared ground tens of meters wide.

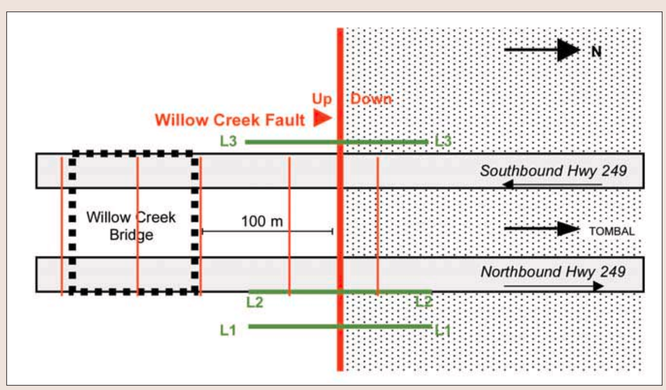

Figure 2. Schematic map of Willow Creek fault at Willow Creek Bridge. The thinner red lines show fracture locations. Resistivity data were collected along lines L1, L2, and L3 (green). Microgravity and magnetic data were collected only along line 2 (L2).

This paper presents and evaluates the use of four noninvasive geophysical methods for investigating the Willow Creek growth fault along Highway 249 in northwest Houston (Figure 1).

Figure 3. *Willow Creek fault scarp across Highway 249. Note the several fractures and asphalt patches on the road. The picture was taken facing east. The car was going toward the bridge on the south (upthrown) side of the fault.*

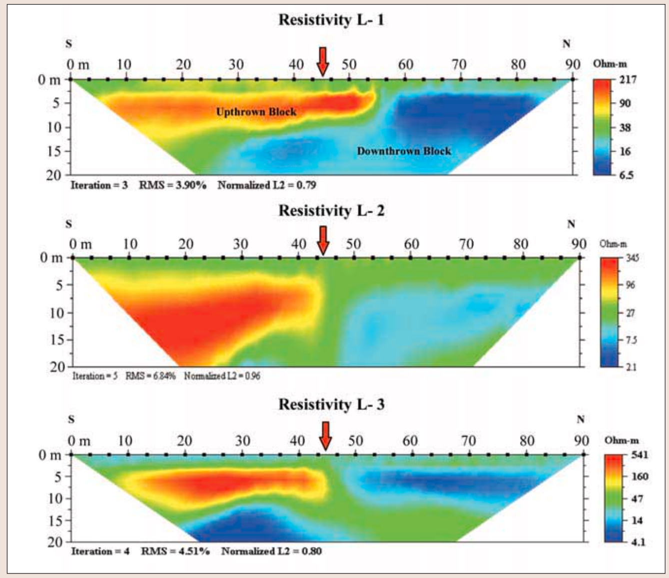

Figure 5. *2D resistivity imaging profiles taken along the east and west bounds of Highway 249 across Willow Creek fault.*

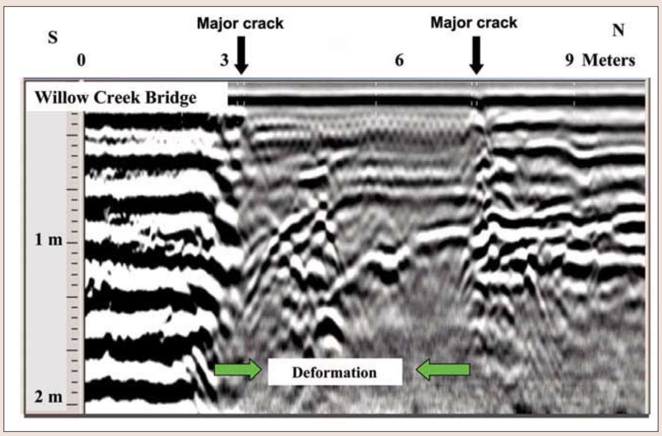

Figure 4. *GPR data taken adjacent to the northern end of the Willow Creek Bridge. Similar GPR results were also obtained at the southern end of the bridge.*

