Growth Faulting and Subsidence in the Houston, Texas Area:

A Guide to the Origins, Relationships, Hazards, Potential Impacts, and Methods of Investigation

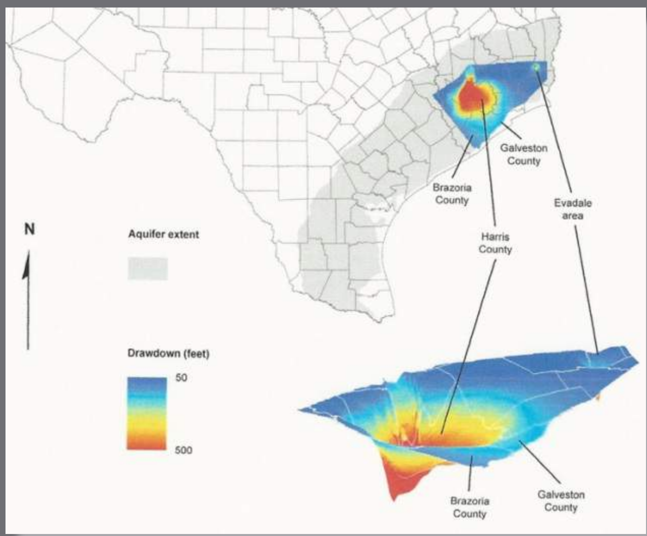
For the Graduates and Members of

The Institute of Environmental Technology
Houston, Texas,

The Houston Geological Society,

and

The American Institute of Professional Geologists



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Growth Faulting and Subsidence in the Houston, Texas Area:

Guide to the Origins, Relationships, Hazards, Potential Impacts and Methods of Investigation

by

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Abstract

The Houston area, and the Gulf Coast in general, is laced by numerous growth faults which are geological hazards that are known to impact and damage house slabs, building-support structures, highways and associated foundations. Water-supply wells and pipelines, oil and gas wells and pipelines, and other anthropogenic structures are also affected by growth faults, and have cost millions of dollars to repair over the years as a result of the small, but significant, movement of these faults. At depth, these faults have created economically important oil and gas reservoirs, sulfur and uranium deposits, and geopressured-geothermal energy. But they also provide pathways for dissolved uranium and radionuclides (e.g. ^{226}radium and ^{222}radon) and natural gas to migrate from great depths upward into Houston's groundwater supplies in various areas within the Evangeline and overlying Chicot Aquifers. Such pathways also allow other hazardous substances from human activities to migrate vertically or from one water-bearing unit to another. Such faults impact the Houston environs as a subsurface geological hazard although their full significance has gone unrecognized for decades since the U.S. Geological Survey (U.S.G.S.) budgets for mapping the faults in the Houston area were eliminated in the late 1970s. Houston's building foundation repair industry has since flourished in fault-prone areas unsuitable for construction without foundation design accommodations. This would require a more complete knowledge of fault locations throughout the Houston area.

We have reviewed and synthesized a wealth of information on the origins and characteristics of growth faults, their apparent relationship to salt domes and subsidence, and the nature of the damage and the economic impact that has occurred over at least the past four decades. With the advent of new technologies, we can now identify, map, and assess the potential for faults to cause structural damage or serve as pathways for the migration of hazardous substances. We also present a discussion of the methods in use to identify near-surface growth faults with special emphasis on Ground-Penetrating Radar (GPR) to characterize faults below roadways in the relatively high-moisture soils of the Houston, Texas area and environs. New aerial technology, such as Light Detection And Ranging (LiDAR), will help to identify the locations of many fault systems, both new and those previously known, but additional surface mapping is also required.

We have called for a new hazard alert system to be developed by the U.S.G.S. that is consistent and compatible with the County Flood Plain maps to warn builders and home buyers of the potential risks known in the Houston area regarding the presence of faults. Such a system could identify faults that exist under existing pipelines and other structures, and faults where natural hazardous substances are known to occur in the groundwater of the aquifers providing a significant part of the Houston water supply and that of surrounding municipal utility districts.

Section 1.0 Introduction

Growth faulting has an impact on a wide variety of related geological and hydrochemical conditions in the Houston area as well as other areas along the Gulf Coast. These conditions range from the relationship of the faulting to local subsidence and large-scale groundwater withdrawal to the occurrence of radionuclides and natural gas in the principal aquifers of the Houston area, which in turn relates to the health and safety of the general public and their perception of risk, and costly adjustments to building designs and/or repairs to foundations.

Geological and environmental investigations converge when a natural resource affects human health and the environment. When constituents of concern, whether they are dissolved constituents (e.g., solvents, BETX, uranium and associated degradation products, ^{226}radium and ^{222}radon, etc.), or gas (e.g., methane, hydrogen sulfide, etc.), migrate into the groundwater used for drinking water, or otherwise migrates to the surface, their presence, once identified, often trigger both environmental and geological investigations. and costly adjustments to building designs and/or repairs to foundations.

The Houston area, as well as much of the Gulf Coast, depends on groundwater produced from thick, unconsolidated aquifers and on oil and gas from the sediments deep below. Oil and gas movement in the area is often driven by the hydrogeological dynamics of heated brines migrating into reservoirs structurally arranged by rising salt domes. Economic minerals are sometimes also formed within environments located over and around the flanks of salt domes. Groundwater, oil and gas, and mining (e.g., uranium and sulphur) investigations are often interrelated, having much in common (Baker, 1994; Hanson, 1994; Rhodes, 1994). However, in many cases, they are still treated separately by the three fields of geology involved (hydrogeology, petroleum, and mining). The opportunity exists for new collaborations and technical synergism, particularly in the study of faults and fault-related hazards in the Houston area. The absence of this opportunity was noted by Toth (1963 and 1968) and also noted and explored over the years by Campbell and Lehr, (1973, p. 416), Dahlberg (1982) and by LaMoreaux (1994).

Section 2.0 Acknowledgements

The subject matter of this report was identified, in part, by the graduates and instructors of The Institute of Environmental Technology (IET) in Houston, Texas, which together with many of the senior environmental professionals in the Houston area, provided a forum for continuing dialogue and technical discourse to support some 400 graduates of the IET program since its beginning in 1992 (more). IET also invited funding for research on environmental methods and techniques, field conditions in and around Houston, Texas, and for assessing the technology in use today and in the foreseeable future in the environmental consulting field in the U.S.

This guide was produced primarily for the IET graduates and their continuing education on the subjects treated herein. However, this guide also serves the same function for the members of the Houston Geological Society, especially the young geologists in the region (more) and for the members of the Texas Section of American Institute of Professional Geologists and the thousands of members of AIPG in the U.S. who may have an interest in the subjects discussed in this guide.

Its usefulness may also extend to other interested parties such as personnel of the various municipal utility districts (MUDs), university students, and personnel of the regulatory agencies of the Gulf Coast and wherever growth faults reach the surface.

The views expressed here are solely those of the authors and may not represent the views of: 1) those acknowledged below who provided input to the authors during the preparation of this report, 2) those members of IET who were not involved in this project, or 3) those cited in this report. Finally, the research for this project was conducted by the authors and by those who provided input during the project. The authors appreciate the input, reviews and comments provided by a number of associates, especially: Robert Gabrysch, P.E., (Emeritus of the U.S. Geological Survey); H. C. Clark. Jr., Ph.D., P.G., (Emeritus of Rice University); and Carl Norman, Ph.D. (Emeritus of the University of Houston). Mustafa Saribudak, Ph.D., P.G., (an I2M Associate and a geophysist of Austin-based Environmental Geophysics Associates (EGA)), provided the geophysical equipment for preliminary application of GPR and resistivity surveys, and offered associated technical input to test his "umbrella concept" in the Houston, Texas region.

The authors also appreciate the assistance and dedication of Jessica Campbell Bludau, of HRA Gray & Pape (more) for assembling and collating the comprehensive bibliography concerning the topics covered in this Guide (more). Early versions of this research provided the basis for a conference presentation by Campbell, Campbell, and Saribudak (2004) at Texas A&M University. More recently, Campbell and Wise (2013) discussed many of the issues examined here to the Houston Geological Society's Engineering and Environmental Group in May, 2013 (more), the details supporting the presentation slides are discussed further in this Guide (more).

Funds to support the research for this investigation were provided by M. D. Campbell and Associates, L.P. Houston, Texas (more) for the period 2002 to 2010; thereafter, I2M Associates, LLC, Houston and Seattle, provided the funds from 2010 to the present (more).

Section 3.0 Growth Fault Origins & Hydrogeology

The Houston area, and the Gulf Coast in general, is located on a vast sloping platform of sediments more than 30,000 feet thick which sit on great salt beds, underlain by more sedimentary intervals favorable for the accumulation of oil and gas (see Baud, *et al*., 1998). The sediments (including volcanic ash (tuff) have been shed from the eroding highlands to the north and northwest and have been transported toward the Gulf via a complex paleodepositional system operating over millions of years in fluvial-deltaic and shallow-marine environments (more). This depositional system is still active and continues to build out into the Gulf of Mexico. Actively submerging wetlands along coastlines are indications of large-scale subsidence, although the anticipated sea-level rise may also be contributing to coast-line submergence (Morton and Purcell, 2001).

The classical geological history of the Gulf Coast is discussed by Chowdhury, *et al.*, (2013) reporting that numerous growth faults (curved faults that are syndepositional and grow with depth of burial) occur parallel to the Gulf Coast and control sediment accumulation and dispersal patterns during deposition. Salt domes are more common in the northern than the southern parts of the Texas Gulf Coast. These salt domes locally penetrate shallow areas of the Gulf Coast aquifer. Rapid burial of the fluvio-deltaic sediments in the Texas Gulf Coast caused the development of overpressure zones in the subsurface.

We will deal in some detail with: 1) the evolution of the Gulf of Mexico basin and associated sediments of the Texas Gulf Coast aquifer; 2) structural features including faults, salt domes, and overpressure zones; 3) depositional environments; and 4) the stratigraphy of the Gulf Coast aquifer in Texas.

Texas Gulf Coast sediments consist of unconsolidated, lenticular deposits of clays, silts and sands with occasional organic beds generated in shallow water, marsh-dominated depositional environments. Growth faults are common throughout the unconsolidated sediments along the Gulf Coast area (see Figure 1). Some are thought to be regional faults because they can be traced in subsurface records from the Mexican border to Louisiana (see Wermund, 1955; Stricklin, 1994). In the larger picture, the causes of faulting treated in this paper deal with: 1) basin loading, 2) regional faulting, 3) salt-dome formation and movement, 4) basement response (indicated by aseismic earthquakes and recordable seismic activity), and 5) near-surface subsidence, slumping, and faulting in response to the above causes. Overprinting the causes of faulting is the impact of large-scale ground-water removal causing changes in pressure relief and the attributed slumping within the sediments of the Evangeline and Chicot Aquifer Systems in certain areas of Harris and surrounding counties. So-called soil consolidation considered by geotechnical engineers during the design of building foundation is also involved in some cases of surface disturbance (e.g., Holzer, 1984).

We have concluded that each of the above processes plays a role to an extent and in concert and in conflict with soft-sediment faulting within the near-surface and generally unconsolidated sediments of the Gulf Coast down to depths exceeding 30,000 feet in many places. Such disruptions lead to hazards at or near the surface that have the potential for causing harm to humans and damage to engineered structures. Once recognized, engineered structures, such as buildings, homes, highways, pipelines, and other surface and underground structures can be designed to mitigate such conditions.

Section 3.1 Regional & Local Relationships

Four regional faults (shown in Figure 1) pass through the Houston area and can be correlated as: 1) the Wilcox Fault Zone (just north of the Harris County line), 2) a fault zone passing through the southern portions of Harris County as the Yegua Trend along the Mykawa fault and the Battleground fault, and 3) a fault designated as the Hitchcock fault as part of the Frio fault system just northwest of the Galveston area. A local fault system (not shown in Figure 1 but is indicated in Figure 46) consists of the Addicks Fault and associated faults, and the Long Point Fault system (which, in places, includes antithetic faults such as the Piney Point Fault, some two miles to the southeast). This system lies between the Yegua trend to the southeast and the Wilcox fault trend to the northwest.

These regional faults may transmit stresses to nearby regions already under stress to create new fault zones some distance away from the regional faults and may stimulate movement along sections of existing faults (Bruce, 1973). Large-scale forces, such as deep crustal warping and tilting, earth tides (solar-lunar tides), or other forces still unidentified, may also play significant roles in growth faulting in the Gulf Coast region (Heaton, *et al*.,1982; Rydelek, *et al*., 1992; Goings and Smosna, 1994; and Vidale, *et al.*, 1998). The associated faulting often creates structural oil and gas traps at depths of 10,000 to 30,000 feet and perhaps even deeper (Baud, *et al*., 1998; Trahan, 1982).

Overprinting this regional structural fabric are the structural forces present in areas over and around salt domes and associated structures and in the subsidence bowl of Harris County and environs.

The subsidence bowl in the Houston area is the result of geologically recent anthropogenic activities stimulated by groundwater production for the City of Houston and the surrounding municipal utility districts (MUDs), augmented by production for industrial and irrigation purposes, and more locally by oil and gas (and associated brine) production. In a recent geophysical study, Yu, *et al*., (2014), found no measurable compaction within the Jasper Aquifer or within deeper strata and concluded that deep-seated subsidence is not likely occurring in the Houston-Galveston area.

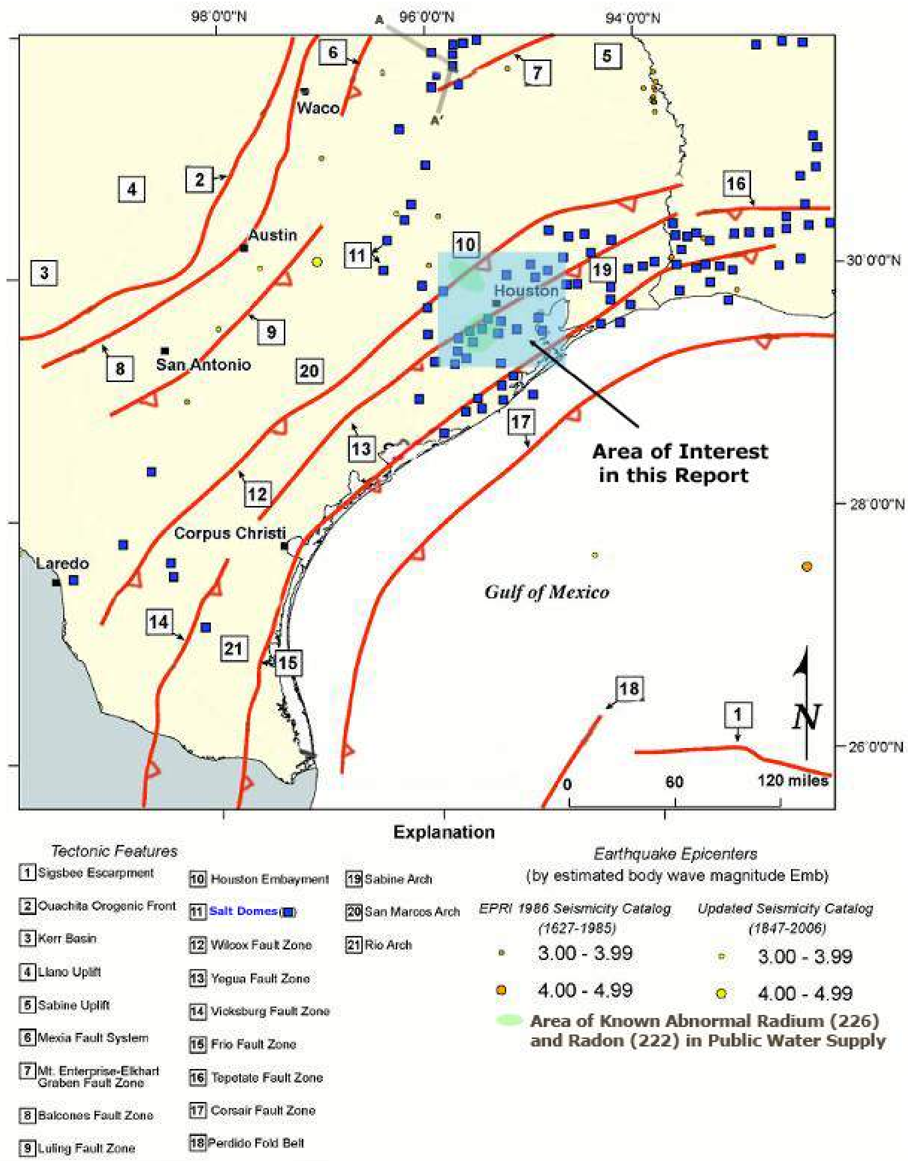


Figure 1 – Regional Faults in Texas Passing through the Houston, Texas Area and Environs
(Modified from Nuclear Regulatory Commission, 2009)

Although our principal emphasis in this report is on growth faults, associated geological and geochemical phenomena are also discussed to some extent because they are a direct (and indirect) result of the faulting that provides avenues for the migration of fluids and gases.

Section 3.2 Houston Area Salt Domes

The 25 Houston area salt domes, which have risen from the great salt beds, collectively called the Louann Salt, were deposited more than 60 million years ago (see Halbouty, 1967, and 1979; Ewing, 1983, 1986). Subsequently covered by thousands of feet of fluvial clastics, great pillars, or domes, of salt began to rise because the salt was less dense than the surrounding sediments (Nettleton, 1934). Salt domes known by the late 1960s are shown in various stages of growth in Figure 2.

Jackson and Seni (1983) conducted a detailed review illustrating the characteristics and mechanisms of emplacement of 15 domes from salt pillows, diapirs and related structures present in the East Texas Basin. A typical cross-section for the East Texas Basin is provided in Figure 3. The salt domes were not only responsible for creating favorable structural traps to hold numerous and prolific oil and gas resources in the region, they have also created structures ranging from the doming of sediments to complex fault systems over and around the salt domes (see Figure 4), many of which produced millions of barrels of oil, gas, and brine. Collapses on and around some of these salt domes have been well studied over the past 30 years (Seni, *et al.*, 1985).

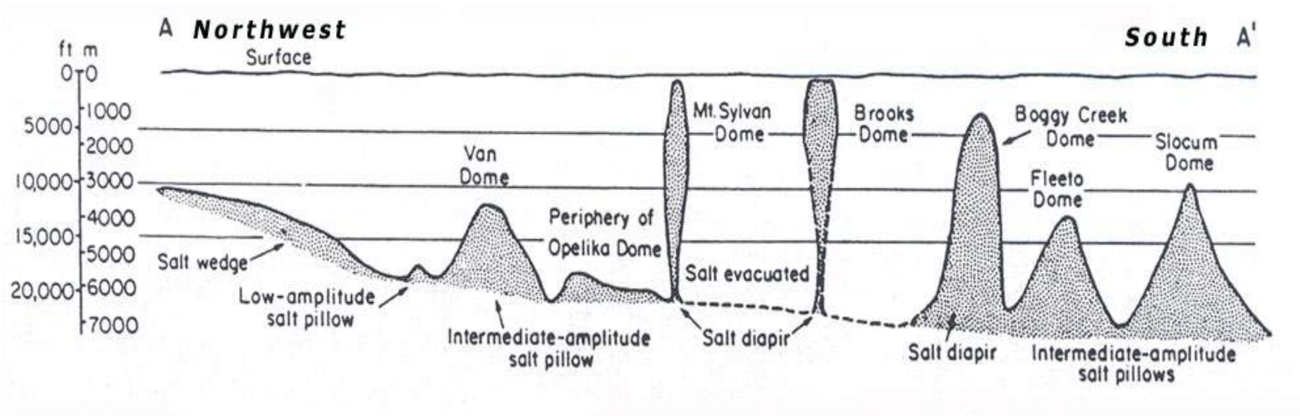


Figure 2 – Cross Section of Salt Domes in the East Texas Basin
(See Figure 1 for the general location of cross-section A-A')
(After Jackson and Seni, 1984)

Section 3.3 Stratigraphy below the Houston Area and Faulting around Salt Domes

The stratigraphy underlying the Houston area is illustrated in Figure 3**.** Note that the lower Evangeline Aquifer is also designated in stratigraphic terms as the Goliad Formation. The hydrogeological names for certain units and geological names of formations and intervals are further complicated even below the Evangeline Aquifer-Goliad Formation.

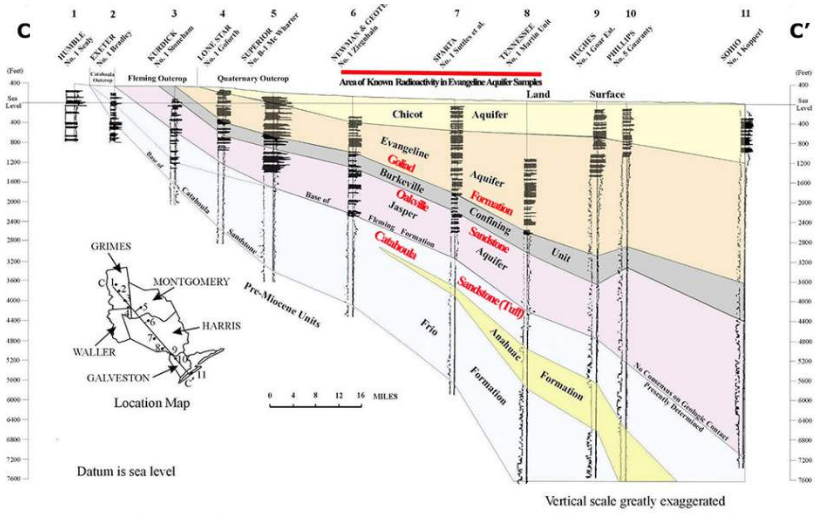


Figure 3 – Cross Section of Stratigraphy Underlying the Houston Area (Salt Domes Not Shown)
(After Chowdhury and Turco, 2006)
Note: Some Figures can be expanded via mouse-over and click

In Figure 4, for example, two salt domes occur along the same trend as the section shows in Figure 3 and in Figure 5 below. These salt domes have penetrated hydrogeological units and their down-dip stratigraphic equivalents. Note that the Jasper Aquifer is overlain by the Burkeville Shale (Confining Unit) and down-dip sediments are referred to as the Oakville Sandstone and Catahoula Sandstone (and Tuff). All three units occur above the major marker bed called the Frio Clay (Figure 4).

There are more than 10 salt domes in the Houston area and more around the periphery of Harris County (see Figures 1 and 5 for general locations and Figure 17 for specific locations). Some are relatively shallow while others are relatively deep. All have produced oil and gas in the past. Some have also produced commercial halite (if shallow) and sulphur, while a few have also created favorable geological environments for the formation of roll-front uranium deposits in sediments over or offset from particular salt domes.

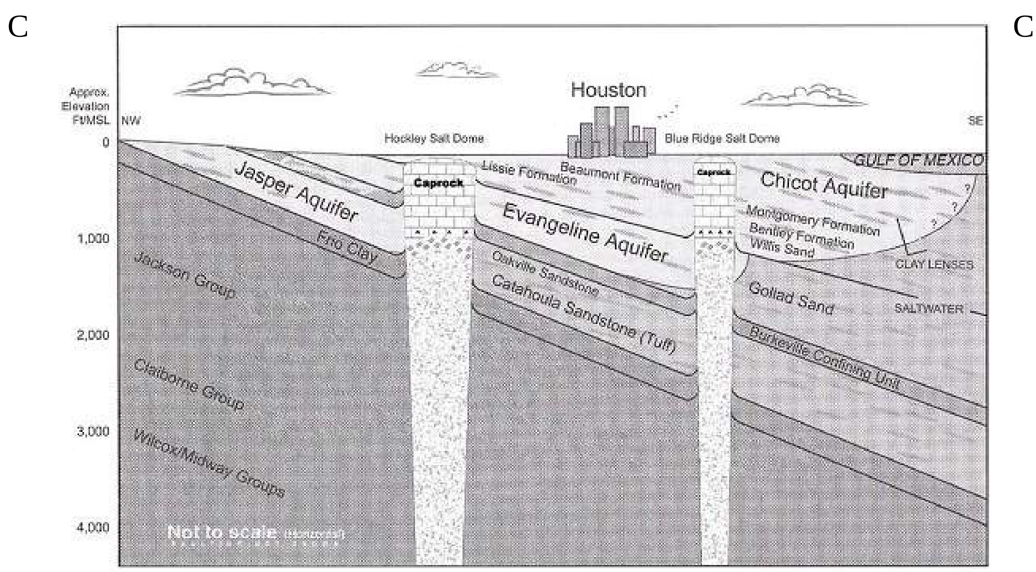


Figure 4 – Two of the Numerous Salt Domes in the Houston Area
(See Cross-Section Line C-C' in Figure 5)

Faulting has likely played an important role in the formation of all of these deposits. It is generally accepted by the uranium industry in south Texas that uranium deposits are re-reduced as a result of faulting that provides an avenue for natural gases such as methane or probably hydrogen sulfide to create an additional reducing environment for uranium precipitation from groundwater by chemical and biological mechanisms. Sulphur also is likely precipitated in such environments over salt domes and in permeable carbonate units where hydrogen sulfide introduced or created at depth is present to precipitate sulfur via other avenues of chemical and/or biological processes. Not all salt domes produce sulfur, like the Stewart Beach and the Block 144 domes shown in Figure 5 as well as others like the Boiling, Orchard, and 12 other domes below Houston and surrounding areas (Seni, *et al.*, (1985), especially Table 2, pp.40-42).