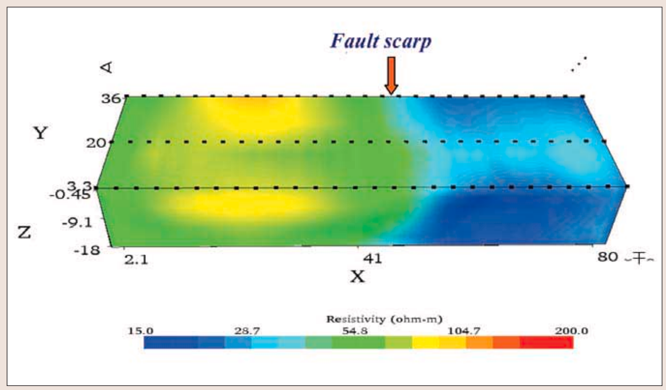

Figure 6. *3D resistivity image across Willow Creek fault.*

Geophysical instruments and survey design. GPR, resistivity imaging (2D and 3D), magnetic and, microgravity methods were customized for this application. We utilized a SIR 2000 GPR unit with a 400-MHz antenna which, considering the soils, was estimated to have a 2.5-m maximum depth of investigation over the fault location. A Geometrics G-858 Cesium vapor magnetometer allowed automated data collection with samples recorded every 0.2 s (or 5 Hz), corresponding to a data point about every 1/3 m or so.

Microgravity data were acquired using a LaCoste & Romberg G-Meter, SN-670. Data were tied to three gravity base stations at a building formerly used by Photogravity, Inc., one at the Willow Creek site, and one at an intermediary location in Spring, Texas. This allowed rapid reoccupation of gravity base stations and increased gravity data repeatability (<0.04 mGals) throughout the survey. The gravity station spacing was 3 m across the fault scarp and 6 m away from the fault scarp.

AGI's Super R1 Sting/Swift automatic resistivity unit was used with a dipole-dipole resistivity array having 28 electrodes. This increases the sensitivity to horizontal changes in the subsurface and provides a 2D electrical image of the subsurface geology. Electrode spacing was held to 3 m along all profiles.

Geophysical results. The Willow Creek fault is about 100 m north of the Willow Creek Bridge, trends in the NE-SW direction, and dips to the north (Figure 2). This fault is an antithetic listric fault related to the south-dipping regional Tomball synthetic listric fault about 3 km north. A discrete pavement break crossing both south and north bounds of Highway 249 clearly marks the presence of the fault (Figure 3).

Many fractures adjacent and across the bridge can be attributed to the presence of the fault. A GPR survey profile near the north end of the bridge (Figure 4) indicates a significant deformation zone next to the bridge. We also collected GPR data across the fault scarp, but the GPR data did not show any anomaly across this scarp. However, the GPR data do detect differential subsidence between the bridge and the footing as seen in the deformation zone detected and the Willow Creek fault movement is a likely catalyst for this.

2D resistivity data (three profiles) taken across the fault along Highway 249 indicate a sharp resistivity contrast over the fault scarp (Figure 5). The resistivity contrast is probably caused by the combination of increased moisture content and changes in the clay content of the subsurface lithology on the downthrown side of the fault. Increased surface moisture has been observed on the downthrown side of the Willow Creek fault on every visit to the site.

A 3D resistivity image was created by combining the three (L1, L2, and L3) 2D resistivity profiles, and is shown in Figure 6. The fault scarp observed at the site closely matches where a significant resistivity contrast exists on the

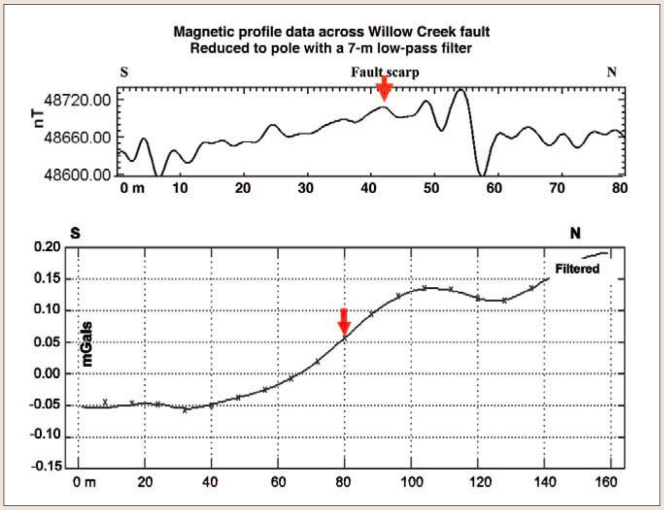

Figure 7. Correlation of (top) magnetic and (bottom) gravity data across Willow Creek fault. Note the gravity high on the downthrown side. The regional gravity field is not removed.