Other studies indicate that deep brines also apparently carry dissolved fatty acids (e.g., acetate, propionate, and n-butyrate) which are ultimately degraded by bacteria as they migrate into shallower, cooler zones (Workman and Hanor, 1985). Furthermore, Loucks, *et al*, (1979) suggest that because secondary leached porosity dominates in the deeper Tertiary sediments, this process promotes higher permeability and therefore higher groundwater flow rates along the faults and flanks of the salt domes. Ranganathan and Hanor, 1989, also reported on upward groundwater migration near the flanks of salt domes based on the distribution of dissolved salt, volatile fatty acids and trace metals and other constituents naturally occurring in the groundwater.

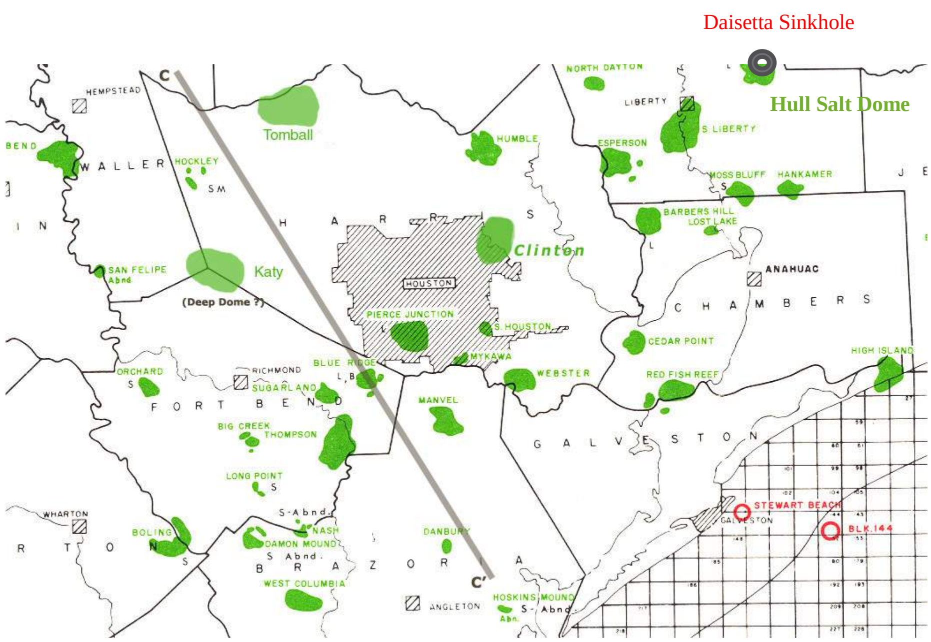


Figure 5 – Salt Domes in the Houston Area and Environs (Modified After Halbouty, 1967, p. 120)
O = Offshore Salt Domes w/ Known Sulfur Production (See C–C' Cross Section in Figures 3 and 4)
(After Ellison, 1971) Sinkhole: See Paine, *et al*, 2009.

Halbouty (1967), and others before him, recognized the potential of these domes as having formed favorable physical traps for oil and gas on top of or around their periphery as a result of the upward movement of the salt dome after it deformed or displaced sediments. He explored many salt domes in Texas and made numerous discoveries of economic importance. The plan view of the domes shows geological structures ranging from simple to complex faulting patterns, no doubt exhibiting the physical result of each dome's upward migration through thousands of feet of sediment over millions of years (Figure 6).

Section 3.4 Faults within and around Salt Domes

The complex network of growth faults, from Texas through Louisiana, has also caused the subsurface environment to form another type of energy resource in the form of geopressured geothermal energy (Dickinson and Duval, 1977; Gustavson and Kreitler, 1977; Jones, 1969 and 1977; Stricklin, 1994). This geopressured water within isolated zones may facilitate movement of salt masses as a result of the pressure differential and the volume-creating dehydration of gypsum into anhydrite (Kupfer, 1976). Hotwater at relatively high and low pH would leach out and transport metals and other constituents from their source into the groundwater system with residence migration times of millions of years.

The source of these constituents originate from organics and carbonaceous material in the sediments, such volcanic tuffs, organic clays and lignite through which groundwater migrates from its recharge zone and, in some cases at least, up through such sediments. Lignite and volcanic units in Texas contain a remarkable array of metals and other elements (including uranium) that would be leachable, in part, over the millions of years of groundwater flow through such intervals (Warwick, *et al*., 1999).

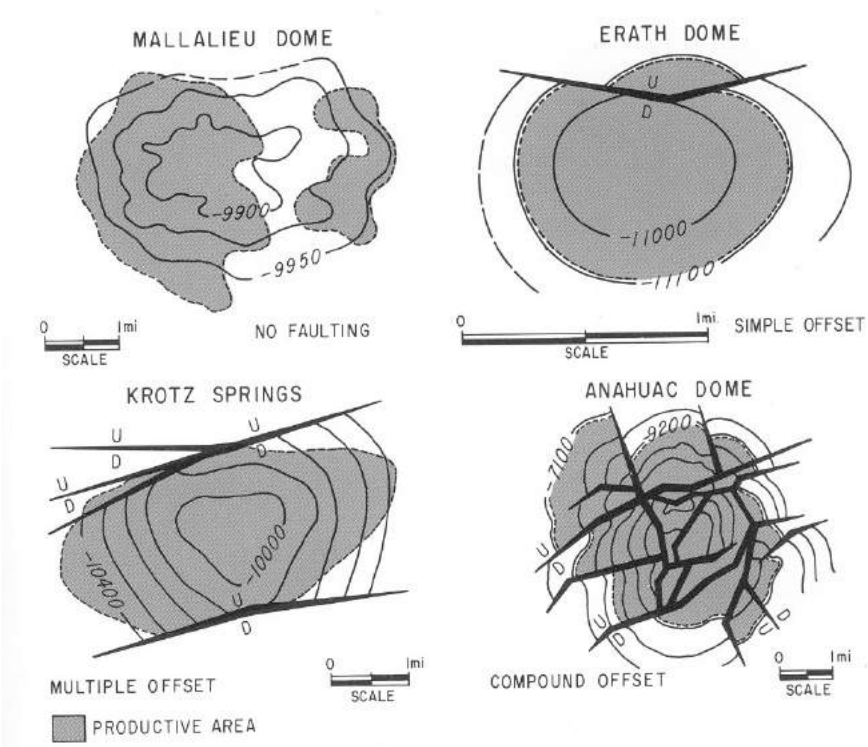


Figure 6 – Plan Views of Selected Salt Domes Illustrating Typical Structures, Ranging from Simple to Complex Faulting (After Halbouty, 1967)

Surface expressions of the resulting faulting and associated sand-body displacements in Louisiana combined with high rainfall and numerous storms and hurricanes throughout time have increased the low-land system of wetlands far inland, see Figure 7.

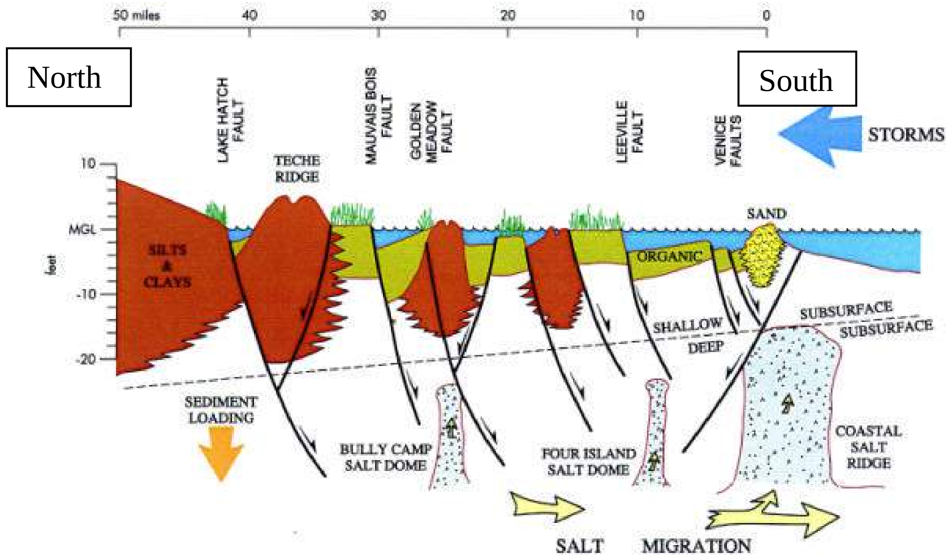


Figure 7 – Typical Growth Fault Cross Section in Louisiana
See Figure 8 for Location (After Gagliano, *et al.*, 2013)

Fault movements in the Gulf Coast are known to be slow but even distant earthquakes have been known to impact growth faults in the area. Gagliano (2003) reports that there is evidence that the major earthquake of 1964 in Alaska also impacted the Gulf Coast area. Records of many deep water wells in confined aquifers clearly show the pulses passing through the Gulf Coast just after the time of the Alaskan earthquake. Abnormal fault movement and even a broken well casing below an off-shore platform in Louisiana were reported to have occurred as a result of that single earthquake. Further, Guglielmo, *et al*., (1995) have modeled the mechanics of mass movement of the Louann Salt and found that the sediment-salt boundary is not flat but irregular. They concluded that some currently unknown mechanism is involved in preferentially triggering one irregularity in preference for another in the salt-bed surface to initiate mass movement in the beginning of the density-driven rise of a particular mass of salt to form a salt dome or ridge.

There are numerous reports and papers on Louisiana growth faults and subsidence that are available from and sponsored by the Baton Rouge Geological Society, (see more), and by the Louisiana Geological Survey and the Louisiana State University (more). The presence of a salt ridge suggests that movement in basement rocks that create deep geopressured stresses above and along regional fault zones seems to be one cause. However, as indicated above, a combination of conditions may also be involved.

Louisiana has numerous instances of east-west trending fault-line scarps in southwest areas of the State. The scarps are prominent topographical features ranging in height from 10 to 24 feet above MSL. Heinrich (1997) suggested that "these scarps are the surface expression of early Tertiary growth faults reactivated during the Pleistocene," which is consistent with the work of Nunn (1985) who proposed that the fault-line scarps resulted from reactivation of early Tertiary growth faults in conjunction with the rapid sedimentary loading of the Louisiana continental shelf during the Pleistocene. However, this results in a more complex configuration of salt masses and associated sediments than that present in the Houston Salt Basin (Kupfer, 1974).

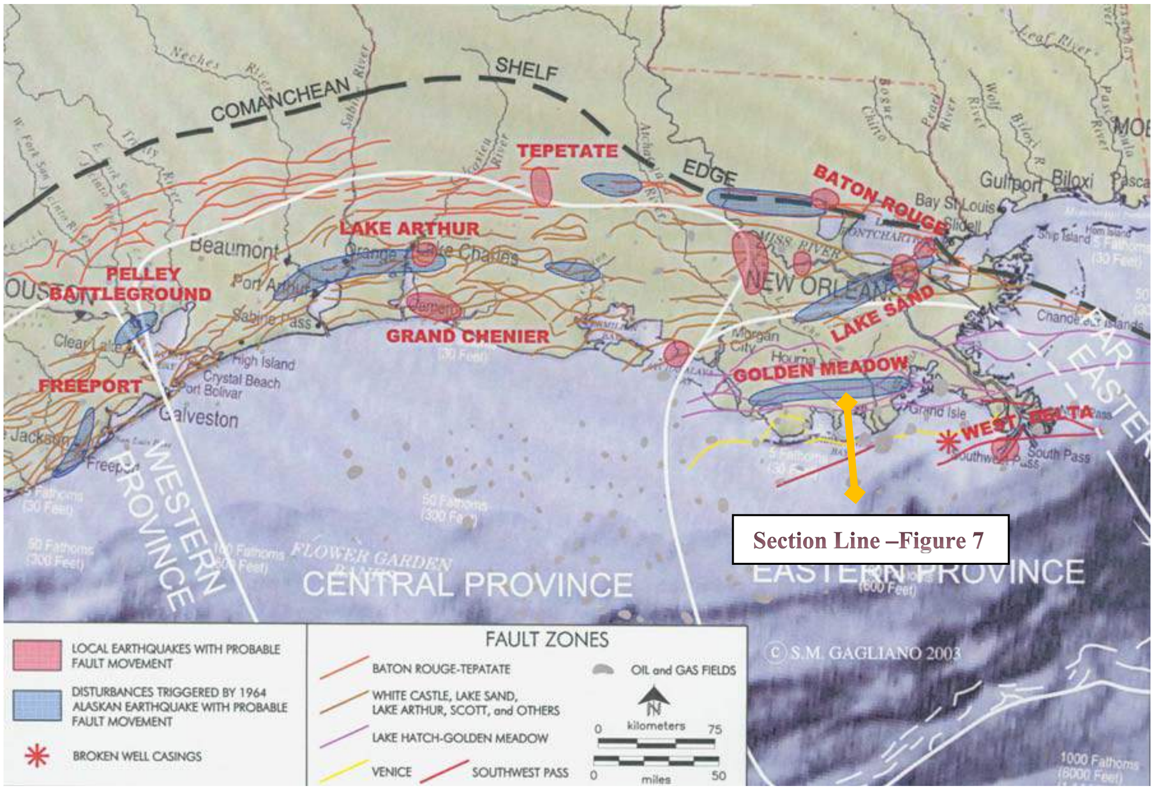


Figure 8 – Plan View of Principal Growth Faults in Louisiana and Texas, and Areas Disturbed by 1964 Earthquake in Alaska (After Gagliano, et al., 2013)

In his early work, Dumas (1976) estimated the depth to the Louann Salt using passive seismic data. Three domes were selected for his study: Hockley, Nash and Hoskins Salt Domes, located along a line from northwest of Houston to the southeast toward the coast. He found that the estimated depths to the top of the Salt near theses domes were: 21,500, 24,000 and 33,000 feet, respectively. Between the Hockley and the Nash Domes, he calculated that the top of the salt slopes gently at less than one degree but between Nash and Hoskins Domes the slope is approximately 4 degrees.

In 1988, Mullican (1988) provided a review of subsidence above and around salt domes in the Houston diapir province. In addition, Kreitler and Dutton (1983) investigated the origin and diagenesis of cap rock in salt domes, and Smith (1998), Dix and Jackson (1982), and Taylor (1968) reported on the various types of mineralization found in the cap rock of salt domes. Smith (1998) provided an illustration on where various types of mineralization typically occur above and in salt domes and their general utility as a source of salt and for the storage of crude oil and natural gas (see Figure 9).

Overton (1979) reviewed the geochemistry present in shallow salt domes, which when combined with salt-dome hydrochemistry provides a specialized environment for mineralization. Sulfur was a major resource in salt domes but its availability and economic viability have declined (Martinez, 1969; Ellison, 1971). Uranium is also a resource of interest in the Gulf Coast region because of the favorable geological environment within the Tertiary sediments, which includes the sediments above salt domes (Eargle and Weeks, 1973, Campbell and Biddle, 1977; Henry, *et al*., 1982; Smith, *et al*., 1982; Galloway, *et al*., 1979; and McCulloh, 1982).

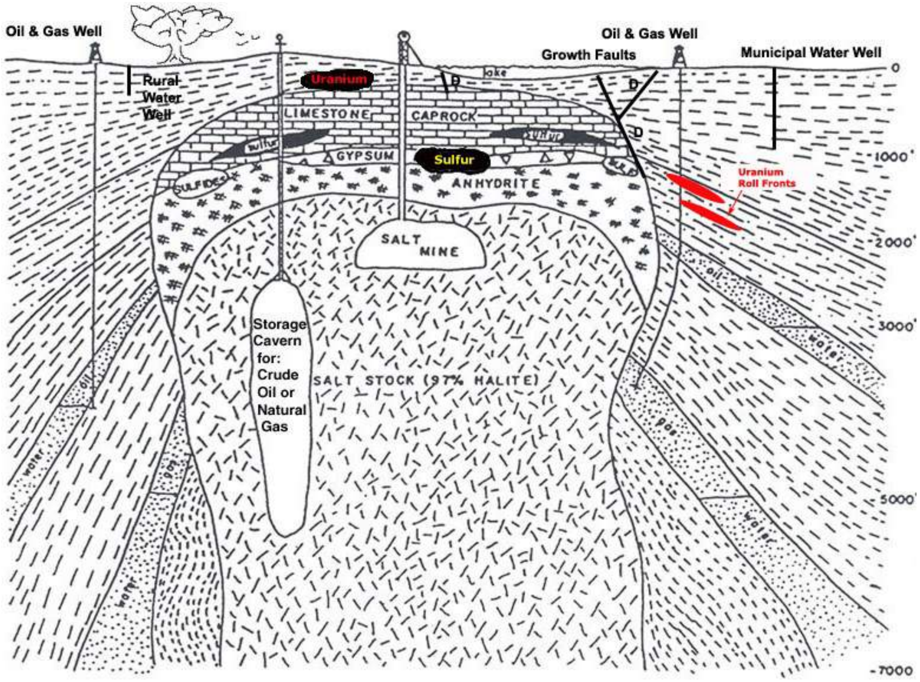


Figure 9 – Typical Multi-Use "Piercement" Salt Dome
(Modified after Smith, 1998)

Only recently has exploration shown that the combination of the Gulf Coast depositional, biological, and structural environments has also likely contributed to the generation of huge reserves of frozen methane hydrate present at great depths in Gulf of Mexico seafloor sediments and elsewhere in the world in similar environments (Plunkett, *et al.*, 2003).

Offshore investigations involving seismic mapping and deep coring and drilling of the distal end of the Gulf Coast geosyncline in the Gulf of Mexico have provided additional insight into the sediments and associated structures below the Houston area and even below the Louann Salt (see Baud, *et al*., 1998), which was once thought to represent the bottom of the geosyncline. Known surface faults have been traced from one dome to the next, like the Clear Lake-Friendswood-Mykawa corridor (see Figure 17), with some domes exhibiting faulting on either side of the trend or over only a particular salt dome. Others show listric normal movement downward on the coast side and without apparent antithetic faulting (see Bradshaw and Zoback, 1988).

It is interesting to note here that these investigators presented least-principal-stress considerations in relation to frictional strength of normal faults and found that a tangent rule would govern the orientation of the principal stress axes in sandstone and shale. This is a condition similar to fluid flow in a porous media where flow refraction also is governed by the tangent rule, which suggests that the flow domain is guided in part by the orientation of the stress domain (see Freeze and Cherry, 1979; and Hubbert, 1940), a mechanism which may play a role in creating avenues for the upward migration of groundwater from considerable depth below the Evangeline Aquifer along fault zones associated with salt domes and ridges up into the Aquifer.

As indicated earlier, Halbouty (1967 and 1979) presented examples of some of the typical, although generalized, faulting configurations encountered above and around salt domes and associated structures (see Figures 6, 10 and 11).

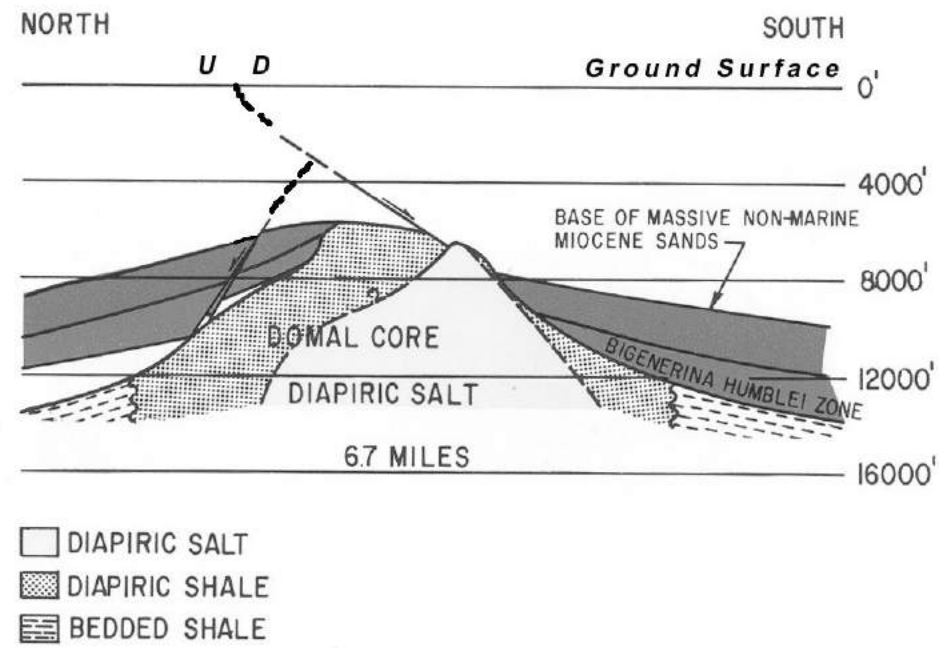


Figure 10 – Typical Diapiric Salt Carrying Diapiric Shale
(Modified after Halbouty, 1967)

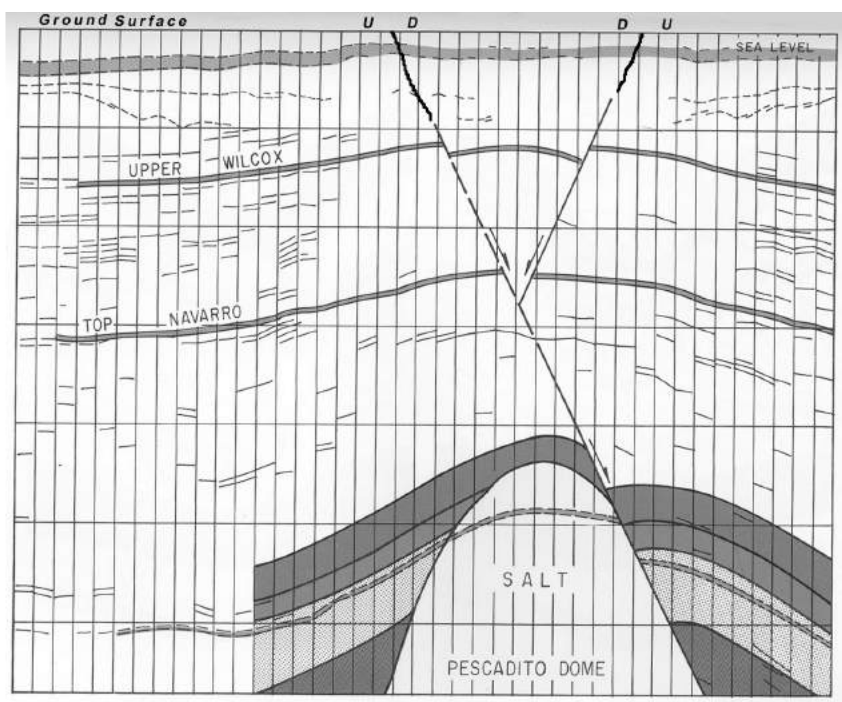


Figure 11 – Simple Structure Above Pescadito Dome with Antithetic (or Keystone) Fault
(Modified after Halbouty, 1967)

Section 3.5 Groundwater Flow in and around Faults of Salt Domes and Ridges

Faulting associated with some salt domes allow dissolved radioactive materials (e.g., uranium, and with time, daughter products such as ^{226}radium and ^{222}radon) to migrate upward from uranium source sediments present in sands, clays and lignite (or organic clays) associated with the Catahoula Tuff and other units below and within the massive Evangeline Aquifer. Also, natural gas and associated hazardous substances migrate along faults and between different stratigraphic units.

As indicated previously, the Evangeline Aquifer is Houston's principal source of high-quality groundwater that was used for years as its primary source of drinking water until subsidence and declining potentiometric heads (i.e., water levels in well casings) were recognized as serious economic problems. The general consensus then was that the former was caused by the latter. Each created separate economic issues. The former causes surface disruptions and damages building foundations and pipelines and wells, bridge-support structures, and roads. The latter causes an increase in pumping costs to lift water from greater depths as water levels decline.

The heavy, long-term production of groundwater from the Evangeline Aquifer (and the Chicot Aquifer above) has likely contributed significantly to widespread subsidence, the mechanisms of which are still debated in detail. They are related to the withdrawal of groundwater for consumer drinking water, for industrial process water, for irrigation water, and groundwater containing high salinity (brine) associated with oil and gas production activities.

These mechanisms are also responsible for the depressurization of the fine-grained sedimentary units in the Evangeline and Chicot Aquifers as the potentiometric surface falls below the individual units over time due to heavy pumping of the aquifers. This depressurization removes structural support within the aquifers causing sediments to physically compress (TWDB, 1996). Differential movements of partly isolated to open sand and clay units can create geopressured units that add further stress to surrounding sediments, some of which is transmitted upward toward the surface (Jones, 1977). Also, similar depressurization processes occur when removing brine and oil and gas from deep zones (greater than 2,000 feet below surface) which are often associated with salt domes.

Mullican (1988) found that almost 70% of the 30 domes investigated have experienced subsidence, collapse, or both. This often can be related to natural causes or to anthropogenic causes. He concludes that Frasch sulfur mining from cap rocks caused the most catastrophic subsidence and collapse over salt domes, with 12 of 14 salt domes having sulfur production showing evidence of subsidence and collapse.

Of particular importance to the authors' review of faulting is Mullican's conclusion that trough subsidence of structures associated with the Louann Salt bed at depth is a ductile and microfracturing deformation process centered below the widespread zones of fluid withdrawal, which is expressed as a subsidence bowl (Figures 23, 38, 43 and 44). In other words, the structural and hydrologic instability of the areas above salt domes and ridges is manifested by subsidence, collapse processes, and the resulting deformation (Boehm, 1950; Autin, 1984), but he leaves the widespread down-to-the coast faulting to other interpretations, see Figure 12).

Taken one step further, the question arises as to whether other regional structures pass northeastward through the Houston area that involve ridge-to-trough deformation of the salt beds well below Houston's subsidence bowl.

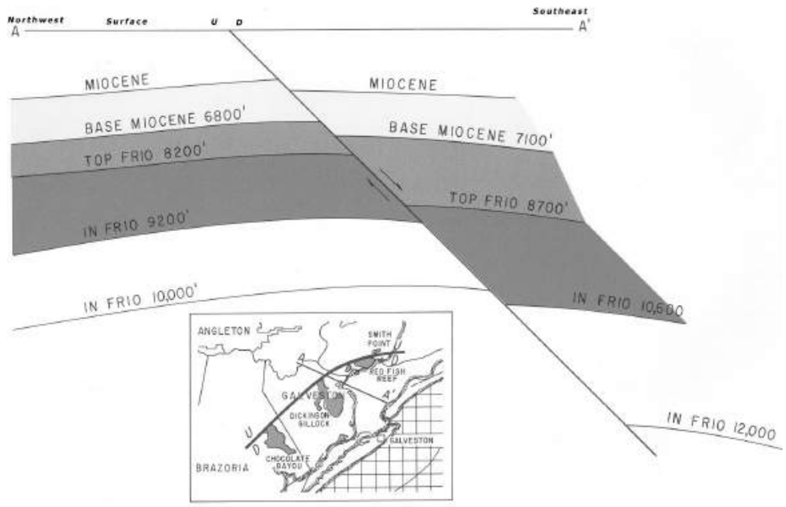


Figure 12 – Classical Interpretation of Typical Down-to-the-Coast Faulting and Favorable Oil & Gas Reservoirs (Modified after Halbouty, 1967)

The relationship of linear traces (indicated from aerial photography) to subsurface faulting has always been problematic (Lattman, 1958), as to whether the major high-angle faults identified in the subsurface actually intersect the surface. There is evidence that some linears are related to faults and that some deep faults do reach the surface and some do not (Kreitler, 1976). The fact that growth-faulted bed displacements increase with depth (decrease displacement upwards) may explain why some faults are apparent at depth but cannot be traced easily to the surface (Lee and Shen, 1969). Withdrawal of deep geopressured groundwater in Louisiana and Texas may also cause growth-fault movement and subsidence in Harris County, Texas over the years (Trahan, 1982).

Section 3.6 New Views on Faulting

Recent work on growth faults in the northern Gulf Coast environment indicates that they should be classified on the basis of the three-dimensional geometry of the faults, welds and ridges, deformed strata, and associated salt bodies (Rowan, *et al*., 2001). Rowan and his associates suggested that these structures are kinematically and genetically linked to one another and to associated salt bodies in the form of extensional, contractional, and strike-slip components.

The fact that fault-bed displacements increase with depth may explain why some faults that are recorded at depth have not been traced to the surface ostensibly because of a lack of shallow data. However, many linears that are apparent on aerial photography may provide the connection for most if not all of the surface faults. The clues to the existence of a growth fault in an area are subtle and easily missed in the field but usually displays such clues as: topographic scarps, a counter regional topographic rise, sharp changes in vegetative communities, wide areas in stream beds, offset stream meanders, segregated marshes, sag ponds, and other field indications, such as frangenic lakes or ponds.

Modern interpretations of growth-fault mechanisms that go beyond the simple model shown in Figure 12 have been based on improved resolution of seismic technology. For example, Hammes (2009) presents a seismic dip section that exhibited a major system of growth faults (dark green – major; black – minor). This system creates a sub-basin and a series of antithetic and synthetic crestal faults (Figure 13). She suggests that these faults compartmentalize the prograding wedge reservoirs (red bar shows the interval). Note that a prograding wedge is shown to be expanding into the main growth fault (at red arrow).

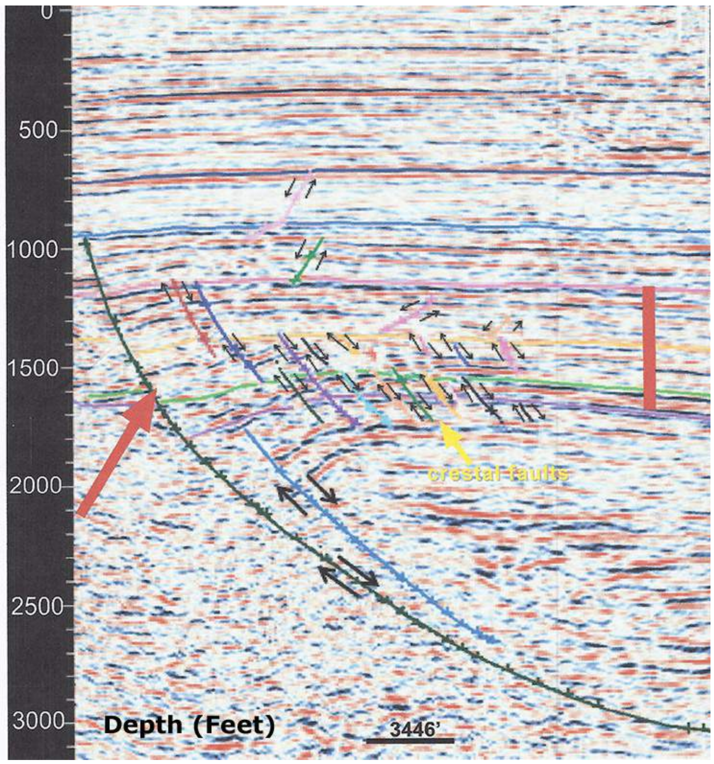


Figure 13 – Modern Geological Interpretation of Growth-Fault Components and Associated Structures (Modified after Hammes, 2009)

Jackson *et al.*, (2003) represent the current thinking on the growth-fault system mechanisms in the Houston area:

> *"…that the ongoing rise of the salt domes in southeast Houston may be driving the current reactivation of the faults to the northwest and also of the regional faults at depth. If the regional faults at depth include roller faults along which salt is being extruded basinward, and that salt is feeding the salt domes, the continuing rise of the salt domes will produce accommodation space at depth into which downthrown roller fault blocks from farther northwest can move."*

The "roller fault blocks" mentioned are illustrated in Figure 14. The reactivated faults are often growth faults that terminate (or sole out) in a detachment surface. A salt roller and salt welds help to accommodate movement that culminates in the rise of a salt dome (Jackson *et al.*, 2003).

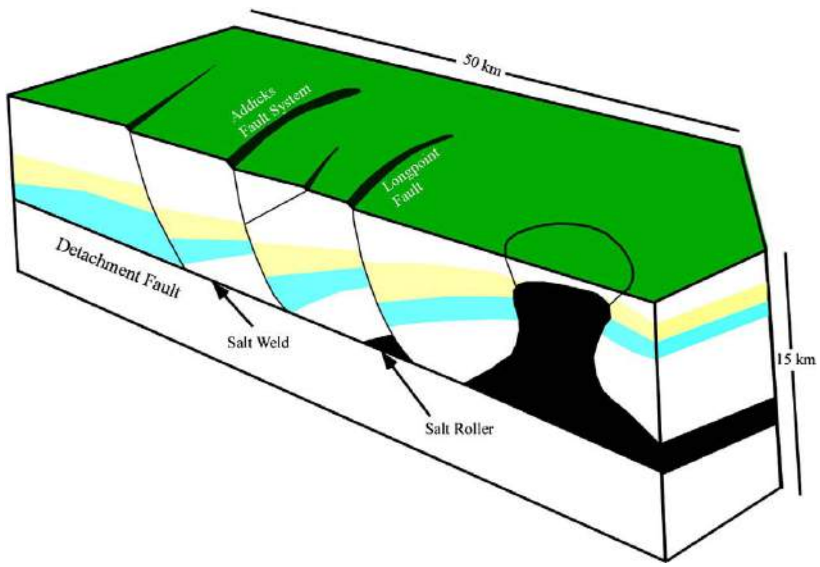


Figure 14 – Sketch Showing Suggested Association between Active Faults and Rising Salt Domes
(From Engelkemeir *et al.*, 2010)

In more recent investigations, Engelkemeir, *et al.,* (2010) report that GPS data acquired during the period between 1995 and 2005 has found evidence of ongoing subsidence (up to -56 mm/year) in northwestern Houston and possible horizontal surface movement towards the Gulf of Mexico (up to 6 mm/year). Most sites are moving just south of east in the above figure. The predominant component is the motion of the North American Plate as measured in WGS 84 (G873) reference frame during the interval. They speculate on the possibility that the active elevation of salt domes, mainly at the south and east of the city, may indirectly influence other surface movements including fault movements and subsidence over areas greater than one km^2.

Section 3.7 Better Geodetic Controls and Measurement of Subsidence

Houston-area faulting and fault movements have been triggered by oil and gas production, groundwater production, and microseismic activity associated with movements at greater depths, earthquakes and/or injection activities. The development of better geodetic measurements via geopositioning systems (GPS) data has provided the opportunity to more easily discern and study subsidence. For example, GPS data clearly document significant ongoing subsidence of the Jersey Village subsidence depression (shown in Figure 15 by the circular shaded area in dark gray), along with lesser subsidence throughout the region. Horizontal displacements were largely due to the motion of the North American plate during the study interval. Engelkemeir, *et al.*, (2010) conclude that displacement differences among occupied sites may be indicative of the regional motion towards the Gulf of Mexico, possibly related to the movement along active growth faults.

When measuring displacements, a baseline elevation station is required to calibrate the *actual* location rather the *relative* location. Geodetic measurements over long periods of time suggest that subsidence rates differ from those measured from one baseline station where relative positions are involved. These subjects were discussed in some detail at a 3-day conference in 2005 near Houston, Texas, with presentations by Dokka (2005); Zilkoski (2005); Shinkle and Dokka (2005); Kasmarek, Milburn, and Turco (2005); and Howe (2005) of particular interest to our study herein.

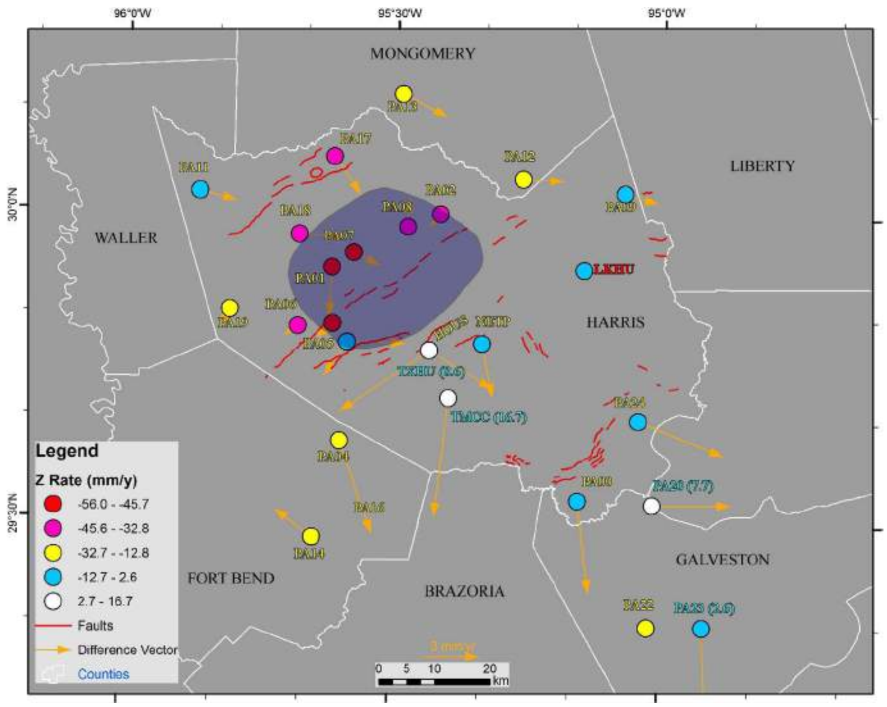


Figure 15 – GPS Displacement Rate Vectors and Associated Error Ellipses
(From Engelkemeir, *et al*., 2010)

The live proceedings were published by the Houston Geological Society in a CD format accompanied by the program and abstracts (more) and field guidebook (more) provided by Carl Norman and others. He included summaries of case histories on a number of sites he has investigated over the years.

Section 3.8 Triggers of Houston-Area Faulting

As early as 1926, Pratt and Johnson (1926) reported that active surface faulting was associated with oil production at the Goose Creek oil field east of Houston, Texas. Sheets (1947) reviewed the possible causes and impact of the observed surface deformation in the Gulf Coast area. DeBlieux and Shepherd (1941) established a relationship between linear features on aerial photographs and surface faults in the Gulf Coast area. Then, Lockwood (1954) discussed the possible relations between faulting, subsidence and the withdrawal of groundwater from the compressible sediments of the Evangeline and Chicot Aquifers, and Weaver and Sheets (1962) first demonstrated that deep faults could be matched to known surface faults. Subsequent studies demonstrate the relationship of oil and gas production to land subsidence (Colazas, *et al.,* (1987), and especially Fielding, *et al*., (1998)).

As part of a study funded by the City of Houston to examine future municipal water demands, Turner, Collie & Braden (1966) produced maps showing known active surface faults and the inferred surface locations of subsurface faults.

In 1976, Kreitler investigated lineations observed on aerial photographs of the Texas Coastal Zone. He also found evidence that many lineations coincide with known faults and with differential subsidence as a precursor to active faulting (see Kreitler, 1977a and b, and 1978).

To understand the phenomena involved, beginning in the 1960s and 1970s, comprehensive studies of faulting and subsidence in the Houston area were conducted by university, state and federal research programs, e.g., the University of Houston (Van Siclen, 1961, 1967 and 1972; Sheets, 1971, 1976, and 1979; Heuer, 1979), and more recently Norman, 1995, 2002, and 2003.

Other groups involved include: the U. S. Geological Survey (Gabrysch, 1969 and 1972; Yerkes, *et al*., 1969; and Yerkes and Castle, 1970), The University of Texas and Texas Bureau of Economic Geology (Reid, 1973 and Kreitler, 1976, 1977 and 1988), and Rice University (Clark, *et al*.,1979; and Clark and Georges, 1981). Studies on subsidence and faulting issues were also conducted in Louisiana (Wintz, *et al*., 1970). Murray (1961) illustrates the known faults in Louisiana as they extend into eastern Texas. Recently, Heltz (2005), Gagliano, 1999, and Gagliano, *et al.*, 2013 revisited fault-slip rates and associated conditions in Louisiana.

Everett and Reid (1981) continued to identify active faults in the Houston area by using and interpreting Landsat imagery. Clanton and Verbeek (1981) recalled in politically-correct terms that efforts during this period "resulted in a lively and continuous debate on the possible mechanisms of fault movement", e.g., Castle and Youd, 1972a and b; Frierson and Amsbury (1974); Gabrysch and Bonnet, 1975a and b; Clanton and Amsbury, 1976; Gabrysch, 1978; Gabrysch and Holzer, 1978; Verbeek and Clanton, 1978; and Verbeek, *et. al*, 1979; Verbeek, 1979; Clanton and Verbeek, 1981; and O'Neill and Van Siclen, 1984. Subsidence and associated faulting were also related to solution extraction of salt (Ege, 1984).

Recently, on the basis of studies of borehole logs and seismic reflection data, faults have been identified from the surface to depths below 12,000 feet (Kasmarek and Strom, 2002). Because the faults involve soft sediments, very little seismic energy is built up as these growth faults move, usually far less than an inch per year. Generally, the movement is episodic. However, earthquake magnitudes up to 4 on the Richter scale have been recorded in Texas with epicenters plotted above areas of oil and gas production, within waste fluid reinjection intervals, along the trend of the long, regional faults and in areas without known causes. Some of these unknown causes may have been related to sonic booms, which have been mistakenly reported as earthquakes (see Davis, *et al*., 1989 and Figure 16). Earthquakes of significant magnitude would not be unexpected along the Rio Grande Rift Zone in West Texas as the rift opens over time. These would likely be a result of movement in deep zones where the sediments have consolidated and undergone some metamorphism storing energy until stressed or where crustal downwarping (or parting) involve consolidated rocks that store seismic energy that can be released quickly causing significant seismic "noise".

On the whole, the U.S.G.S. does not consider the Houston area a seismically active area. Both Rice University's Earth Science Department and University of Houston's Geosciences Department had operational seismographs, usually operating on a 24-hour basis that monitored major earthquakes and nuclear testing from around the world. In addition, the U.S.G.S. has been funding The University of Texas to operate and maintain a state-of-the-art seismic station located in the salt mine at the Hockley Salt Dome northwest of Houston (Frohlich and Davis, 2002) near the Hockley fault.

Nevertheless, the hypothesis that soft-sediment/growth faulting is related to subsidence and fluid withdrawal from the subsurface in some areas (Holzer and Gabrysch, 1987, Mortan and Purcell, 2001) was once soundly discounted (Holzer, 1981; Holzer and Bluntzer, 1984). The relationship of faulting to subsidence (or *vice versa*: Van Siclen, 1981) and the mechanisms for the observed faulting are still being debated.

On the basis that compelling evidence is available that supports each of the three principal causes of faulting under consideration, one might safely conclude that all three mechanisms are often involved to one extent or another.

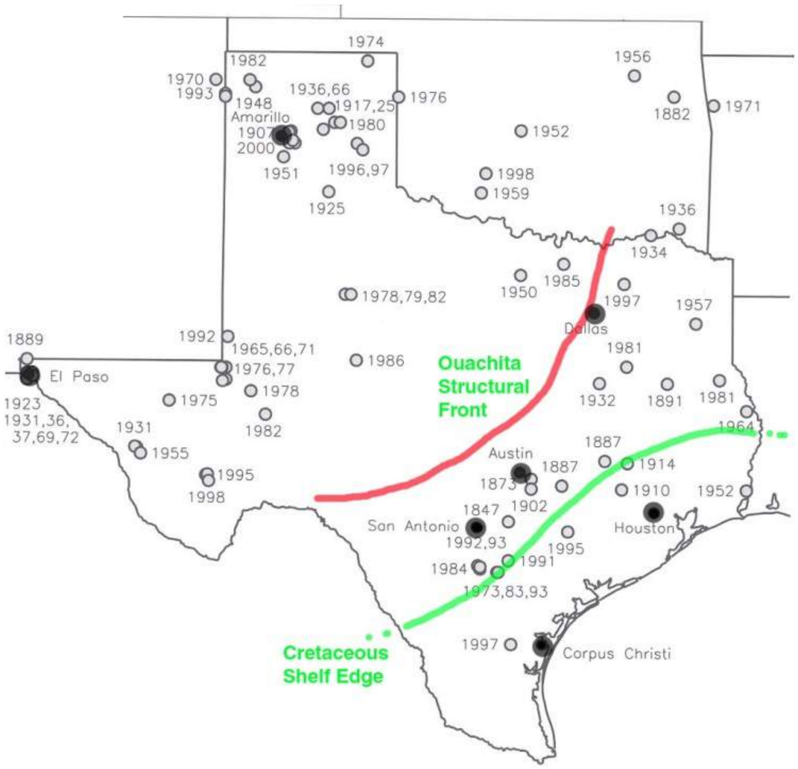


Figure 16 – Earthquake Locations in Texas: 1847-2001
(Modified After Frohlich and Davis, 2002)

Reid (1973), in an outstanding contribution to understanding the issues, provided early insight on the roles of the independent mechanisms of active faulting in the area. More recent discussions on the possible causes of faulting and subsidence suggest that bed compaction and faulting may result from mechanisms other than gravitational or tectonic forces (see Dewhurst, *et al.*, 1999). However, the role the Louann Salt plays in surface faulting may be substantial (Guglielmo, *et al*., 1995).

In general, the possible causes of the main geologic hazard of shallow faulting can be summarized as follows:

1) Faulting is caused or triggered by subsidence as a result of fluid extraction at the depths of production (within the Evangeline and/or within oil and gas reservoirs at depth),
2) Faulting is caused by the movement of salt domes, ridges and intervening troughs at various depths, and
3) Faulting is caused by load-induced crustal warping at depths even greater than that of the Louann Salt.

The principal salt domes, growth faults, subsidence contours, monitoring sites (to be discussed later), water-well locations, and profile locations (also to be discussed later) are presented in Figure 17. The map also shows the approximate boundary of the Beaumont Clay and Lissie Sand at or near the surface.

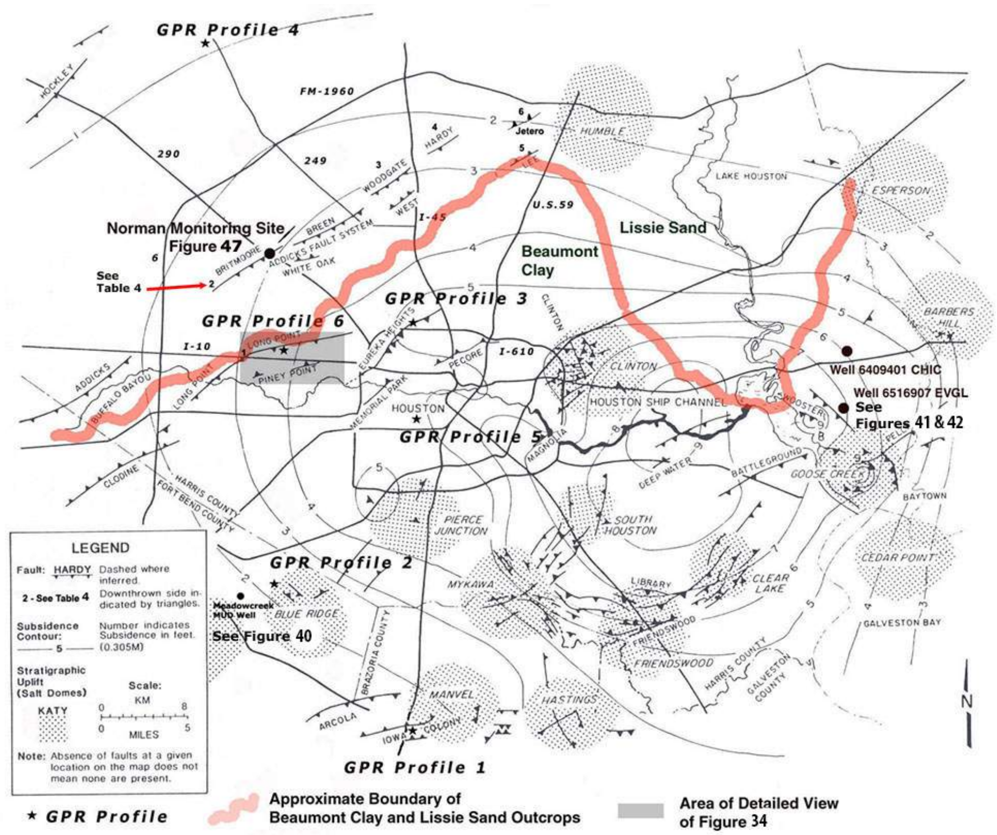


Figure 17 – Principal Active Faults Relative to Subsidence Contours (After O'Neill and Van Siclen, 1984)
Approximate Boundary of Beaumont Clay and Lissie Sand (From Proctor and Hall, 1974)
(click to enlarge)

The technical-based literature on seismicity and injection-well activities has expanded substantially in the past few years. As an example of the new approach, Rutledge, *et al.*, (2004) investigated five hydraulic fracture treatments in the Carthage gas field of east Texas. The treatments were conducted in two adjacent boreholes within interbedded sands and shales of the Upper Cotton Valley formation. The microearthquakes were clearly shown to be induced within narrow horizontal bands that correspond to the targeted sandstone layers as a result of injecting large volumes of fluids.