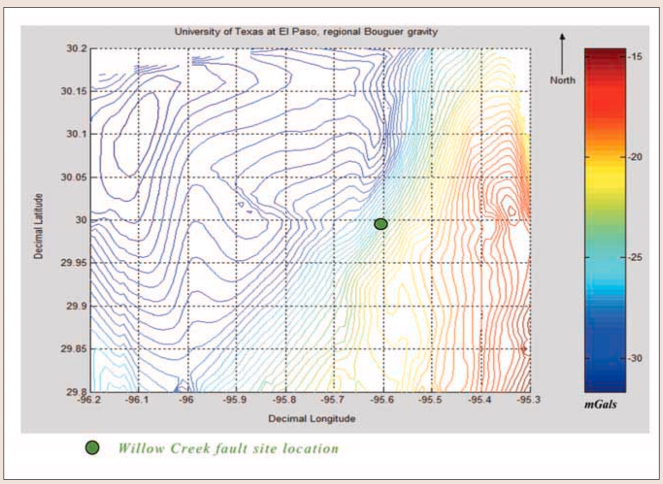

Figure 8. Map showing University of Texas El Paso regional complete Bouguer gravity in NW Houston. Note the steep gravity gradient at the location of the Willow Creek fault site. The Willow Creek fault is visible on the surface at the location marked (Figure 3).

3D resistivity block diagram. Note the low resistivity on the downthrown (north) side.

Microgravity and magnetic data (Figure 7) were acquired along resistivity line 2 (L2 in Figure 2). The simple Bouguer gravity data are referenced to the IGF1967 and the GRS1967. The data were terrain- and elevation-corrected using elevation from a Berger/CST auto-level tied to local reference/bench marks. A Bouguer correction density of 2.2 gm/cc was utilized for the shallow, unconsolidated sediments. Microgravity data were filtered using a 7-m low-pass filter. Data can be interpreted to indicate a gravity high correlated with the downthrown side of the fault. The magnetic data, reduced to pole and filtered using a 7-m low-pass filter, show a magnetic low on the downthrown side of the fault.

The fault locations interpreted from the magnetic and gravity data correlate extremely well with the location of the pavement break (fault scarp) observed on the ground.

Gravity data across the fault have been modeled and interpreted using the analog equation for a thin fault, the thin-slab equation, and Talwani-type 2D modeling. The results obtained from the thin-slab equation and analog equation for a thin-fault indicate the vertical throw for the shallow fault at Willow Creek could possibly be as small as 3 m while the main fault appears to have a vertical throw of approximately 17 m. The full vertical throw of the fault is not detectable on the microgravity data whereas it appears detectable in the regional data (Figure 8). This difference is due to the scale of the feature detected by the microgravity versus the feature detected by the regional gravity. A regional gravity field was not removed from the microgravity as we are attempting to detect an extremely low-amplitude (<0.25 mGal) effect at the site.

Discussion and conclusions. Geophysical data are interpreted to indicate significant geophysical anomalies exist within the known Willow Creek fault zone. 2D and 3D resistivity data appear to image the downthrown side of the fault as possessing less resistive materials than the upthrown side — i.e., sand versus sandy clay and/or sand with increased moisture. A gravity high observed on the downthrown side of the fault in the microgravity data is probably caused by the compaction of the unconsolidated sediments in the downthrown side (dewatering). The GPR data were sensitive to near-surface deformation next to the Willow Creek Bridge. Magnetic data are characterized by a well defined magnetic low on the downthrown side of the fault.

In conclusion, data acquired and used to evaluate the effectiveness of geophysical methods to detect growth faults in the NW Houston area allowed correlation of unique and consistent anomalies with a known fault zone. It is still unclear that these methods could be used to map fault zones independently; however, it is clear these techniques can be useful to quickly and inexpensively map the continuation of these Gulf Coast faults from one known site to another. Continuation of geophysical studies of these Gulf Coast faults will allow their geophysical signatures to be catalogued. Confidence to independently describe growth faults in the Houston metropolitan area in the future should be possible as successful detection of fault-based anomalies becomes routine and predictable. Depending on site conditions, any future fault study should include as many of the geophysical techniques described here as possible to both improve and extend characterization of the subsurface.

Suggested reading. "Photographic portraits of active faults in the Houston metropolitan area, Texas" (in *Houston Area Environmental Geology: Surface Faulting, Ground Subsidence, Hazard Liability*, Houston Geological Society, 1981). "Living with faults in Houston" by Elsbury et al. (*Soundings*, Fall and Spring, 1981). *Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Chicot and Evangeline Aquifers, Houston, Texas, U.S.* by Kasmarek and Strom (Geological Survey, Water-Resources Investigations Report 02-4022, 2002). "Historically active faults in the Houston metropolitan area, Texas" by Verbeek and Clanton (in *Houston Area Environmental Geology: Surface Faulting, Ground Subsidence, Hazard Liability*).
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