Section 4.0 Associated Geologic Hazards

The principal hazards associated with faulting are surface subsidence and the presence of radiocludies and natural gases in the Evangeline Aquifer, Houston's primary source of drinking water. Hunt (2007) suggests that subsidence, collapse, and heave are less hazardous than slope failure or earthquakes in terms of lives lost, but total property damage that results each year likely exceeds all of the other hazards. This does not include the cost to control flood waters in specific areas of surface subsidence located in various areas of Houston where subsidence has occurred over the past 50 years.

Section 4.1 Occurrence of Radionuclides

Of particular interest in the Houston area, ^{226}radium and ^{222}radon, considered to be another type of geologic hazard, have been sampled from the Houston ground-water supply in surprisingly high concentrations in dissolved form (Cech, *et al.*, 1987, 1988; Wise, 1990). Groundwater sampling suggested that the sources of the radionuclides were depth dependent, that is, they came from a specific interval ranging from approximately 540 feet to 960 feet below ground surface (within the Evangeline Aquifer). Recent reports of a zone of high gamma emission in a water well along U.S. 290, combined with recent U.S. Geological Survey (U.S.G.S.) groundwater sampling, indicate that scattered uranium mineralization also occurs in the western areas of Houston from such depths.

As indicated earlier, the lower Evangeline Aquifer is by definition the Goliad Formation, which is now known to contain commercial uranium deposits in Goliad County to the southwest. Apparently, groundwater migrates upward from uranium mineralization in sands and clays associated with the Catahoula Tuff and Oakville Sands at some 3,000 feet below the surface in the Houston area (see Campbell and Biddle, 1977; Dickinson and Duvall, 1977; Eargle and Weeks, 1973; and Fisher, *et al*., 1970). The Wilcox Formation is also known to contain radionuclides (Bartow, and Ledger, 1994).

The anomalous radionuclides reported in Houston area drinking water are apparently not widely distributed but are apparently produced only from specific intervals within the aquifers; some samples appear to come through salt dome-related fault structures while other anomalous areas are in areas of poorly-known fault structures. Brock (1984) reported that at least 12 municipal utility districts (MUDs) in the northwest of Harris County violated standards for ^{226}radium in the public drinking water at concentrations greater than 5 pCi/l (see Figures 18 and 19 which illustrate the distribution of analyses). ^{228}Radium was not tested during the investigations by Cech, *et al*., (1987), who only sampled water wells in selected areas of western Harris County and around the Humble Salt Dome area. Much of eastern Harris County is supplied by surface water and was not sampled for radionuclides.

Uraniferous deposits have been found in the sediments that flank or overlay Gulf Coast salt domes, most notably in south Texas at the Palangana Dome (Weeks and Eargle, 1960) and Kingsville Dome also in south Texas (Wise, 2004), and even at the nearby Hockley Dome (Kyle and Price, 1986), among others. Uraniferous deposits are also present in the Catahoula Sandstone and in the Oakville and Wilcox Sands that continue into Louisiana, which may contribute radionuclides that migrate from uranium mineralization upwards to the groundwater supplies in that area as well (McCulloh, 1982).

The occurrence of these natural contaminants raises questions about the pathways and rates at which they have migrated over such large vertical distances and about the permeability of the associated fault zones (Brutsaert, *et al*., 1981) as well as the movement through other permeable zones associated with salt domes that extend up into the Evangeline and Chicot Aquifers and their equivalents.

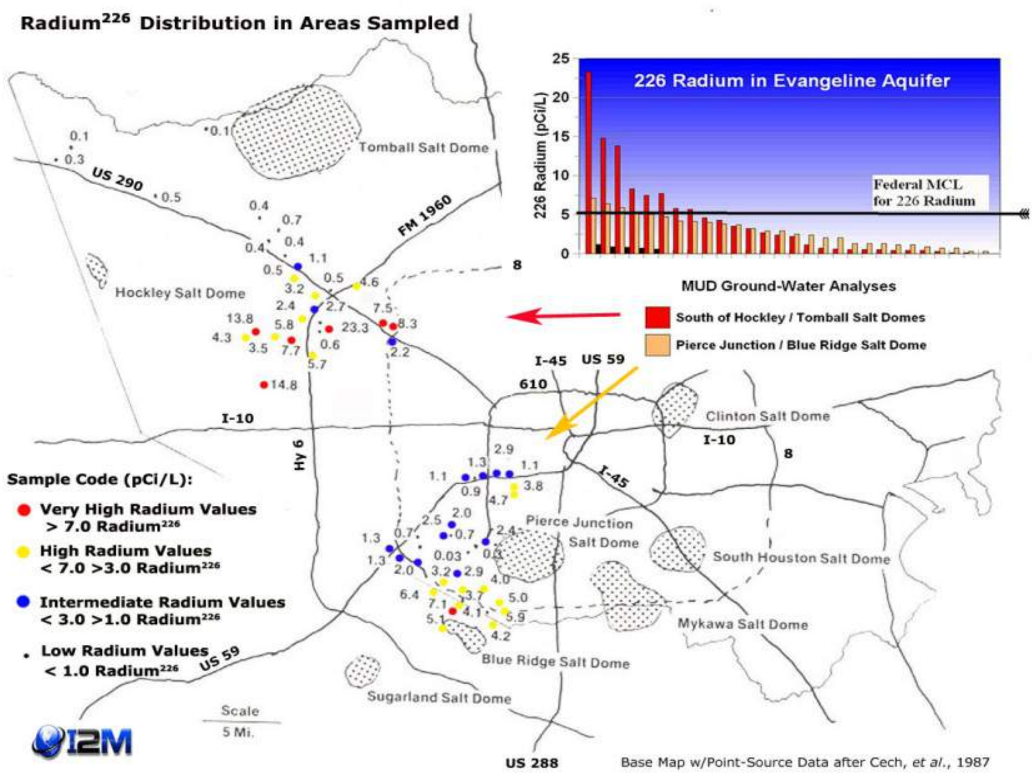


Figure 18 – Point-Source Analyses of Groundwater for ^{226}Radium (1985-1986)
(in pCi/L-Data After Cech, *et al*., 1987)

Hand and Banikowski (1988) suggested that dissolved radiogenic constituents, such as ^{226}radium and ^{222}radon, could move rapidly along structures where dissolution of salt has enhanced permeability acting as tracers of groundwater flow. The elevated concentrations of ^{226}radium and ^{222}radon have been reported as a result of sampling the groundwater from water wells on the west side of Harris County. No sampling was conducted for the central and eastern side of Harris County because much of that area is now supplied by surface-water sources impounded by the dams at Lake Livingston, and other lakes.

The presence of radionuclides in the groundwater in other areas of the Gulf Coast is well documented (Duex, 1994; McGehee, *et al.*, 1994; Bartow and Ledger, 1994; and Jobe, *et al.*, 1985, Wise, 1990; and Campbell and Biddle, 1977). Kuecher (1997) indicated that in work conducted in southern Louisiana, a vertical transport mechanism has been identified for upward migration in the form of periodic releases of saline fluids from deep aquifers to shallow aquifers along regional growth faults, which, in this case, are the Tepetate and Baton Rouge fault systems (Renken, 1998; Hanor, 1982; Hanor, *et al.*, 1986). Of particular note is that these fault systems can be correlated with the regional faults passing through Harris County and nearby counties as indicated in Figure 1.

Groundwater flow velocities within the sands and silts are values measured in centimeters per year around salt domes. Hanor (1987) and Ranganathan and Hanor (1987 and 1988) promote a density-driven concept in the movement of groundwater (in contrast to the commonly accepted Darcian concept) near salt domes that produces overestimates of horizontal as well as vertical ground-water flow velocities by a factor of more than 1,000 (Miller, *et al*., 1990 and 1986; Bethke, *et al*., 1988).

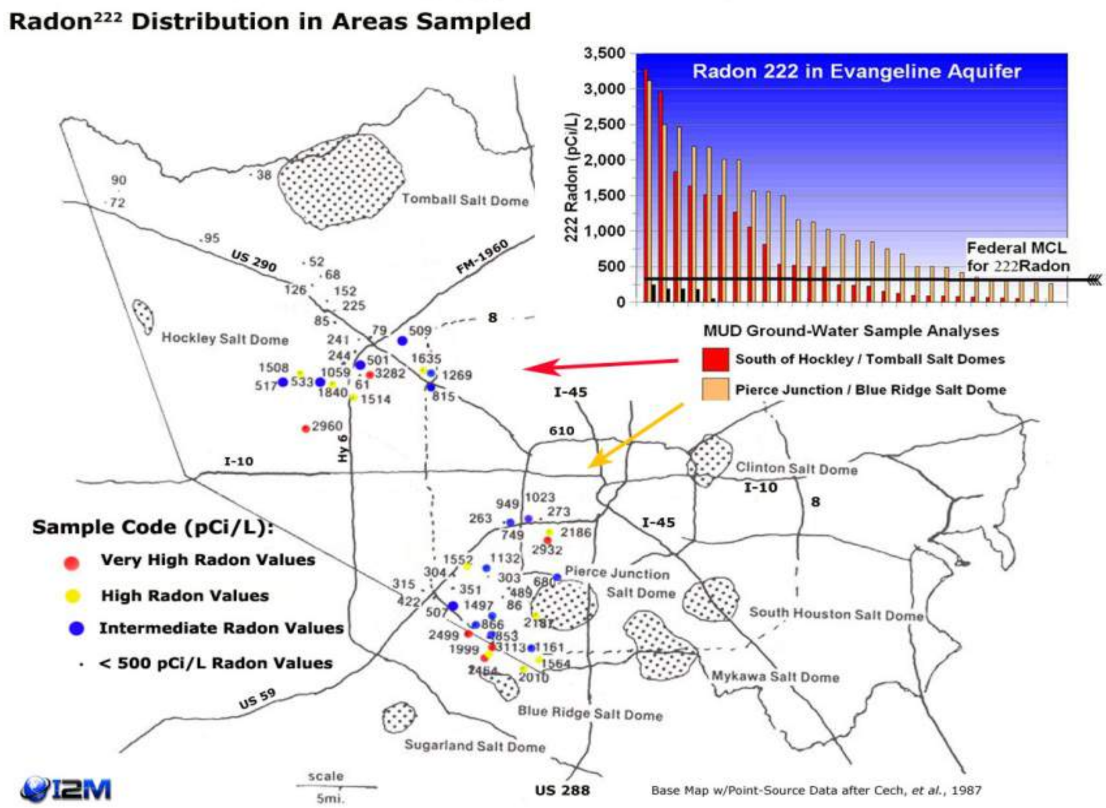


Figure 19 – Point-Source Analyses of Groundwater for ^{222}Radon (1985-1986)
(in pCi/L-Data After Cech, *et al*., 1987)

However, Bodner, *et al.*, (1985) and Petersen and Lerche (1994a) conclude that the upward migration of groundwater and associated brines and oil and gas is driven by heat advection within the more permeable sediments of faulted zones or along salt dome flanks. Mineralogical and petrological evidence also indicate that groundwater moves up along growth faults (Galloway, 1984).

Campbell and Wise (2013) indicated that the dissolved radium and radon are degradation products from uranium that has precipitated at favorable locations in the Tertiary Evangeline Aquifer in the Houston and other areas along the trend in east Texas (more). A water supply well was recently drilled (2013) along U.S. 290 northwest of Houston and encountered an anomalous radioactive zone at a depth of about 500 feet into the Evangeline Aquifer. Further, sampling data from the 1970s National Uranium Resources Evaluation (NURE) program indicate anomalously high uranium values (i.e., greater than 5 ug/l uranium) in the groundwater from water wells sampled in the western and northern parts of Harris County and other counties (more). Figure 20 illustrates the anomalies as red flames in the Google map below.

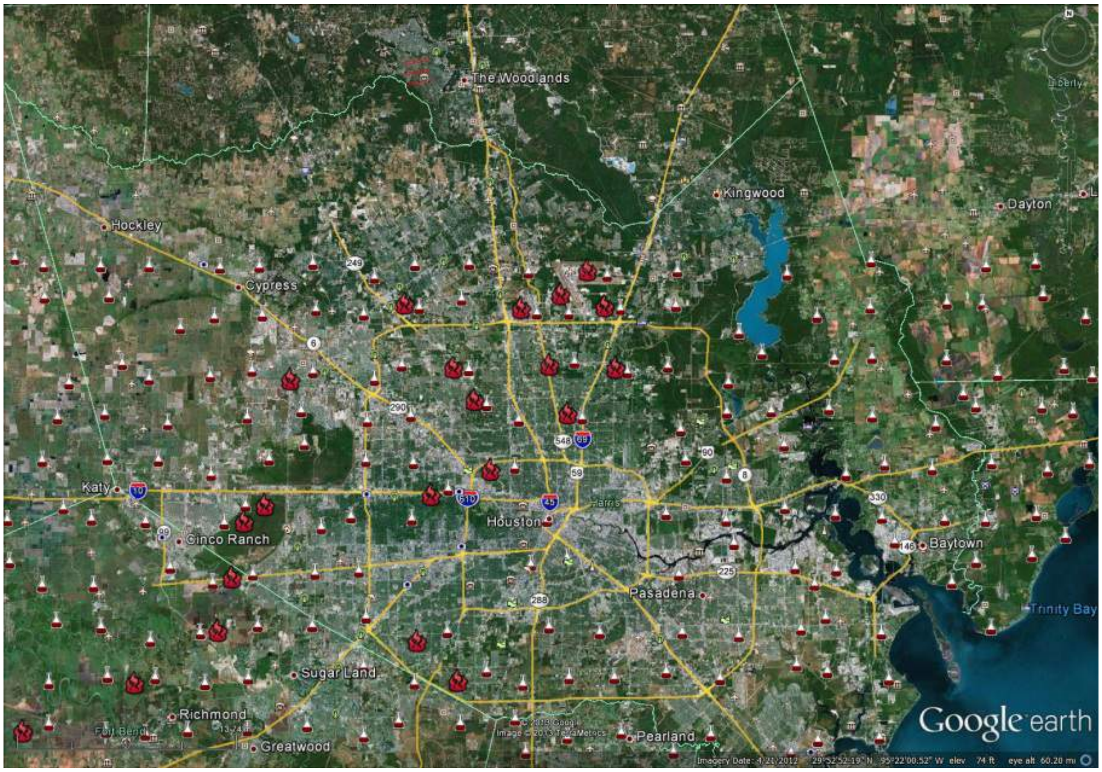


Figure 20 – Distribution of Uranium (ug/l) Sampling of Water Wells in Houston Area
(Red Flame Greater than 5 ug/l U, from Campbell and Wise, 2013)

The type of uranium mineralization in the Houston area is likely related to the typical roll-front uranium deposits known in south Texas, Wyoming, Kaskahstan and elsewhere in the world. The configuration of the mineralization would be similar to the roll front (bio-geochemical cell) shown in Figure 21. This shows a roll-front of uranium mineralization within an individual sand unit. The units may be thick, as shown in Figure 21, or thin and scattered, as are likely present in the Houston area.

Uraninite oxidizes as the hydrogeological conditions change over time and degrades to minerals containing radium, radon and other daughter products. Notice that molybdenum and selenium are also often associated with such bio-geochemical cells (Figure 21). As indicated earlier, the source of these metals, including uranium, is assumed to be volcanic units such as the Catahla Tuff. Even Texas lignite (that also contain thin volcanic units) carries elevated uranium and other metals and may be a source of uranium in such deposits (Warwick, *et al*., 1999).

Section 4.2 Impact & Remediation

Although ^{222}radon regulatory limits are relatively high, radon gas may concentrate in houses to dangerous levels, and can be especially harmful if a person also smokes tobacco. If radon is found to be present in elevated levels in the home, it can be removed by installing an air ventilation system. Recent selective sampling of water wells for radon by the U.S. Geological Survey confirms the high levels of radon (see Figure 22). It should be noted that samples were only collected in a few areas and may not indicate that high levels of radon are as widespread as indicated in the figure. However, additional sampling is clearly warranted to address the associated potential health hazards.

Figure 21 – Typical Roll-Front Uranium Mineralization in an Open-Pit Mine of the 1970s in South Texas
(Campbell, *et al*., 2004)

Removal of radon gas at a MUD water well can be easily accomplished by venting. If it is a continuing problem, using Granulated Activated Carbon (GAC) technology is a cost effective method of removal. However, accumulating such material over long periods, the GAC material does become a waste product containing low-level radioactivity and will require special disposal.

The use of aeration technology involves an initial cost of approximately $2,500 to $4,000, which is estimated to be about twice the cost of employing a GAC system. The aeration method employs an air diffuser that makes air bubbles rise through a water column to strip radon and then vent it above the roof line. This is known as diffused-bubble aeration. Most units are rated to be about 99% effective in removing radon from a water supply. A similar system that removes natural gas from a drinking water supply is shown in Figure 30.

A recently updated bibliography is available that relates to the occurrence of uranium, gaseous radionuclides, and methane in the Houston Area and around the U.S. (more). The health-related aspects of human exposure to radon have been studied extensively (PubMed, 2014). These studies have been focused on uranium mining and milling activities around the world and the alleged health aspects associated with the activities. The need for these studies arose because media coverage and lawsuits arose in and around areas of uranium mining activities of the late 1950s and 1960s. Much of the interest related to Native Lands in Arizona, Utah, Colorado, and Wyoming where uranium was mined by open-pit or underground methods during those periods.

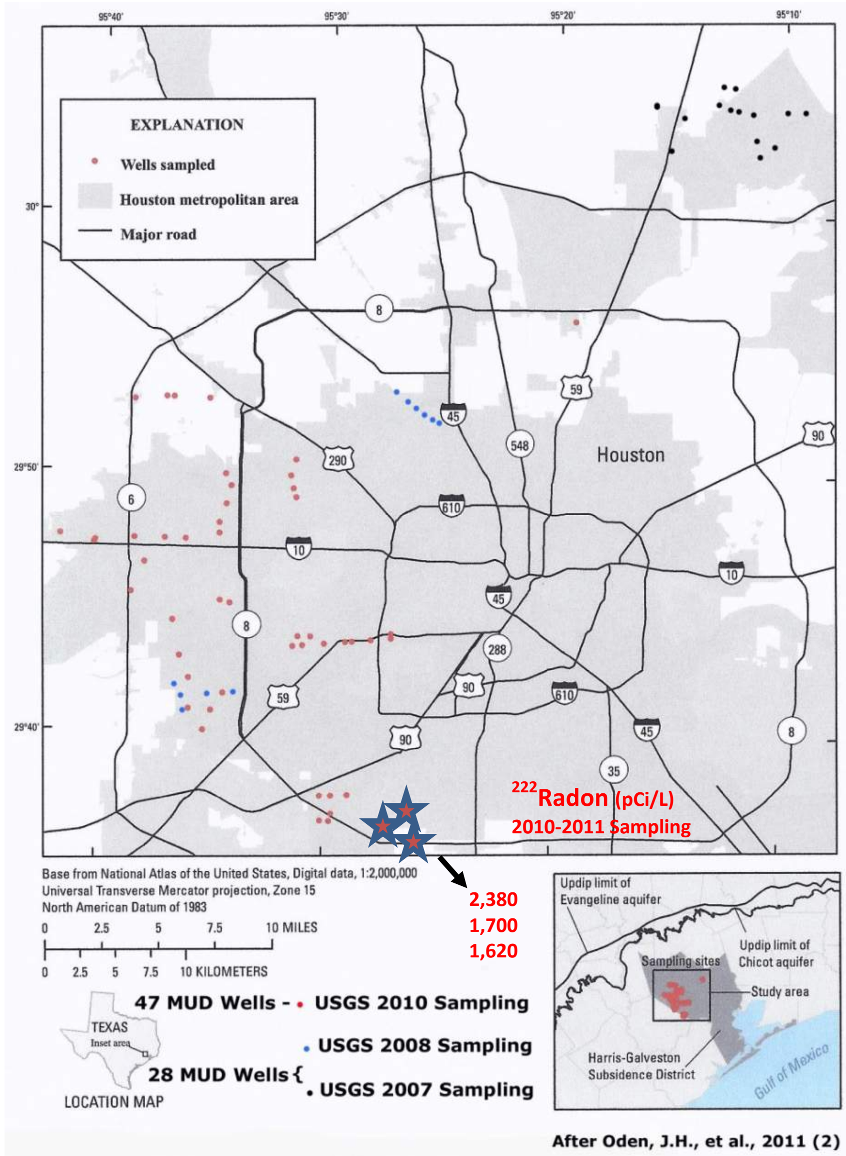


Figure 22 – Recent USGS Sampling: ^{222}Radon

The general conclusions of the studies suggest that men who worked in the underground uranium mines, and who smoked tobacco, were many times more likely to contract lung cancer than the men who did not smoke, and especially those who neither smoked nor worked in the underground uranium mines. Radon, apparently is inhaled along with the tobacco smoke deep into the fine tissues of the lungs, and causes tissues to mutate causing cancer.

Over the years, the general public has been alerted by U.S. EPA to the dangers of radon that naturally occur in the surface rocks and sediments in the U.S., and in the groundwater and drinking water in certain areas. Houston happens to be one of those areas where uranium is present in the groundwater of the Evangeline Aquifer in some areas, as discussed above, and in other areas in the Gulf Coast with similar underlying geological conditions favorable for uranium to concentrate in the subsurface. This has not gone un-noticed by the local and national news media from east Texas to South Texas, as well as in other areas of the U.S., from Virginia to the western states where uranium occurs in the subsurface rocks and sediments.

Numerous stories have been published over the years highlighting the apparent dangers of the uranium that occurs naturally in the subsurface and the radioactive byproducts that have entered the groundwater and local drinking water supplies.

With press coverage of "radioactive" groundwater, the news media reports to the general public on what the reporters provide, no matter how misleading, exaggerated, or incorrect their coverage may be. Campbell, *et al*., (2014) have been confronting the associated media bias for a number of years by critically reviewing those articles deserving comment. There are common themes that adversaries employ to promote a clearly anti-nuclear, anti-uranium mining, and even pro-wind and solar agendas.

Although radon gas is by definition "natural", there are other natural gases that often enter the groundwater reservoir and associated drinking water aquifers. These natural gases are gaseous hydrocarbons that generally originate from organic rich source rocks at great depth. The release of methane and associated gases at the well site and from offshore sediments is contributing to climate concerns (see Campbell, (2014), bottom of page 2).

Section 4.3 Natural Gas Wells & Faults

Another associated type of geologic hazard present in the Houston area involves natural gas-well blowouts and natural gas in the Evangeline Aquifer. One such blowout occurred in 1944 in the FM 1960 area of Houston's northern suburbs (Rose and Alexander, 1945). Under such circumstances, faults can act as zones of permeability allowing natural gas to migrate up into the overlying Evangeline and Chicot Aquifers. As an example, in 1942, a well (known as Mieneke No. 2) was drilled to the Cockfield Sand of the Yegua Formation, part of the Claiborne Group, to a depth of approximately 6,200 feet. The well was completed within an anticline (over a salt dome) with faults trending southwest to northeast, faulted down to the coast (see Figure 23 for the general location of the blowout).

Over a four-month period, water levels in nearby water wells about 5-miles from the site began to rise to unprecedented levels; then, months later local water wells began to flow at the surface, and gas wells began to produce groundwater from between the casing strings. Some months later in 1944, water wells finally failed because of excessive artesian flow around the surface casings and the Mieneke gas well caught fire and burned out of control over the ensuing seven months.

Looking back, Cartwright (1987) recounts that control was only regained after a relief well was drilled and about 15,000 sacks of cement slurry were used to finally extinguish the fire and to control bottom-hole pressures. Ground-water levels then began to decline in local water wells. However, even today the natural gas released during the 1944 blowout is still present in the Evangeline Aquifer in the general area (Gutierrez, 1990). Over the years since, a number of Municipal Utility District wells have had to be abandoned because of the gas hazard while some wells were outfitted with de-gassing, aeration and venting equipment to address the hazard.

The above case demonstrates that natural gas and its associated distillate containing benzene, toluene, ethylbenzene, and xylenes are likely to have migrated upward, not only along leaking well casing, but also along fault structures that are penetrated by wells from depths at least 6,000 feet below the surface, which, in this case, is some 3,000 feet below the probable source of radionuclides.

The presence of natural gas would be expected in selected areas underlain by shallow, permeable fault zones that may provide pathways for escaping natural gas and associated distillates toward the surface.

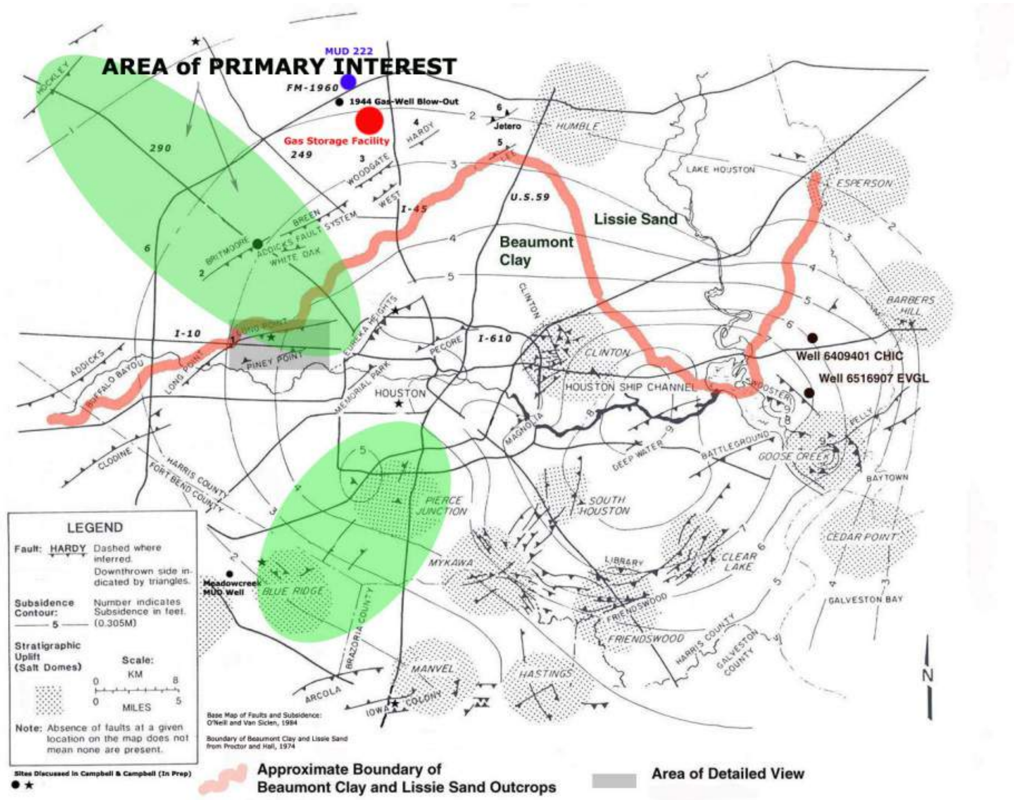


Figure 23 – Location of Natural Gas Blowout and MUD
(After Campbell and Wise, 2013)
(Click to Enlarge)

During a previous project involving two of the authors of this report, they investigated why pumping rates had decreased in a Houston FM 1960 area MUD water well. The MUD well maintenance records were reviewed and a downhole video survey of the well was conducted. This involved pulling the pump assembly to inspect conditions inside the intake pipes. The MUD well was purged and the groundwater was sampled as was the air in the headspace within the well casing (Figures 24 and 25).

Figure 24 – Purging MUD Well in Northern Houston Area
(Campbell, Campbell and Saribudak, 2004)

Figure 25 – Sampling MUD Well-Casing Headspace and Groundwater
(Campbell, Campbell and Saribudak, 2004)

The results of the investigations identified the presence of natural gas and advanced scaling on the down pipe exterior and interior segments of the well screen at depth.

The natural gas analyses obtained from sampling the groundwater and headspace of the MUD water well are shown in Table 1. Of particular note is that both ethylene and propylene are absent, suggesting that they have been consumed by bacteria specifically adapted to metabolize these hydrocarbons. This may also indicate the stage of maturation of natural gas present in the aquifer. Two hypothetical candidate sources were noted: the 1944 blowout almost 70 years ago, or the natural gas storage facility nearby, (or from other sources of natural gas). The data suggest the natural gas present is not from a natural gas supply line but rather has undergone changes in composition as a result of slow migration through the subsurface zones inhabited by petrophillic bacteria. Further study is merited to identify the source of the natural gas and whether it was related to either the gas well blowout of 1944, located about two miles away from the present M.U.D., or hypothetically to natural gas leaking from a large natural gas storage facility located nearby.

The data in Table 1 (and illustrated in Figures 26 and 27) indicate, among other things, that the headspace above the standing water level in the well (i.e., representing the potentiometric surface) contained concentrations of methane that exceeds the lower explosive limit (LEL) and that methane concentrations are within almost 90 percent of the concentration capable of reaching the LEL (see Figure 26).

Clearly, the presence of natural gas represented a hazardous condition and the MUD's operator promptly initiated procedures to eliminate the potentially explosive hazard by venting the well and storage tanks, sampling consumer outlets and informing them of the potential hazard.

Table 1 – Head-Space and Groundwater Analyses

Samples Taken 10/16/98

(Campbell and Wise, 2013)

Head-Space Sample (ppmv)	# 1	# 2	# 3	**Water Sample (ug/l)**	# 1	# 2	# 3
Methane	4,358	4,577	4,894	Methane	11,437	11,319	9,704
Ethane	206	212	230	Ethane	1,112	1,156	1,086
Ethylene	**ND**	**ND**	**ND**	Ethylene	**ND**	**ND**	**ND**
Propane	113	118	126	Propane	610	587	566
Propylene	**ND**	**ND**	**ND**	Propylene	**ND**	**ND**	**ND**
Iso-Butane	31.2	32.2	35.0	Iso-Butane	149	144	143
N-Butane	30.2	31.8	33.1	N-Butane	96	69	60
Iso-Pentane	14.9	15.8	16.6	Iso-Pentane	56	53	53
N-Pentane	8.9	9.3	11.0	N-Pentane	12	9	8
Hexanes	12.5	12.5	11.0	Hexanes	28	28	26

Note: ND = Not Detected

Major natural gas leaks are not uncommon. The area in and around the City of Mont Belvieu, Texas has exhibited similar problems with leaking natural gas storage reservoirs, and residents of Tomball, Texas have also experienced leaking abandoned gas wells, according to various news reports.

However, elevated methane has been found in relatively shallow sediments as well as in deep sediments (Lundegard, *et al*., 2000). For example, Grossman, *et al*., (1989), indicate that methane can be produced *in situ* by bacteria using substrates derived from lignite or disseminated organic matter, with the associated groundwater exhibiting different hydrochemistry and isotope configurations than that produced by thermocatalytic processes in deep oil and gas reservoirs.

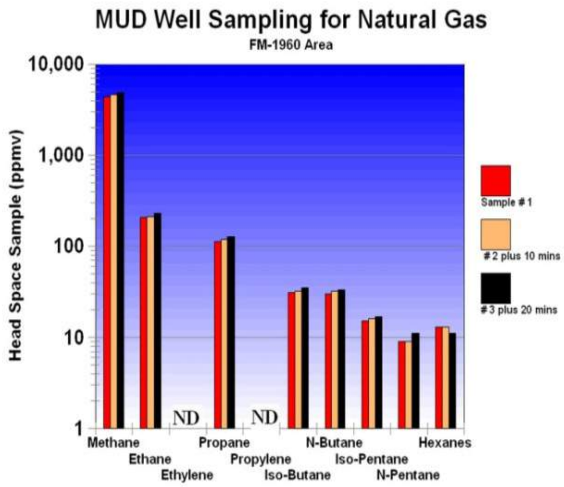


Figure 26 – Ground-Water Sampling of MUD Well
(From Campbell and Wise, 2013)

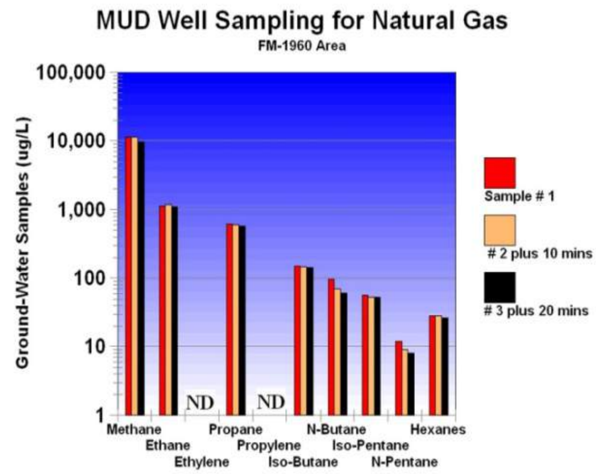


Figure 27 – Head-Space Sampling of MUD Well
(From Campbell and Wise, 2013)

Bacterial processes that produce methane in shallow sediments, (Grossman, *et al*., (1989)), do not produce higher-chain hydrocarbons (as indicated in Table 1 and Figures 26 and 27), although microbes can oxidize thermogenic natural gas by preferentially removing the higher-chain hydrocarbons (Martini, *et al*., 2003). The impact of bacteria on thermogenic natural gas is indicated in Table 1 (and Figures 26 and 27) by the striking absence of ethylene and propylene in the groundwater from the Evangeline Aquifer at depths of 710 to 1,100 feet (the screened interval of the MUD well) below the surface and in the headspace of the well. Therefore, based on available information, natural gas apparently had migrated through the Burkeville Confining Unit from below from a source that would require further investigation to identify by isotope composition or other methods of fingerprinting.

Downhole video logging is commonly conducted as a regular maintenance program in some MUD water wells to evaluate the conditions inside the well casing and screen intake intervals. Scale often is formed over the screen openings and, if present, the intervals in the well can be identified for subsequent cleaning by rig-mounted downhole rotary brush assemblies. In the process, some well surveys have encountered natural gas. For example, a video survey shows a few bubbles of gas at a depth of 678 feet (Figure 28) but at lower depths a plethora of gas bubbles is observed entering the well at the top of the screen (see Figure 29).

The differences at the two depths illustrate that as the bubbles of gas enter the well and rise, much of the methane dissolves, decreasing the number of gas bubbles as they rise. The video view of the potentiometric surface (water level in the well) appeared as a churning mass of iron-rich biomass and water. This was generated by the break-up of the scale created by iron bacteria that has been dislodged from the encrusted screened zone below by the mechanical action of the bubbles coming through the screen into the well and rising to the water surface.

Figure 28 – Minor Natural Gas Bubbles Rising in MUD Well Casing at Depth 678 Feet
(From Campbell and Wise, 2013)

Figure 29 – Natural Gas Bubbles at 710 Feet Entering the Well at the Top Screened Zone
(From Campbell and Wise, 2013)

Such iron-based scaling in water wells is not uncommon. It is the principal reason for regular maintenance programs to mechanically clean the inside of the well screens and casing and chlorinate the water. Because most MUD wells are reamed and gravel-packed during the initial drilling and well construction from the bottom of the well to above the top screen, the location of just where the gas enters the well along the gravel pack cannot be determined.

In the case discussed above, because the gas was missing the two hydrocarbon isomers that are generally present in produced natural gas (i.e., ethylene and propylene), their absence in the gas sampled suggests that the natural gas isomers have been removed by bacteria over a long residence time in the Evangeline Aquifer. They would not likely be part of the natural gas that recently migrated from great depths. However, there are other interpretations for the source of the natural gas other than the 1944 blowout or other deep sources. One candidate hypothetical source would be the large underground natural gas storage facility located nearby (see Figure 23), where long residence times would also be involved with the stored natural gas. Identification of the actual source was beyond the scope of this investigation.

The MUD well system was outfitted with well-head degassing, hydrocarbon removal, de-sanding, and storage-tank venting equipment to mitigate and manage the presence of natural gas in the produced water (see Figure 23 for location and Figure 30 for the system layout).

Section 4.4 Impact of Natural Gas Migration via Faults

In another area to the north of FM 1960 near Tomball, Texas, benzene and associated contaminants have been reported in the groundwater in at least two cases where leaky fault zones (as opposed to operator shortcomings related to poor maintenance of producing or abandoned oil and gas fields) are the likely natural sources of the elevated methane in the groundwater supplies. Once identified in the water supply, steps can be taken to remove the natural gas with domestic and municipal venting and filtration equipment as shown in Figure 30.

Figure 30 – MUD Well and Storage Facility at FM 1960 w/ De-Gassing & De-Sanding Equipment
(From Campbell and Wise, 2013)

Fingerprinting of produced natural gas is the first step in characterizing the hydrocarbons present in groundwater of a producing water well (Coleman (1995); Zhang, *et al*., (1998); Molofsky, *et al*., (2013); Campbell and Wise, 2013). Baseline sampling of high-pressure natural gas wells is in itself hazardous and needs to be conducted by trained personnel of the gas company that owns the well (Figure 31).

Gorody (2012) also provides a series of case histories on identifying the source of stray gas in drinking-water supplies This involves comparing the gas composition in affected groundwater supplies with gas samples collected while drilling, produced gases, casing-head gases, pipeline gases, and other potential point sources.

Figure 31 – Sampling a Natural Gas Well
(From Campbell and Wise, 2013)

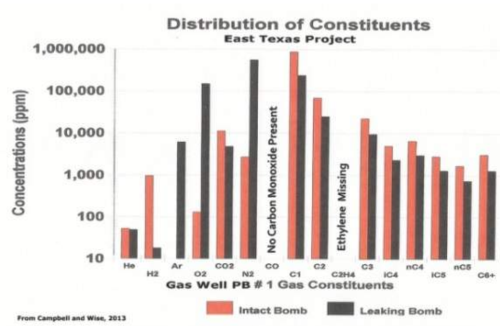


Figure 32 – Sampling Results: Natural Gas Well
(From Campbell and Wise, 2013)

The laboratory results of such sampling can become an issue when one of the sampling containers shows contamination from the atmosphere, likely occurring during transfer at the lab. The results exhibiting contamination with the gases in the atmosphere would contain argon, oxygen, and nitrogen. Results indicate that a natural gas producing zone environment would contain higher hydrogen, carbon dioxide, and a range of hydrocarbons, which would be higher in concentration than those in the sample contaminated by exposure to the lab atmosphere (Figure 32).

The absence of ethylene suggests that either the gas was not present in the formation and/or it has been consumed by bacteria at some stage during the evolution of the natural gas. When laboratory errors cannot be ruled out, additional sampling and analysis (duplicates, etc.) would be required to clarify the data.

Existing in the dynamic conditions at depth in the Gulf Coast geosyncline, the 1944 natural gas well blowout was a costly and dangerous hazard at the time, with remnant effects still present in the subsurface of the area today. Deteriorating casings of abandoned or aging natural gas and oil wells represents additional potential sources of natural gas contamination not unlike those cited above. Most MUD and private well owners conduct regular sampling and maintenance programs to monitor and manage these potential hazards.

Groundwater production has declined in and around the eastern areas of Houston over the last few decades because water wells have been replaced by pipelines carrying surface water from Lake Livingston and other sources, ostensibly to reduce subsidence. The threat of the groundwater being contaminated by natural gas and other contaminants has therefore declined. The MUD water-well systems replaced have either been mothballed or dismantled. If needed in the future, monitoring would be resumed. However, the western parts of Houston and outlying communities will continue to use groundwater as their primary source of drinking water, and the hazard will remain in the form of natural gas, distillate, and radionuclides that may migrate up permeable fault structures from deep sources or from leaking gas-storage reservoirs into either the Chicot or Evangeline aquifers.

A recently updated bibliography is available that relates to the occurrence of natural gas and other constituents in the Houston Area and around the U.S. (more). The Ground Water Protection Council also produced a white paper on stray gas (more). The State of Pennsylvania has also examined cases (more).

Section 4.5 Product Pipeline & Waterline Impacts

Another type of potential geologic hazard created by faulting is associated with potential pipeline ruptures resulting from stresses applied by fault-zone movements where they cross fault zones. Because Harris County contains an unusually high density of active pipelines, this geologic hazard is most pressing (see Figure 33). The figure shows only the generalized locations of the active pipelines in the Harris County area. Natural gas pipelines are usually operated under very high pressures, and if dislodged or cracked causing a leak, this presents a major explosive potential if the gas encounters a source of ignition. In conducting regular pipeline inspections in rural areas, personnel look for turkey buzzards circling over a length of pipeline; this often indicates a leak in the line. The birds' keen sense of smells is tuned in to the rising methane that usually indicates food (carrion).

Although the map below (Figure 33) shows only the general locations of the pipelines, sites of potential hazard from fault movement would be located where the pipelines cross over fault zones. An initial tally of such sites of potential hazard along well known faults was developed from an overlay of the map of the well-known fault sites shown in Figure 25 on the pipeline map, as shown in Figure 33. The number of sites where hydrocarbon pipelines cross known fault zones is provided in Table 2.

The pipelines are underlain in a number of key sites in the Houston area. Because of the scale of the maps used, we present this information as approximate locations only to illustrate the issues involved.

To establish with any certainty the specific areas where they cross and the potential hazards involved would require fieldwork and detailed mapping.

Table 2 provides data for only well-known faults which includes only a small sampling of the faults known in the Houston area. In eastern Harris County, the pipelines in and around the refineries and the Houston Ship Channel are too numerous to count using the scale of the map of Figure 33, especially along the Clear Lake-Friendswood-Mykawa corridor (see Figure 33). For example, a field survey counted at least seven pipelines that cross the Battleground Fault in eastern Harris County.

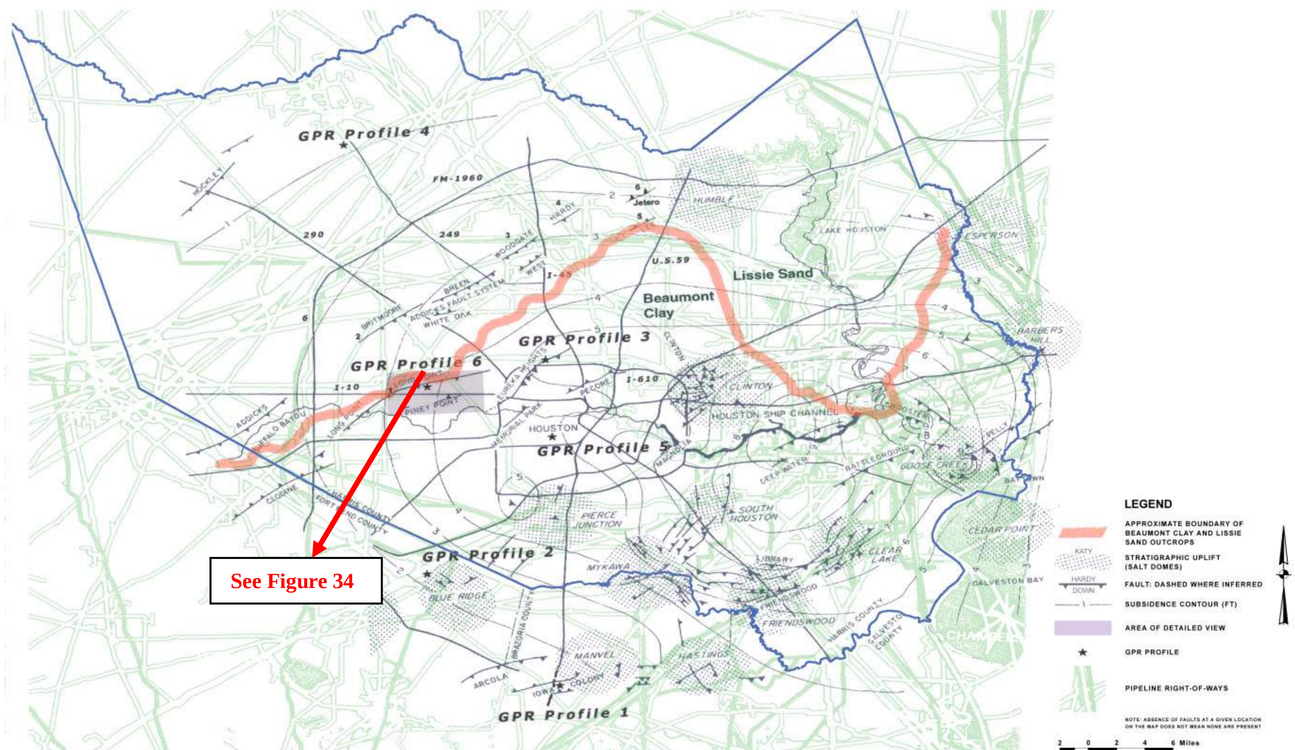


Figure 33 – Pipeline Corridor Location Map for Harris County
(From Railroad Commission of Texas, 2003; Map after Reid, 1973)
(Click to Enlarge)

Because growth faults pass into decreasing flexures along the strike of the feature, straight-line extrapolations of these known faults shown in plan view are often inappropriate. The Piney Point Fault system shown in Figure 34 consists of two fault segments, some of which are linear. Extrapolating known faults is appropriate only when fieldwork and mapping substantiate such extensions with defensible indications of movement at the surface. It should be noted here that these indications can be similar to the effects of consolidation of fine-grained sediments (clay) during prolonged droughts.

Table 2 - Number of Pipeline Crossings for Selected Faults

(See Figure 33)

Fault Name	Pipeline Crossings
Long Point	3
Piney Point	3
Eureka Heights	2
Pecore	3
Memorial Park	1
Addicks	6
Clodine	9
Blue Ridge	2
Brittmoore	4
Breen	2
Addicks NE	2
White Oak	1
Woodgate	4
Hardy	1
Hockley	1
Willow Creek	2

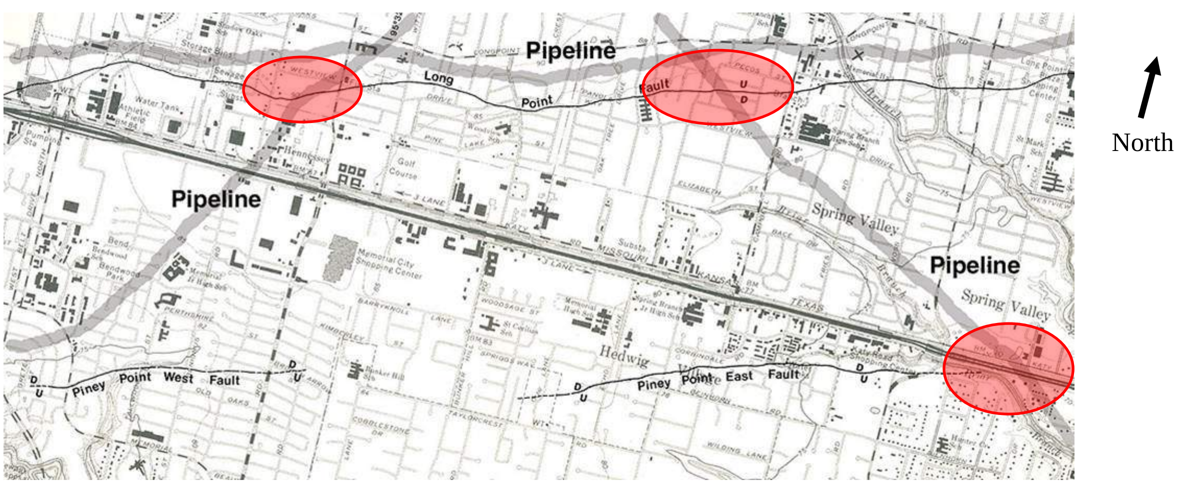


Figure 34 – Example of Hazard Zones to Be Monitored **(See Figure 33 for location)**

Base Map After: O'Neil and Van Siclen, 1984

The known sites of potential hazards can be monitored on a regular basis, but critical areas where fault extensions or unknown faults presently go unrecognized represent a potential hazard. Unless special attention is paid to these areas, a pipeline leak or rupture, combined with a source of ignition, could create an explosion and fire in a populated area.

For an example of a section of one of these areas, Figures 34 shows segments of the now well-known Long Point Fault, which typically strikes northeast to southwest with its down side toward the coast. An associated fault system, the Piney Point Fault, is located approximately one mile to the south (Figure 34). The down side of the fault is away from the coast, which is shown in Figure 17.

It is interesting to note that one of the pipelines shown in Figure 34 (near the upper margin of the figure) appears to have been constructed to avoid crossing the Long Point fault. This figure is based on the pipeline map (Figure 33) where the subject pipeline was constructed along Interstate Highway I-10. As it approaches the Long Point fault from the west, it changes direction and runs along the northern edge of the fault (on the upside of the fault) throughout the area. The other two pipelines shown in Figure 34 appear to cross both the Long Point and Piney Point faults at an angle. The presence of a creek highlights the Piney Point Fault to the southeast.

The Clodine fault and the Renn escarpment was mapped in the 1970s by the USGS southwest of this area through the Mission Bend subdivision and extends across the Harris and Fort Bend County line (more). Whether the Clodine fault is an extension to the Piney Point fault has yet to be confirmed. In any event, the Clodine fault has been crossed by at least 9 pipelines (see Table 2).

The Eureka Heights Fault that is known to occur inside the northwest corner Highway 610 crosses 610 in two places. Here again, detailed mapping would be required to confirm these conditions. Highway construction in this area provided near-surface evidence of this fault. Surface and near-surface pipelines carrying drinking water in distribution lines throughout the Harris and surrounding counties are also prone to rupture as a result of fault-zone movements (and from consolidation). In fact, these sites of rupture may well be good guides to locating unknown faults in the area. In one study for a MUD in Fort Bend County of repair records showing dates and locations of reported leaks, these can lead to new sites of likely fault movement, and to extensions of previously known or suspected faults.

Of course, maintenance records of local MUDs and the City of Houston can be screened and interpreted for other possible causes of water-pipeline ruptures, e.g., contractor ineptitude, local consolidation (soil heaving) that usually occurs during and just after drought periods, corrosion of unprotected pipelines from stray galvanic currents in the area (and improper galvanic controls on pipelines causing corrosion), and creep damage to surface facilities, such as to fire-plug assemblies where stresses can be transmitted to underground pipelines. These may rupture and leak for months or years later as a result of damage not previously identified and can create cavities below a street or dwellings. The ceilings of such cavities will eventually fail because the leaking water carries away the sediment creating “sink holes” often reported in the media.

Also, pipeline companies have programs for monitoring pipeline crossings of the well-known faults in the Houston area and elsewhere in Texas. Records of the frequency, location, and date of pipeline repairs would also be useful in assessing this type of hazard. These data would aid in locating and monitoring known as well as new faults in the area.

Section 4.6 Landfills & Faults

Other geohazards exist that involve permitted and unpermitted landfills, active or inactive. Although common in and around most major cities, these sites, when underlain by growth faults represent a potential threat to the shallow and deep ground-water resources, especially those present in the Harris County area and surrounding counties.

We have combined information on the approximate location of landfills in the map showing the well-known surface faults (see Figure 35). Of particular note are the sites indicated on or near the Addicks Fault system and in proximity to the Clinton, Pierce Junction, Humble, Goose Creek and Wooster Salt Domes (see Figures 35 and 17).

Active landfills, with or near faults, are also a potential source of hazardous substances to Houston's groundwater. Table 3 provides examples of landfills with reported violations from the monitoring well sampling over the past few years.

The large number of active landfills and inactive (dumps) and sewer lines in a large city such as Houston usually makes the underlying shallow groundwater of limited use. With appropriate sampling and monitoring, shallow groundwater and the associated aquitards represent the first line of defense against such contamination reaching Houston's major groundwater supplies below, in the Chico and Evangeline Aquifers.

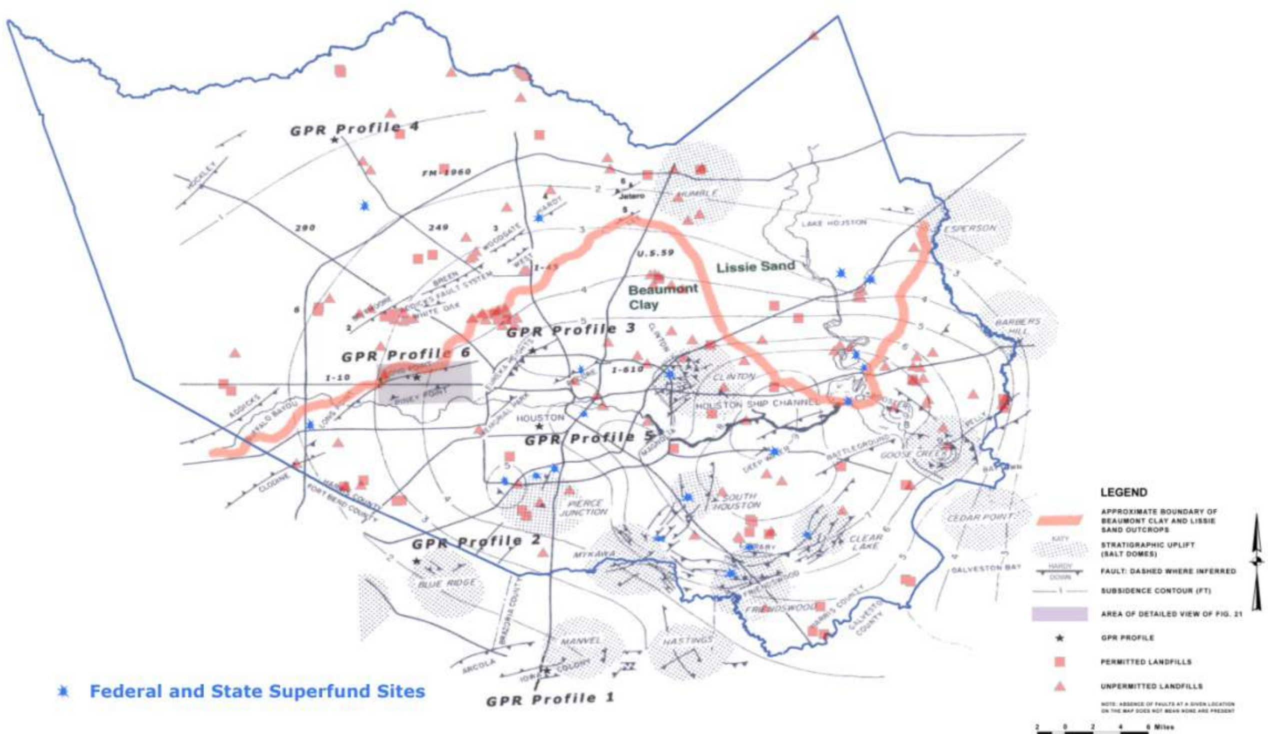


Figure 35 – Landfill Location Map for Harris County w/ Known Faults
(Data from City of Houston, 2004; for a List of Current and Inactive Landfills (here))
[For the locations of the Superfund Sites in Harris County, see (here)]
Click Above Figure to Enlarge

It should be noted that not all growth-fault contacts are sufficiently permeable to permit contaminants to migrate from below a landfill or old dump down into the aquifers. There are clay-to-clay contacts across the fault zone, sand-to-clay, and sand-to-sand. The latter represents a worst possible set of conditions of the three and would permit migration of contaminants, given favorable hydrogeological conditions of flow direction and gradient. The volume of contaminants also comes into play.

If only a relatively small volume is involved, contaminants may degrade or be adsorbed by clay. If it consists of solvents, it would be capable of moving through clay and sand intervals rather rapidly. Being immiscible in groundwater, solvents represent the most serious contaminants in the Houston area, as indicated in Table 3.

Table 3 – Examples of Active Landfills in Houston Area with Reported Leaks

Landfill Name	Landfill Location	Violation
BFI McCarty Road Landfill	NE U.S. 90 E. FM527	BETX. Carbon Tet, 1,4 DCB, 1,1DCE, MECL, PCE, VC
WM Atascocita Recycling Facility	SW Humble E 59 Atascocita Road	1,4 DCB, Cis-1-2 DCB, Benzene, CB
Casco Hauling and Excavation Landfill	East Anderson Road	Arsenic

Note: The source of the information above is available (here).

Section 4.7 Flooding, Subsidence, and Faulting

Another result of subsidence is flooding in areas that were not known to flood years ago but now flood when major rainfall events occur from stalled tropical disturbances, some hurricanes, or repeated weather patterns creating unusually high rainfall in the Houston area. The City of Houston and surrounding MUDs install drainage channels (open and enclosed) to control and divert excess surface water into water ways and bayous. The 100-year and 500-year floodplains are shown in Figure 36 along with the basemap of known growth faults at the surface and the various salt domes at some depths.

The costs to construct and maintain the flooding draining channels are substantial and there is nothing that can be done to prevent subsidence, except by reducing the volume of groundwater production in the areas affected. In the late 1970s, the rate of subsidence was reduced in the Brownwood Subdivision along the eastern shore of Galveston Bay and along refinery row still located along the western shores of the Bay. This was accomplished by bringing surface water piped from Lake Livingston and other dammed sources of surface water the area. Since then, the City has converted to surface water in all but the western part of Harris County and has placed most City water well on a standby status (for more on this subject, see Section 5.4).

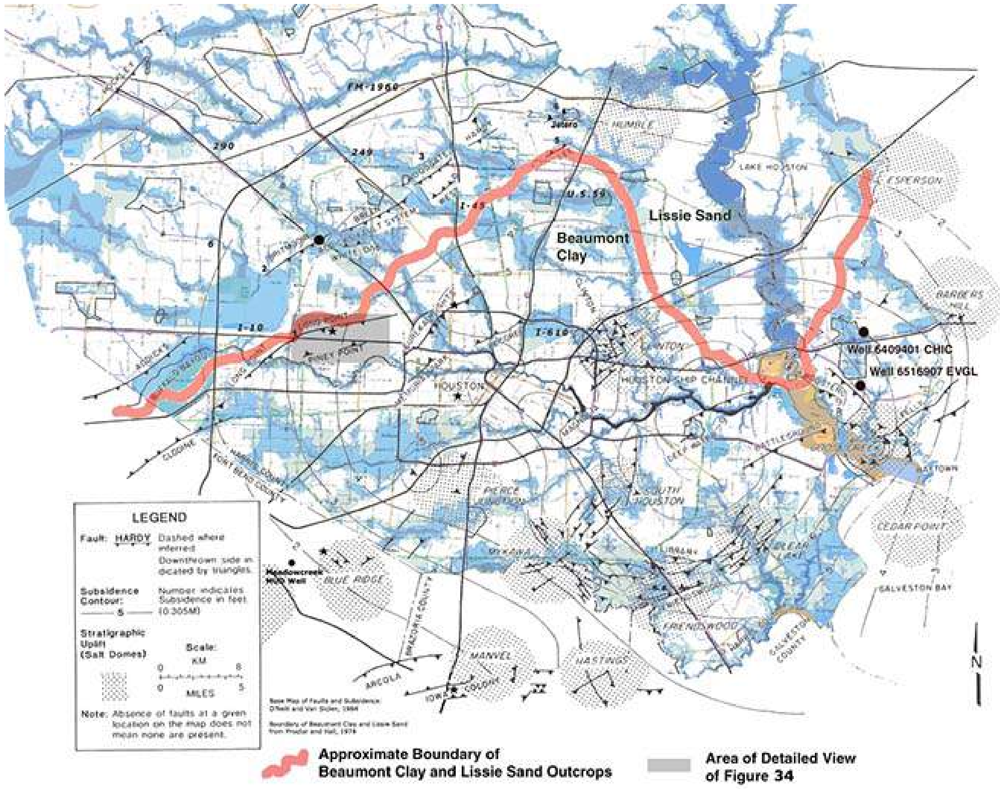


Figure 36 – 100-Yr and 500-Yr Floodplain Map for Harris County w/ Known Faults
(Data from City of Houston, 2014; for the Harris County Fooldplain Map (here)
Click Above Figure to Enlarge

Section 5.0 Faulting-Subsidence-Hydrogeological Issues

Site-specific structural stresses caused by faulting can be reinforced by other stresses like subsidence that are, in turn, induced by changes in the potentiometric surface within the Evangeline and Chicot Aquifers from excessive pumping over broad areas in Harris County. The problem was documented as a geologic hazard in the early 1970s along the Houston Ship Channel and refinery row (Gabrysch, 1972).

The Houston area is not the only area where similar problems have developed. California has experienced significant subsidence in the fertile San Joaquin Valley and Sacramento Basin areas that can be directly attributed to ground-water withdrawal as well as the associated structural stresses involving faulting (see Poland, 1972; and Poland, *et al*., 1975; and Borchers, 1998, for case histories on other areas with subsidence problems in California, the U.S. and overseas, such as in Venice, Italy where subsidence has been in evidence for centuries, and India (Saxena, 2013)).

Fissures, located in West Texas in the Red Light Draw and Fort Hancock areas southeast of El Paso, Texas may also be related to excessive groundwater withdrawal in the region, which depends wholly on groundwater resources for domestic, agricultural, municipal and industrial needs. However, the cause of these fissures also may be related to movements within the Rio Grande rift, with or without the influence of excessive groundwater production in the area (Heynekamp, *et al*., 1999; Haneberg, 1999; and Haneberg and Friesen, 1992). For similar occurrences in Arizona, Gelt (1992) relates the occurrence of similar fissures directly to over-pumping and declining potentiometric surfaces.

For the southwestern United States as a whole, geologists of the U.S.G.S. suggest that the major cause of subsidence is overdrafting of aquifers (Leake, 2003 and Gallaway, *et al*., 2000). As indicated, the underlying causes of the common geologic hazards in the Houston environs are likely related to the interplay between movement of the deep regional structures and the upward and lateral movement within and around salt domes and associated features. The extension of the deep faults up through the Evangeline and Chicot Aquifers to the surface exposes these shallow faults zones to changes in stress as each cone of pressure relief around high-capacity wells fluctuates during and after pumping, constantly spreading stress and then relaxation over miles within the regional pressure system, especially within and along the shallow fault zones. Changes in the regional hydraulics within the thick, confined aquifer systems below Houston play a major role in the associated geologic hazard, subsidence.

Section 5.1 Regional Hydraulics

The principal characteristic of the Evangeline Aquifer is that it is a confined system, and requires that when a high-capacity MUD or City of Houston well is pumped, the standing water level (or potentiometric surface) rapidly declines to its particular pumping level relative to the rate of withdrawal and aquifer hydraulic conductivity. The depressed surface around the pumping well represents a pressure boundary in the configuration of a cone of pressure relief. This is in contrast to an unconfined, or water-table aquifer. When pumped, wells installed in this type of aquifer would create a physical cone of depression, which dewaters the sediment around the pumping well. With confined aquifers, when one pumping well is disturbed by other pumping wells in the confined system, this pressure surface is perturbed along its rather flat cone with an elliptical shape pointing towards the outcrop of the aquifer (see Figure 44 and 45) to the north and oriented according to the slope of the regional potentiometric surface to the southeast towards the Gulf of Mexico.

Section 5.2 Cones of Pressure Relief

The cone of pressure relief of each well will "interfere" and combine with each cone of every well operating within a radius of 5 miles to as much as 30 miles, depending upon the nature of the lithologic units and faults in the area. The series of maps prepared by the U.S.G.S. (Gabrysch and Bonnet, 1974b; Gabrysch, 1980, and 1982), and more recently by Harris-Galveston Subsidence District personnel illustrate the effects of subsidence in the shape of a bowl, which was created by the additive effects of interfering cones of pressure relief (see Figure 10). This, in turn, depressurized the fine-grained sediments (many within fault-bound compartments).

This process removes the physical support of the water within the aquifers and creates an induced form of sediment consolidation. Furthermore, Kreitler (1977b and 1978) suggested that when differential compaction has occurred and when faulting has displaced sand across from clay, fault zones can act as hydraulic barriers (see Figure 37).

Typically, the perturbed potentiometric surface becomes a composite cone consisting of the sum of the drawdown at any point within the zone of influence of the overlapping cones of pressure relief (see Driscoll, 1986). The configuration of the zone depends on the duration of pumping of each of the wells, which, in turn, determines the location of the far edge of interference or the extent of overlap of the disturbance on the regional pressure system within the Evangeline Aquifer. Some faults would be expected to interfere with the relaxation in pressure of the cone of the potentiometric surface when a well has ceased pumping.

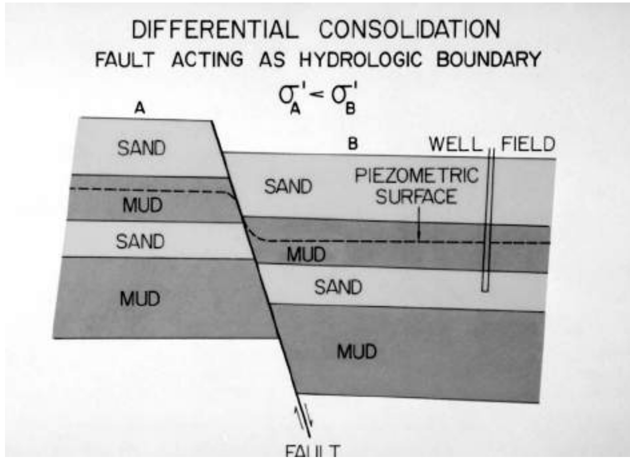


Figure 37 – Fault Zone Acting as a Hydrologic Restraint
(From Kreitler, 1977b)

Section 5.3 Pressurization of Growth-Fault Blocks

The compartmentalization and sealing properties of growth-fault blocks, as initially suggested by Kreitler (1977b and 1978), have received increased attention by oil and gas industry investigators in the past few years (Berg and Avery, 1995 and Hammes, 2009) and have direct application to the issues discussed in this report. They evaluated the origin of sheared zones involving shale (or clay-rich sediments) and of ductile flow along normal or growth faults.

Because the Gulf Coast sections contain unusually low sand-clay ratios, this suggests that many clay-rich sheared, sealed fault zones may be present in the sections in the area. However, some sand sections also may be dragged across clay units and no seal would develop although the permeability would be enhanced (see Figure 38). As indicated earlier, this is significant because the presence of a complex of unsealed fault zones located adjacent to or above a salt dome may provide preferential pathways in places for the upward migration of groundwater carrying radionuclides and hydrocarbons from their sources, through the Burkeville Confining Unit, into the Evangeline Aquifer (discussed previously).

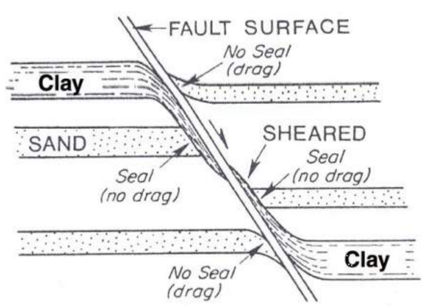


Figure 38 – Growth-Fault Sheared Zone With and Without Seal
(Modified after Berg and Avery, 1995; and from Weber and Daukoru, 1975)

Sealing (or pressurizing) and non-sealing faults in the Tertiary sediments of the Gulf Coast area have been discussed at some length (Smith, 1966, and 1980). Sealing can also occur in the sediments below and within the Evangeline and Chicot Aquifers apparently to the extent hydraulic compartmentalization, strain, and confining pressure can persist in the sands, silts and clays of these aquifers (see Handlin, *et al*., 1963).

This may explain why faults move episodically along certain sections of salt domes (Petersen and Lerche, 1994b). Added to these stresses must be those contributed by earth tides, by the tug-and-pull of the solar and lunar cycles. Movement on the scale of most growth faults measured within the unconsolidated sediments of the Gulf Coast, and in the underlying basement rocks, is probably similar throughout and therefore share stresses from a variety of sources near the surface and at depth.

To measure these stresses, monitoring of the potentiometric surface in shallow aquifers is relatively straightforward. As an example, project staff needed to characterize groundwater flow in two aquifers along the coast of Washington. The diurnal tidal effects are clearly evident in the records plotted for three monitoring well sites for the two aquifers (more). The impact on the shallow aquifer during heavy precipitation can be observed. Three-dimensional modeling also provides hydrogeological information on the local distribution of pressure in the subsurface (more).

Preconsolidation stress of aquifer systems has been investigated as well (see Holzer, 1981; and Holzer and Thatcher, 1979). In the 1970s, the potentiometric surface along the Houston Ship Channel was decreasing as a result of pumping high volumes of groundwater, especially for use by industry. The source of the reported saltwater encroachment in the shallow Chicot Aquifer along the Channel was found to be from the Channel via vertical leakage, not from upconing of the deep coastal saltwater boundary common along the Gulf Coast (Jorgensen, 1977). In a later study, Jorgensen (1981) conducted one of the first major digital modeling efforts to simulate potentiometric declines in the Chicot and Evangeline Aquifers, which also simulated the volume of water derived from clay compaction and the associated subsidence in the area. Dutton (1994) has conducted similar modeling to the west of Houston in the Matagorda-Wharton County area.

To observe the subsidence that had occurred by the late 1970s, the following map by O'Neill and Van Siclen (using data of the 1970s but published in 1984) illustrates the impact of overpumping of the groundwater resources on land subsidence by the oil refineries and other industries along the Houston Ship Channel. The map is an enhancement of Figure 17 showing the extent of subsidence of more than 9 feet centered on the Channel area (more).

Section 5.4 History of Declines & Recoveries of Potentiometric Surface

Rapid declines in the potentiometric surface expressed by the water levels present in the MUD wells around Harris County were noted in the 1970s as the regional effects of excessive use of groundwater were recorded, even in new housing developments in surrounding areas such as the FM 1960 area, the Fort Bend area, and elsewhere (Garcia, Ming and Tuck, 1991; Dutton, 1994; Mace, *et al*., 1994). The regional extent of the excessive pumping is illustrated in Figure 39.

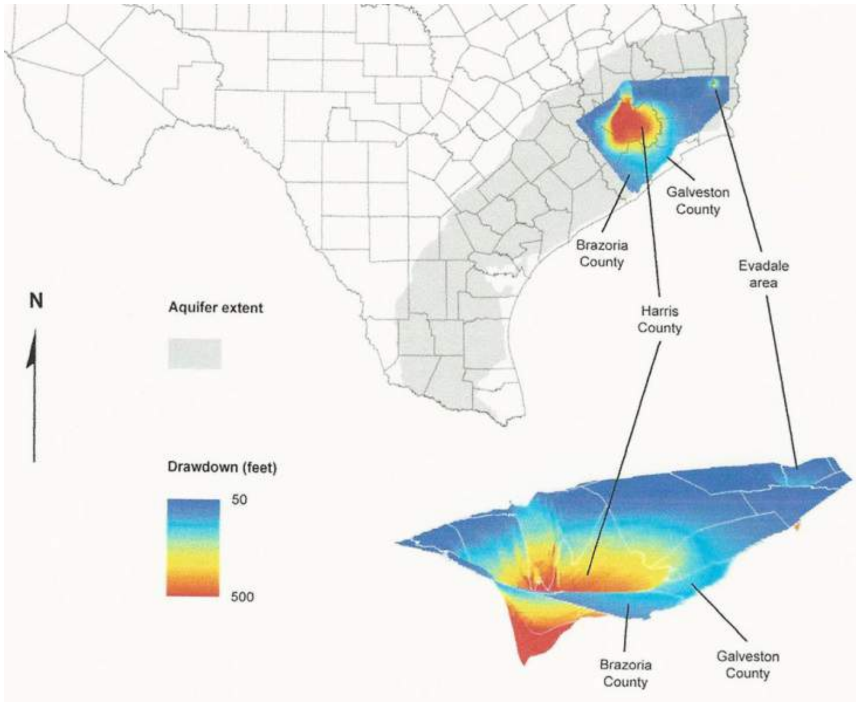


Figure 39 – Illustration of the Water Level Decline in Water Wells: 1940-2000
(From George, Mace, and Petrossian, 2011)

Ten years later, as the ground-water consumption decreased along the Houston Ship Channel and the City of Houston led the great switch from groundwater to a surface-water supply, the potentiometric surface of both the Chicot and Evangeline aquifers began to rise rapidly all over the region. After only a few years, and as far away from the Ship Channel as Fort Bend County, pressure levels began to rise (see Figure 40).

As suggested in Figure 40, by the early 1980s the rate of decline of the potentiometric surface began to decrease in the Evangeline aquifer. By the early 1990s, the decline had ceased and by the late 1990s the potentiometric surface recovered at a higher rate than it had declined in the early 1970s. This history indicates that the recovery of the surface of the pressure system can be found in the records of each of the wells in the region and the well records indicate that recovery occurred rather rapidly over the entire region.

To further examine the timing and lateral extent of the decline and recovery of the potentiometric surface in the Harris County and adjoining counties, we reviewed long-term water-level data published by the Texas Water Development Board (2003) and prepared histograms with especially long–term records for two wells, Well #6409-401 completed in the Chicot Aquifer and Well #6516-907 in the Evangeline Aquifer, both located northeast of the Houston Ship Channel in the general area first noticed in the 1970s to be affected by significant subsidence (see Gabrysch and Bonnet, 1974a).

The water-level records for Well #6409-401, completed in the Chicot Aquifer to a depth of 420 feet below grade, extend back to the year 1947 (see Figure 41). Of particular note is that the water level declined at an increasing rate from 1947 to a minimum elevation during the period 1973-1974, after which the potentiometric surface recovered rapidly at a rate of about half the decline rate.

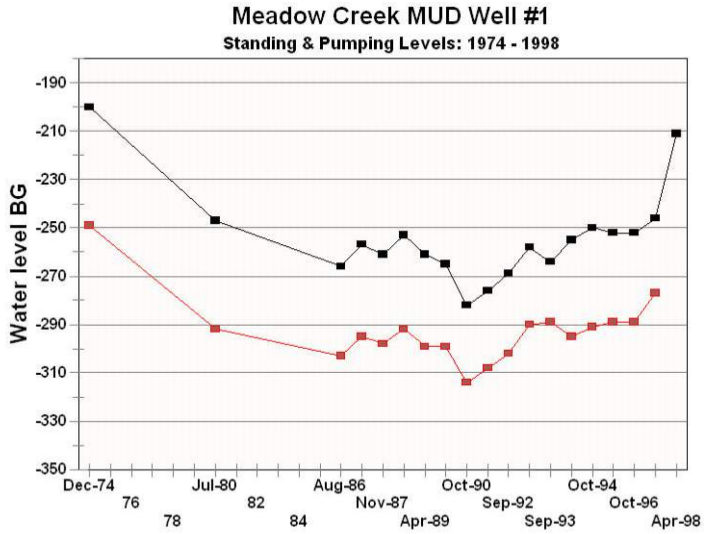


Figure 40 – Historical Record of Standing Water Level (Potentiometric Surface) and Pumping Level (Below): 1974-1997
(Data obtained from Meadowcreek MUD - See Figure 17 for well location)

The water-level records for Well #6516-907, completed in the Evangeline Aquifer to a depth of 1,727 feet below grade, extend back to the year 1953 (see Figure 42). The water level (i.e., the potentiometric surface) declined at a uniform but high rate from 1953 to a minimum elevation during the period from 1975 to early 1977, after which water levels recovered rapidly at about the same rate as the decline rate.

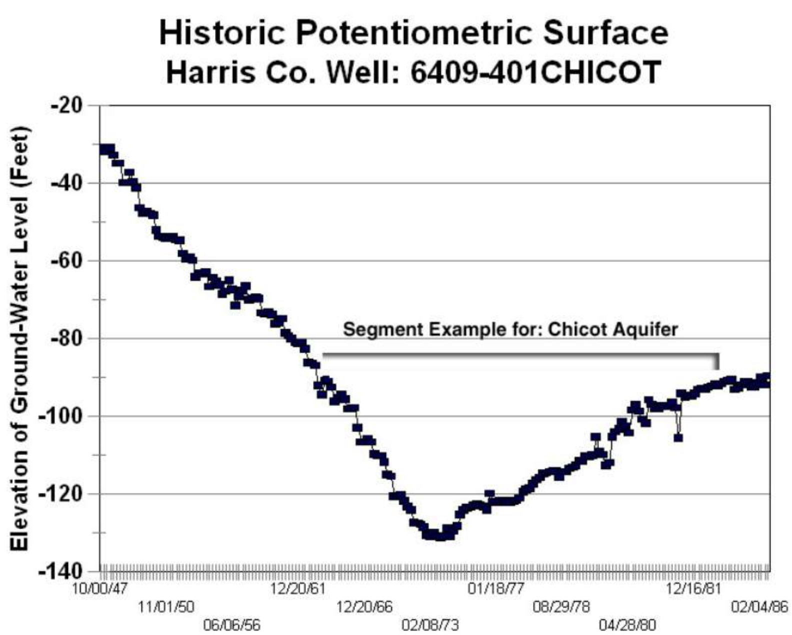


Figure 41 – Well #6409-401 Chicot Well Water Level Record: 1947-1988
(See Figure 17 for well location)

We have evaluated the trends in qualitative terms but quantitative assessment of these trends may reveal additional insights. Gabrysch, *et al*., (1974a and b) investigated two areas in some detail and concluded that land subsidence was related to ground-water withdrawal. In an early attempt to overcome subsidence at the NASA-Johnson Space Center, artificial recharge of the ground-water reservoir was considered in some detail (Gaza, 1977).

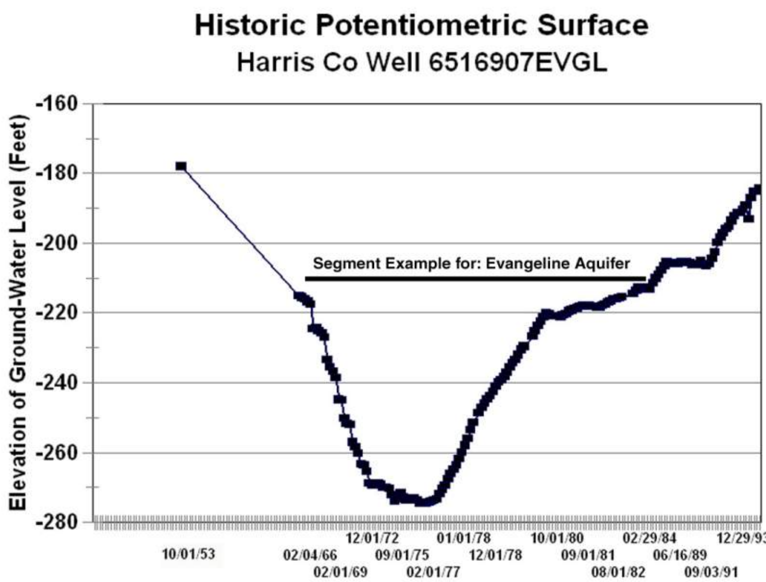


Figure 42 – Well #6516-907 Evangeline Well Water Level Record: 1953-1997
(See Figure 17 for well location)

In more recent attempts to control subsidence caused by oil and gas production, re-injection wells were drilled in Long Beach, California (Colazas, *et al*., 1987) and in Florida to deal with similar issues (Tibbals and Frazee, 1976). U.S. Geological Survey simulations of underground storage and recovery of treated effluent has also provided new insight into one day controlling the hydrodynamics of subsidence and, perhaps, the related faulting (see Yobbi, 1996 and 1997).

New approaches to monitoring aquifer expansion resulting from recharge provide additional possibilities (Lu and Danskin, 2001, and Bawden, *et al*., 2001). The somewhat irregular trend of the detailed records of recovery for both wells (Figures 41 and 42) may represent the history of varied production or a result of the lack of production within the area of influence of the pumping wells nearby. The pattern may also represent sequential or progressive repressuring of the more coarse-grained intervals within the area of influence of this Evangeline well's cone of pressure relief and, to some extent, that of the Chicot aquifer also.

When comparing the records of these two wells over a common time period of water-level elevation measurements, both aquifers responded quite rapidly to decreasing groundwater production in the area that experienced the maximum stress, i.e., along the Houston Ship Channel, Baytown and refinery row area (see Figure 43 for a comparison of the well records and Figure 17 for the location of the wells within the eastern section of the Houston subsidence bowl, just north of Baytown, Texas).

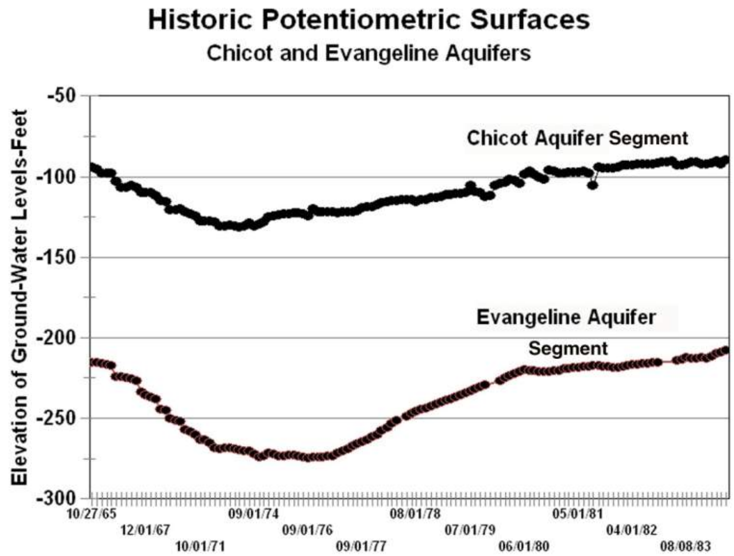


Figure 43 – Comparison of Common Segments of Well Records for Both Chicot and Evangeline Wells
(See Bars in Figures 40 & 41 for Time Period: 1965-1983)

So, the faults within the regional trend roughly mark the outer areas of the subsidence bowl and, together with the faults located over salt domes, may all be stimulated by ground-water production when multiple cones of pressure relief merge and then separate, which may over long periods of collective pumping, cause depressurization in the aquifer over the entire area of influence, activate and induce weakened fault zones to deform where potentiometric surfaces converge along areas of greatest stress.

This may explain why faults move episodically along certain sections (Petersen and Lerche, 1994b). Added to these stresses must be those contributed by earth tides and the tug-and-pull of the solar and lunar cycle. Movement on the scale of most growth faults measured within the unconsolidated sediments of the Gulf Coast, and in the underlying basement rocks, is probably similar throughout and therefore share stresses from a variety of sources near the surface and at depth.

The configuration of the water-level declines in both the Chicot and Evangeline Aquifers in 2003 shown in Figure 39 is even more revealing in Figure 44 (Chicot) and 45 (Evangeline). Although the former overlies the latter, the center of maximum depth of the potentiometric surface (i.e., water levels) is in central Harris County though offset some 20 miles.

For the Chicot Aquifer, the center is located just southwest of the 610 Loop Freeway in the vicinity of Route U.S. 59, with an anomalous low in the northwest corner of Beltway 8 (near Jersey Village). The principal low for the Evangeline Aquifer is in Hillshire Village with another low in the Jersey Village area. All such areas are also centers of growing populations.

The centers of maximum production for both aquifers are far west of the centers once prevalent along the Houston Ship Channel and refinery row of the 1970s. The water levels of these latter areas increased as much as 220 feet in some wells of the area.

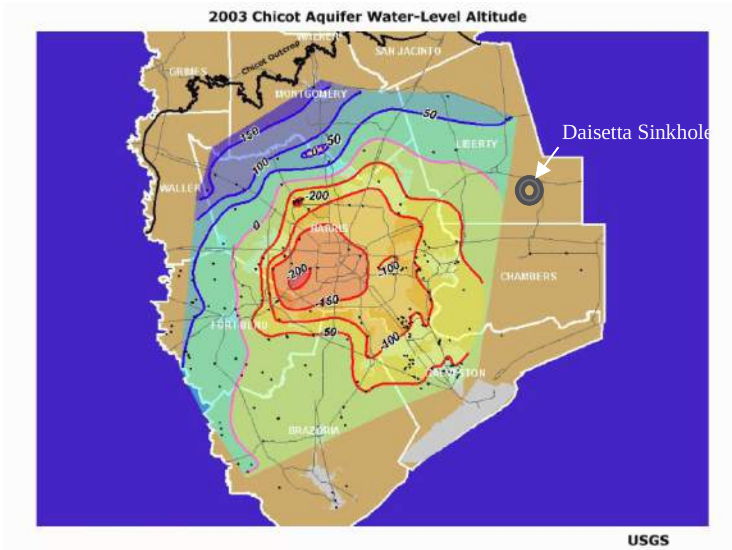


Figure 44 – State of Potentiometric Surface of Chicot Aquifer in 2003
(After Kasmarek and Houston, 2008)

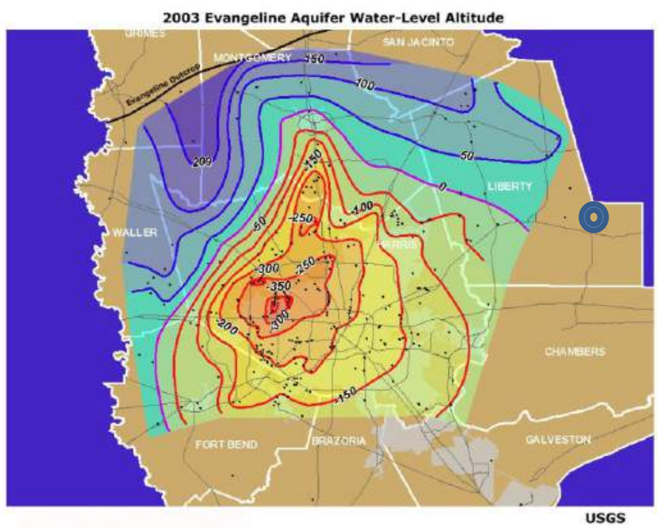


Figure 45 – State of Potentiometric Surface of Evangeline Aquifer in 2003
(After Kasmarek and Houston, 2008)

It should be noted that this has been made possible because of decreased dependence on groundwater production in favor of surface water delivered by pipeline from Lake Livingston and other sources. The well recoveries shown in Figures 41 and 42 (the locations of which are shown in Figure 46) illustrate the early phases of this recovery.

The Meadowcreek MUD well water level history, shown in Figure 39, indicates a less pronounced, but upward trending recovery by 2003 (Figure 45). Taken together, the records of the historical potentiometric surfaces from only a couple water wells also suggest that if surface water had replaced groundwater in this area during the 1960s and 1970s and City wells had been developed around the periphery of the county in order to spread the stress (Campbell, 1975), the extent of subsidence would have been less than that experienced.

Hence, stress would also have decreased on the fault zones in and around the Harris County area and environs and, in turn, on the buildings, homes, freeways, pavements, constructed drainage, municipal water wells, storm drainage and sewer piping, and associated structures that have been damaged by fault movements over the past 30 years.

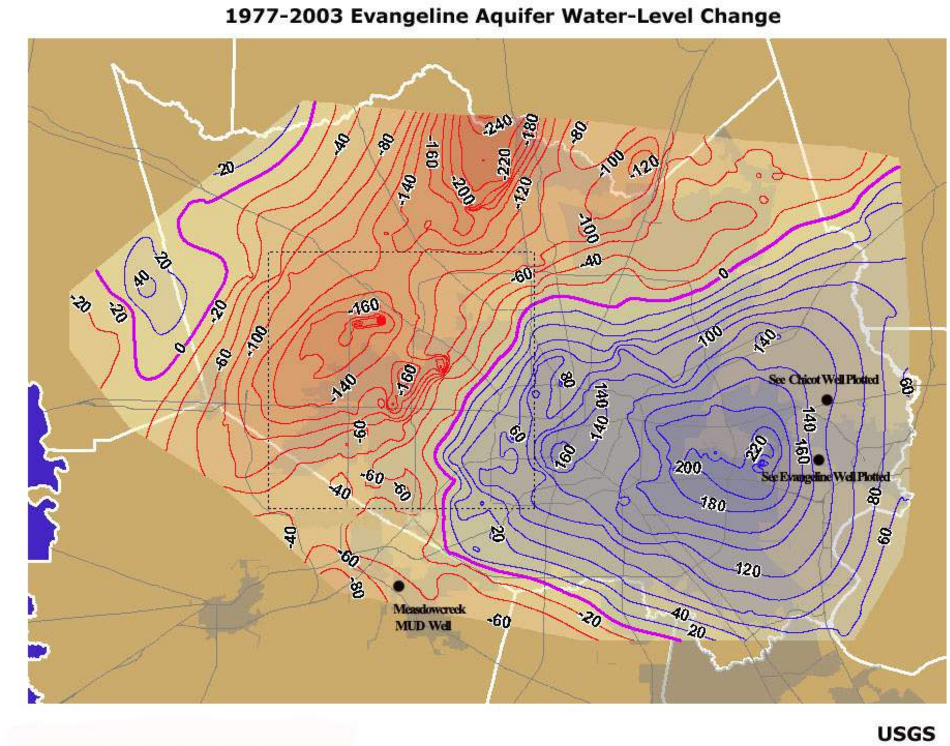


Figure 46 – Water-Level Change (of Potentiometric Surface) in Evangeline Aquifer from 1977 to 2003
(After Kasmarek and Houston, 2008)

U.S. Geological Survey personnel also have recently concluded that pumping from aquifers that are geologically older and that are further inland from Houston would minimize land subsidence as well as saltwater encroachment, which would seem to be reasonable, especially because estimates of future water requirements indicate serious water shortfalls by the 2020s (Ryder, 1996).

If the original City of Houston plans first proposed in the early 1970s had been implemented to replace groundwater use with surface water in the Houston Channel area and to redistribute production wells away from Baytown and other areas of major decline at the time, the damages to surface structures and the increase in pumping costs that stimulated "the great switch to surface water" would probably have been less severe. This would have resulted in a rational combination of surface water and groundwater use in the region that would have resulted in a reduced cost of water to consumers, minimal subsidence, and better security for the area's water resources (Campbell, 1975).

The lands that subsided in the eastern areas of Houston over more than 40 years are not expected to re-emerge from Galveston Bay anytime soon, especially because sea-level rise appears to be underway. However, the pipelines carrying water from surface-water resources now installed throughout central and eastern Harris County and City of Houston to bring surface water into use will be exposed to greater hazard by increasing the exposure to the underlying growth faults located in the general area. Any pipeline breaks would increase water loss and will require increased monitoring and surveillance.

Section 6.0 Economic & Regulatory Impact of Faulting & Subsidence

The impact of unstable ground that moves on the scale of even a few inches each year often damages infrastructure. Water pipes, pipelines, bridges, building foundations, power poles, streets and highways, and airport runways are usually not designed to withstand movement and are subject to various forms of failure, including leaks, ruptures, sinkholes, and other dislocations in the soils and underlying sediments of unconsolidated sands and clays that are present in the subsurface below the Houston area. The ongoing cost to the public, to industry, to the City of Houston and surrounding municipal utility districts is substantial. In most cases, however, such costs can be mitigated by improved design if the location of the unstable ground caused by faulting and subsidence can be identified prior to construction.

Section 6.1 Historical Framework

In his pioneering work, Reid (1973) estimated that structural damage to house foundations caused by fault movement costs between $2,000 and $6,000 per house for temporary repairs (i.e., 1973 dollars). The estimated cost for repairing 165 homes along the Long Point, Piney Point, and Eureka Heights fault zones would have been about $660,000 in 1973 dollars. In 2003 dollars, this would be equivalent today to about $2,700,000, which is equivalent to about $16,000 per home. However, this number could be somewhat lower because it doesn't include the economies introduced in the meantime through new technology and the favorable impact of competition on prices in Houston's foundation repair market.

Reid estimated that for over 95 miles of active faults known at the time, the total damage would have been about $2.6 million, or about $10.5 million today. However, damage to public facilities would have been far greater. Damage to the Interstate highway system in Harris County was caused by 12 faults crossing roads in 1973. Today, that number is perhaps double or more based on the number of new freeways and discovery of new fault zones. Repairs to roadbeds, bridges, and overpasses, including the cost of monitoring movement causing possible vertical misalignments of individual support spans, cost hundreds of millions of dollars to repair today.

Coplin and Galloway (1998) and Holzschuh (1991) suggested that subsidence–damage estimates just along the Houston Ship Channel refineries were in the range of $340 million (1998 dollars) while damage requiring repairs and re-construction to industry-wide infrastructure likely amounted to billions of dollars (as of 1998).

Disruptions of railroad beds and tracks, pipelines, water lines, and storm and sanitary sewers also cost millions of dollars to repair and maintain annually. Jones and Larson (1975) estimated the annual cost of subsidence in the Galveston Bay area alone during the period 1969-74 amounted to $32 million over an area of about 970 square miles. Gabrysch (1984) indicates that Jones and Larson attributed fault-caused structural damage to man-caused subsidence.

He also emphasizes that some investigators [of the time] suggested that “some if not all of the numerous existing faults [in the region] are reactivated by man-caused land-surface subsidence or consolidation [which is caused by excessive groundwater production]”, but because direct or indirect mechanisms have not been worked out to date, and because of the potential litigious impact of such interpretation, the issue may not be settled without further research.

Because the occurrence of land subsidence and faulting may be interrelated, the impact of the damages caused by one may be of similar magnitude as suggested by Gabrysch (1984) and Jones and Larson (1975). In a more recent study, Leake (2003) cites a 1991 study by the National Academy of Sciences that estimates damage costs of subsidence-related problems in the U.S indicating that the damages that have occurred in Texas and California over the years range in the 100s of millions of dollars. This does not include the losses of real estate from flooding caused by subsidence which is pronounced around Galveston Bay and along the southeast Texas Coast (Gibeaut, *et al*., 2000).

Over the years, many firms within the construction industry have taken into account the hazards represented by known fault zones and have planned accordingly. However, the foundation repair industry remains active in the Houston region as a result of soil consolidation or subsidence, or both.

Section 6.2 Other Potential Impacts

There are other types of potential impacts that appear to involve faulting. The cost of the impact of radionuclides and hydrocarbons appearing in groundwater along selected fault trends is measured in extra laboratory costs but also in costs to monitor the ambient air for abnormal radon in buildings and homes. The use of rural water wells along the trend of the known occurrences also requires extra vigilance in regular testing of the water and air to meet reasonable standards of human health and State and Federal regulations (Duex, 1994).

In addition, the presence of natural gas and other hydrocarbons in groundwater from the Chicot and Evangeline Aquifers has caused numerous lawsuits between communities and their water system operators, and because of the presence of oil and gas wells that surround some communities, even oil and gas companies. Faulty operation and maintenance activities by oil and gas companies are not always the likely cause of ground-water contamination, especially in fault-zone areas where such contamination may be of natural origin.

Remnant natural gas present in the groundwater in some locations in the FM 1960 area, for example, is still a geologic hazard today and incurs costs to monitor its presence as well as its impact on water-supply operations. Provisions to offset health and safety hazards caused by natural gas escaping from wells into holding tanks and distribution lines requires retrofitting for explosion-proof interiors and active vents to avoid explosive build-ups of natural gas. Lawsuits resulting from such hazards, imagined or real, will also add additional costs to deliver water in the future.

Indirect costs are incurred by fault movements in the Houston area as well. These include the need to re-level drainage to minimize surface flooding. Also, sellers and buyers involved in real estate transactions often are not aware of fault locations and after a few years after a sale must pay for foundation repairs after doors become misaligned, brick veneer shows cracks, foundations have cracked, and other tell-tale signs of fault movement become apparent to unsuspecting buyers.

It is clear that fault zones extending to the surface are potential geologic hazards. The known faults need to be monitored, and reconnaissance and mapping need to be conducted to locate unknown fault zones in Harris County and elsewhere, especially those that may impact pipelines, railroads, freeway support structures, municipal solid waste landfills, wastewater treatment facilities, and other sensitive sites.

State of Texas regulations require investigations to be conducted by licensed geoscientists or geotechnical engineers experienced in fault determinations and in differential subsidence on many of these facilities. For example: Texas Administrative Code (TAC) for Landfills, see TAC Chapter 330, Part 330.203 *Geological Faults*; Part 330.205 *Soils and Liner Quality Control Plan*; Part 330.303 *Fault Areas;* and Wastewater Treatment Facilities (see Chapter 309, *Location Standards*, Part 309.11 *Definitions*; Part 309.12 *Site Selection to Protect Groundwater or Surface Water (*Texas Admin. Code, 2003).

Section 7.0 Methods of Fault-Zone Investigations

Growth faults generally show disruptions at the surface of roadways, freeway supports, and sidewalks, but especially of fixed structures like cement foundations that will crack and/or separate when differential pressures are applied from below. This includes houses and larger buildings. It is here where the need exists to locate such faults at the surface before house or building foundations are poured. Once located, the designs of such structures can accommodate surface disruptions by avoiding the strike of the fault as it passes through the property, leaving a suitable "clearance distance" on either side of the fault.

The methods of investigations to locate faults begin on the ground by locating such in outcrop. They can also be observed on a larger scale by examining aerial photographs and followed up on the ground to identify the specific areas affected. New technology goes one step further in locating surface faults. LiDAR, an acronym for Light Detection And Ranging, uses the same principle as RADAR that can be used to create high-resolution digital elevation models (DEMs) with vertical accuracy as much as 10 cm. These are one of the primary tools used in Phase I environmental assessments for the purpose of real-estate transactions.

Once identified, the rate of movement then becomes important in determining how significant the fault may be. Of course, because the movement is caused by a number of factors, there is no way to know its historical activity. As a rule, all growth faults move, but some move faster than others and at various periods of time followed by no movement at all. Carefully controlled systematic studies are required over years of study. Rates can vary from zero to 12 inches of vertical displacement and can be different even along the same fault. Some of these studies will be discussed in this report.

Section 7.1 History of Methods

New aerial technology is advancing rapidly. According to NASA (2004) and Mark of the U.S.G.S. (2004), LiDAR equipment, which includes a laser scanner, a global positioning system (GPS), and an inertial navigation system (INS), is generally mounted on a small aircraft. The laser scanner transmits brief laser pulses to the ground surface, from which they are reflected or scattered back to the laser scanner.

Detecting the returning pulses, the equipment records the time that it took for them to go from the laser scanner to the ground and back. The distance between the laser scanner and the ground is then calculated based on the speed of light.

While flying, the airplane's position is determined using GPS, and the direction of the laser pulses are determined using the INS. Because one laser pulse may reflect back from multiple surfaces, such as the top of a tree, a house, and the ground surface, there are multiple returns from each pulse that can be used to map such things as the top of the tree canopy, buildings, and the ground. Post-processing is used to differentiate between these multiple returns to determine the bare-earth surface. Using the combined information from the laser scanner, the GPS, and the INS, very accurate, closely spaced (typically 1 per square meter) X, Y, Z coordinates are determined from which a DEM can be made.

In Figure 47, the principal growth faults are apparent with changing elevation and assigned color changes. The Long Point Fault strikes northeast at the I-10 – Highway 8 Interchange and extends in the direction of Highway 290. Of particular interest is the prominent northeast escarpment indicated by LiDAR in Figure 47, a feature that runs continuously from the North Addicks Dam northeastward toward I-45.

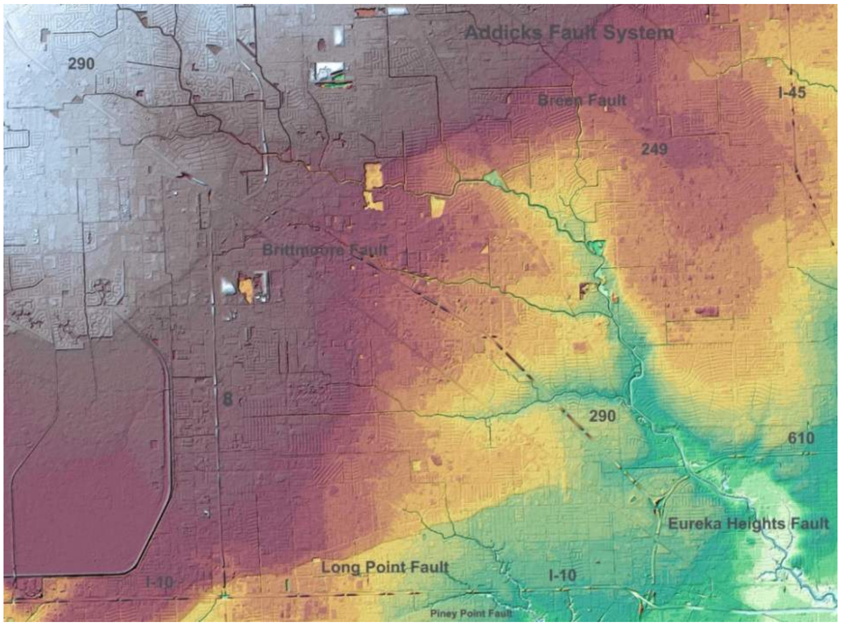
It is now collectively known as the Addicks Fault System but consists of a number individual faults, only two are named in the Figure 47 (see Figure 17 for the other previously named faults along this trend, now clearly identified by LiDAR technology). This feature's relationship to the previously named faults in the area requires additional field inspection, analysis, and confirmation, if merited.

The faults can be clearly observed in the enlarged version of Figure 47 provided below. The color difference represents changes in ground surface elevation. Note the excavations near the center of the map. These are construction landfills or sand and gravel pits in operation during 2005.

Notice that excavations show intervals of lower elevation with corresponding color, whereas mounds show a color corresponding to higher elevations. As indicated above, LiDAR can currently discriminate a vertical separation down to around 10 cm, which allows for outstanding resolution of lateral extensions of surface disruptions such as drainage ditches, highways, and faults that have disturbed a relatively flat surface. Engekermeir and Khan, (2008) provide a summary of the usefulness of LiDAR mapping in the Houston area.

The presence of such faults represents a significant geologic hazard to builders, homeowners, and real estate interests. However, there are other associated hazards that are more indirect than broken foundations and subsidence. These include the occurrence of radionuclides and natural gas in groundwater, pipelines and waterlines that cross faults, and the presence of permitted and unpermitted landfills located on or near faults, all within the Harris County area.

Site-specific investigations designed to locate and monitor faults in the Houston area began with fault maps prepared by engineering consultants for the City of Houston, Texas in the 1960s, e.g. Turner, Collie, and Braden (1966), by U.S.G.S. personnel in the 1970s and 80s such as: Clanton and Amsbury (1976), Gabrysch, 1969 and 1972), and Verbeek, *et al.*, 1979, and others from local universities quoted earlier in this report. The street-specific maps generated clearly indicated where to build and where not to build. To a large extent they have gone unheeded.



North

Figure 47 – LiDAR Map of Northwest Quadrant of Harris County
(Courtesy of Dodson & Associates, Inc., circa 2005)
(Click on figure for enlarged view)

Scale

0.5 Mile

In any event, Norman (2002) suggests that more than 450 active faults intersect the surface in the Texas-Louisiana Gulf Coastal Zone and that about 240 buildings and houses have been damaged along a 10-mile stretch of the Long Point Fault in the Houston area alone, only a short segment of which is shown in Figure 34.

He estimates that “thousands of homes, schools, churches, shopping centers and other commercial and public buildings in the Houston Metropolitan Area have been built unknowingly in fault zones.” Wahls (1981) presented the prevailing view (of the 1980s) concerning settlement of buildings, which depended on a reasonable knowledge of subsurface conditions.

Section 7.2 Systematic Case Studies & Investigations

Since the 1970s and 80s, little systematic work has been done by the U.S.G.S. on monitoring or mapping the faults in the Houston area until recently. The U.S.G.S. continues to be underfunded by the U.S. Congress and, hence, important investigations have either been cancelled or remain on the drawing board. Because reliable maps are not available, other methods must be used, although previous maps by Turner, Collie, and Braden, Inc., 1966, Fisher, *et al.*, 1972, Reid, 1973, Kreitler, 1976, and others using aerial photographs showing linears or curvilinear features have been underrated in the past for use in identifying possible fault traces (O’Neill and Van Siclen, 1984). Aerial photographs can be quite useful if used cautiously in conjunction with other methods.

In what appears to be the most appropriate, presently used hand method for long-term monitoring of growth faults, Norman (2003), in his continuing studies of fault movement in the region, has been monitoring the Brittmoore fault (part of the Addicks fault system, see Figure 17), among other faults, using a method developed by earlier work at Rice University and the University of Houston.

This method involves measuring the level across the fault at a number of "permanent" locations over years of study. In the case selected (from 1986 to January of 2003), since the initial measurement in 1986, the downside of the Brittmoore fault has moved almost 12 centimeters or about 5 inches during the period indicated (see Figure 48).

Earlier, Norman and Elsbury (1991) prepared a supplement to a field trip sponsored by the Houston Geological Society. It provides a wealth of guidance based on their years of experience in monitoring and investigating growth faults in the Houston and surrounding areas.

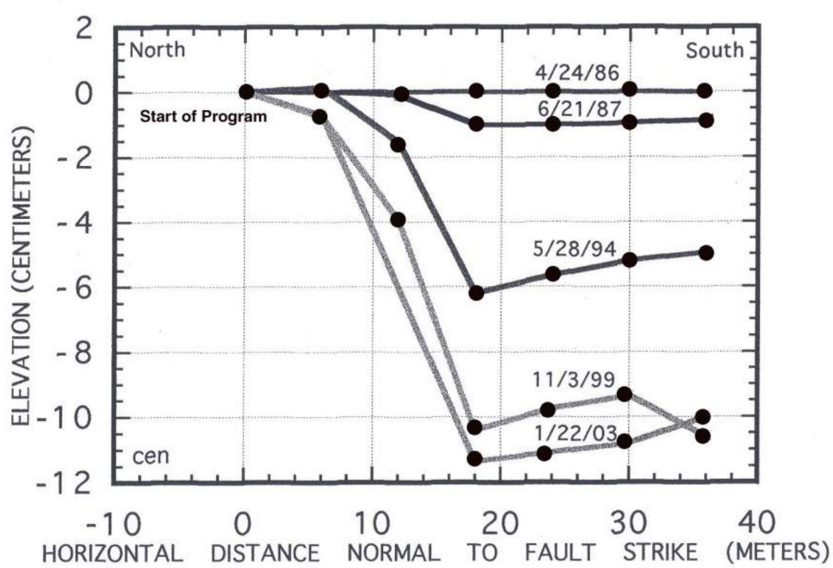


Figure 48 – Brittmoore Fault Monitoring Program, Located Fisher Street at West Little York Road, Houston; May 28, 1986 to January 22, 2003
(After Norman, 2003) (For Monitoring Site Location, See Figure 17)

Summarizing their major points:

1. Differential movement across faults in the Houston area is normally less than 0.5 inches per year.

2. At least four Superfund sites are crossed by active faults (see Figure 35 and (more)).

3. The extensional strain in the near-surface sediment may allow the faults to become conduits for the movement of subsurface fluids.

4. The active surface faults are strictly normal-slip faults. Those monitored for their movement show no strike-slip or net reverse-slip movement.

5. As of 1991, no real effort has been made to trace the faults in the Houston area to their lateral terminations, with the exception of the Long Point and Woodgate faults.

6. Because aerial photographs will not be useful in areas of tree cover, commercial development, or significant topographic relief, much of the north-central and northeastern Harris County, and most of Montgomery County to the north, will have to be investigated by ground surveys in order to identify and map surface faults. Deep faults, indicated in oil and gas exploration, can provide important clues to the location, orientation, and sense of movement of surface faults in these areas.

7. During the period: June, 1985 through September, 1987, Norman and a graduate student from the University of Houston embarked on a study of movement of 29 faults in the Houston area. They recorded movement rates for a selected number of faults in the Houston and Conroe area (See Table 4 and Figure 49).

8. The measurements shown in Table 4 are of only the vertical component of fault motion. The horizontal component is about one third as great because the near-surface dip of most of the subject faults is about 70 degrees.

9. As indicated in Table 4, Norman found that the rates of movement were fairly uniform except at the Conroe Fault (#10) and Big Barn Fault (#9). Also see Figure 49 for locations.

10. Although the fault movements are intermittent throughout any given year, the average rate 0.5 inches/year from 1966 to the present is nearly constant.

11. The first three faults listed in Table 4 are regional contemporaneous growth faults. The Navarro and Big Barn Faults are located on the west flank of the Conroe Salt Dome and their location, orientation and sense of movement corresponds with faults identified in wells to depths of 4,000 and 5,000 feet below ground surface.

12. A 1986 neighborhood survey indicated that 243 structures, mostly homes, along the Long Point Fault rest directly on the zone of disturbance of this fault.

13. The Long Point Fault has been active, at least intermittently, for the 1.5 million years since Horizon F in the lower Lissie Formation was deposited.

14. The Conroe Fault can be correlated to an extensive, deep regional fault system that also was involved in trapping oil and gas in the Grand Lake-Risher Field west of Conroe, Texas. Although only a fault scarp of a few inches is present on the surface, the fault has displaced the top of the Yegua Formation approximately 400 to 500 feet at a depth of 5,000 feet below surface.

Table 4 – Fault Orientation and Movement Data[3]

FAULT NUMBER[1]	FAULT NAME	STRIKE	DOWNTHROWN SIDE	RATE OF MOVEMENT (in/yr)[2]
1	Long Point	N45-75E	SE	0.50
2	Brittmoore	N55-60E	SE	0.47
3	Woodgate	N52E	SE	0.35
4	Hardy	N45E	SE	0.24
5	Lee	N53E	NW	0.27
6	Jetero	N72E	NW	0.25
7	Cantertrot	N75W (at U.S. 59)	NE	0.22
8	Navarro	N52E	SE	0.43
9	Big Barn	N40E	SE	0.00 (8/85-9/86) 0.64 (2/87-9/87)
10	Conroe	N55E	SE	0.00 (8/85-2/87) 0.74 (2/87-9/87)
11	Grangerland	N83W	NE	(Not monitored)

1. Numbers refer to location on map **(See Figures 17 and 48)**
2. Movement rate includes only the vertical component of motion during the period of 6/85-9/87.
3. **From Norman and Elsbury, 1991**

Once identified at the surface in outcrop or on the basis of aerial photographs, the principal method employed to confirm faults in the Houston area is by drilling two or more boreholes to depths of 300 to 500 feet on both sides of a candidate or suspected fault. Once drilled, down-hole geophysical logging, especially electrical resistivity, SP, density and caliper logging, may be useful in correlating a marker bed from hole to hole, noting its elevation difference, if any. Care should be exercised in the interpretations of such logs by employing geoscientists experienced in such studies.

The cost and effort required can be extensive but if there is significant economic risk to an existing or planned building or other installations (i.e., airport runways or highways), such costs would be justified. Shortcuts by limiting borehole numbers or by restraining the interpretation of the data produced can contribute to uncertain results.

In an attempt to guide construction in areas where fault zones are likely to present a geologic hazard to construction, Elsbury, *et al.*, (1980) developed the concept of "clearance zones" for building setbacks along known fault zones. They found that the zones "need to be about twice as wide on the downthrown side of the fault as on the up-thrown side." However, as we will demonstrate, our investigations show that a much wider zone of disturbance (or deformed zone) may be expected when building in the vicinity of growth fault systems, and that the clearance zone width is fault-zone specific.

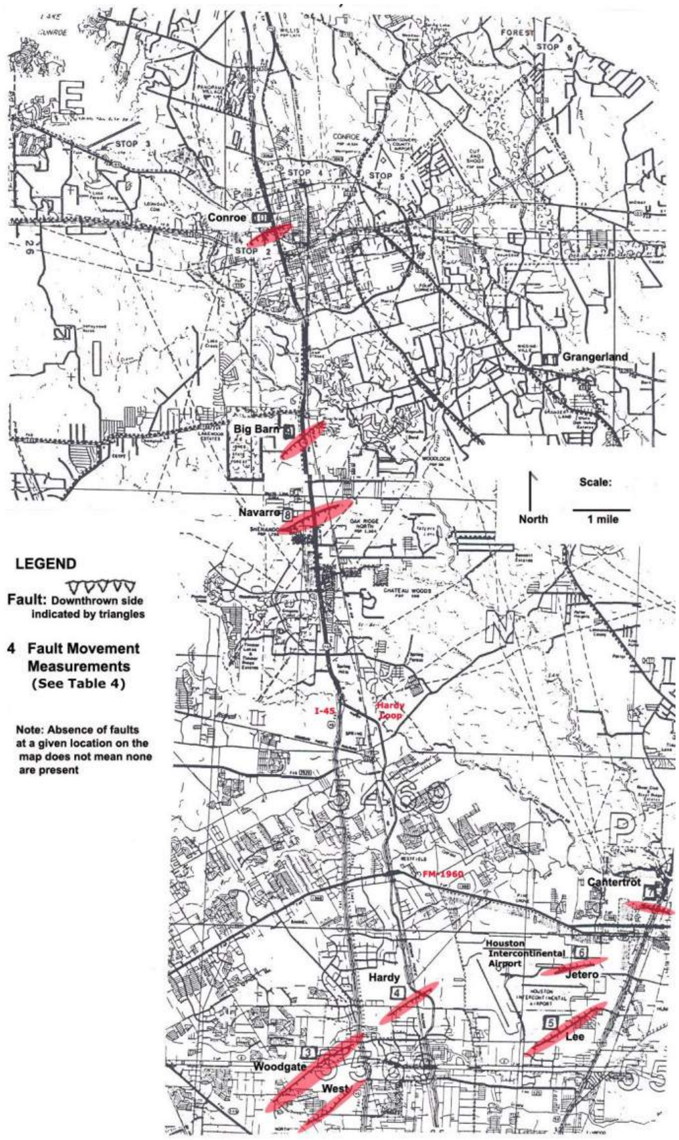


Figure 49 – Principal Active Faults, North Harris, Conroe and South Montgomery Counties, Texas
(After Norman and Elsbury, 1991)
(Click to Enlarge Figure)

Site reconnaissance using global positioning systems (GPS) can reveal significant information about local faulting and can be very useful in monitoring movements on active fault segments, once they have been identified. Cracking of pavement and movement of pavement fragments are primary aids in identifying faults, although local soil heaving during or just after periods of unusually low rainfall can breakup pavement and affect foundations as well.

Shallow trenches crossing areas of possible faults can be excavated to permit closer scrutiny, although the faults in the Houston area are actually zones of disturbance rather than distinct fault lines. The horizontal extent of disturbance previously has been reported to be on the order of 10 to 15 feet, depending upon the local history of movement, although our studies indicate that a much broader zone of disturbance can be expected (see GPR Profile discussions). Saribudak (2014) demonstrates the practical use of geophysical services currently available to the general public.

According to Khan, *et al.*, (2013), active faults in the Gulf of Mexico coastal plains were first studied in 1926 as a result of local land-surface subsidence around an oil production field near Galveston Bay (Pratt and Johnson, 1926). Since then, hundreds of active faults have been identified in the Houston metropolitan area (Verbeek *et al.*, 1979; O'Neill and Van Siclen, 1984; Mastroianni, 1991; Shaw and Lanning-Rush, 2005; Engekermeir and Khan, 2007, 2008).

The activity of these faults may have resulted in land-surface subsidence in multiple areas around the coast. Some of the historical subsidence in the greater Houston area has been attributed to the extraction of subsurface hydrocarbons and more recently to groundwater withdrawal (Sheets, 1971, 1979; Paine, 1993; Coplin and Galloway, 1999).

Kreitler and McKalips (1978), in their studies of the mid-1970s, constructed a trench at the Battleground Fault site during their studies using electrical resistivity to define fault zones (see Figure 50). They also found that the movement of the Battleground Fault is episodic but that electrical resistivity was useful only to some extent for identifying growth faults, if at all. Sarabudak (2014) has also attempted to use resistivity to locate unknown faults. Nonetheless, it is clear that surface geophysics can be useful in identifying fault zones in only some circumstances (Zohdy, *et al*., 1974). Seismic reflection, shallow geothermometry, and time-domain electro-magnetics (TDEM) (see Kuecher, 1997) have all been applied with varying degrees of success.

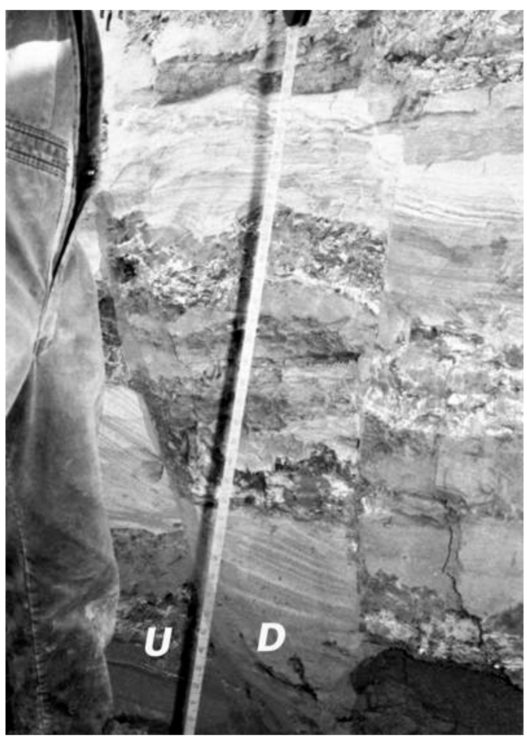


Figure 50 – Trench Across Battlefield Fault, La Porte, Texas
(After Kreitler and McKalips, 1978). Tape for Scale Only.

O'Neill and Van Siclen (1984) briefly reviewed these early methods of investigation. None of the methods applied to date have been entirely satisfactory.

In some recently published university investigations on growth faults in the Houston area, Khan, *et al.*, (2013) airborne LiDAR is an effective tool to identify fault scarps and they have used it to identify several new faults and assemble an updated map for the faults in Houston and surrounding areas.

Two different LiDAR data sets (from 2001 to 2008) provide time-lapse images and suggest elevation changes across the Hockley Fault System at the rate of 10.9 mm/yr. This rate is further supported by GPS data from a station located on the downthrown side of the Hockley Fault System indicating movement at 13.8 mm/yr.

To illuminate the subsurface character of the faults, Khan, *et al.*, (2013) undertook geophysical surveys (ground-penetrating radar, seismic reflection, and gravity) across two segments of the Hockley Fault System. Ground-penetrating radar data show discontinuous events to a depth of 10 meters at the main fault location. Seismic data, from a *Vibroseis* survey along a 1-km line perpendicular to the fault strike, indicate faulting to a depth of at least 300 meters. The faults have a dip of about 70 degrees. Gravity data show distinct changes across the fault. However, there are two contrasting Bouguer anomalies depending on the location of the transects and their underlying geology.

The Khan geophysical surveys were challenged by interference from urban features (especially traffic and access). However, the survey results consistently located the fault and hence hold significant potential to understand its deformational features as well as assist in associated building zoning.

Section 8.0 Ground-Penetrating Radar Profiling

A useful, cost effective, and reliable method is needed that would aid geoscientists in defining so called "clearance zones." Ground-penetrating radar (GPR) has been used widely in a number of applications ranging from archaeology (Conyers, *et al*., 2002), geotechnical engineering for locating lost utilities, pavement and infrastructure characterization (Morey, *et al*., 1998; Powers and Olhoeft, 1996), environmental site characterization and monitoring, and ground-water investigations (Olhoeft, 1986; Sander and Olhoeft, 1994; Brewster, *et al*., 1995); US Radar, Inc., 2014), agriculture, civil and criminal forensic investigations, as well as for detecting unexploded ordnance and land mines (Olhoeft, *et al*., 1994), underground mining, ice sounding, permafrost studies, void and tunnel detection, sinkhole and karst investigations, and a host of other applications (Wallach, 2013; and InspectAPedia, 2014; and Paine, *et al.*, 2009 – for location of the recent Daisetta Sinkhole at the Hull Salt Dome northeast of Houston, see Figures 5 and 44 in this report). However, although widely applicable, GPR is of limited use in soil horizons retaining high moisture, such as in the Houston area, which receives an average of 55 inches of annual precipitation, notwithstanding the impact of long-term droughts in the area.

In the Houston area, the water table is relatively shallow and is present within the Beaumont Clay in the central and southern areas (and within the Lissie Sands in the northern areas, see Figure 17). The water table is generally not apparent in such fine-grained sediments until after a recently drilled, shallow borehole is allowed to stand for a few hours or days in the very low permeability of the clay lithology encountered. Once equilibrated, the water surface encountered while probing the well represents the top of the groundwater reservoir and all intervals below will exist under saturated conditions. Just above the water table, even in very fine-grained sediments such as the Beaumont Clay, is a zone of partial saturation, otherwise known as the capillary fringe.

The thickness of this fringe zone depends on the average grain size present in the zone. The finer the grain size, the thicker the fringe; the fringe found in a typical clay such as the Beaumont Clay would extend approximately 8 to 10 feet above the water table (Walton, 1991). Because the grain size in fluvial-deltaic sediments varies in the area, the depth to the top of the capillary fringe also will vary. However, soil moisture immediately below pavements would be expected to be considerably less than that not covered by pavement where the ground surface would absorb precipitation.

The top of the capillary zone is usually located somewhat deeper than the surface soil-moisture zone, although the two can merge during periods of unusually wet conditions. The radio signals of the typical GPR system in use today are absorbed by moist soil, which obscures any useful GPR reflections that may be returned. However, Saribudak developed the simple concept that pavement, concrete or asphalt, may provide an umbrella for pavement underbeds (with or without the upper soil zone, depending upon local road or parking lot construction practices) to a depth of up to 5 feet or more, where soil moisture is typically significantly less than that in the soil adjacent to the pavement and curbing (see Figure 51).

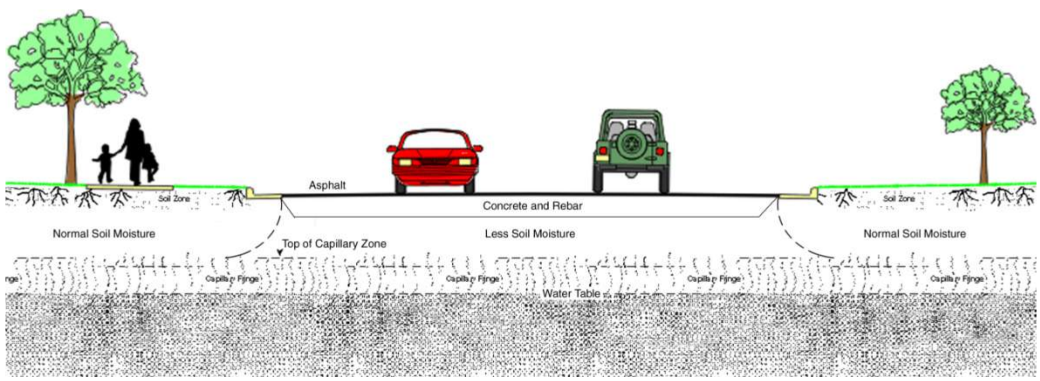


Figure 51 – Generalized View of Pavement Moisture Umbrella Concept

To test this concept, Saribudak and the senior author of this report (as an observer), conducted a GPR profile parallel to GPR Profile 1, but over a grassy area next to the highway pavement (see Figure 17, southern area, and Figure 55). Compare this profile with that in Figure 56.

Although there is some data reflection suggesting the presence of a fault in Figure 52, the data are diffused below the grass, in contrast to the deformation of the sediments shown in Figure 56.

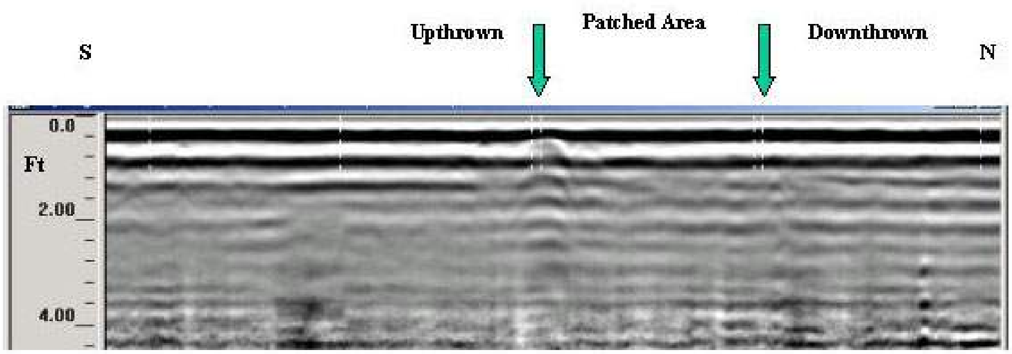


Figure 52 – GPR Profile Over Grassy Area Next to Highway
(Compare with Patched Area in Figure 56)

To test this concept further, he conducted a series of GPR profiles over known and suspected faults in and around the Houston area to determine if radio signals would return meaningful data (for the locations of the GPR profiles, see Figure 17).

The purpose of our test surveys was to identify the near-surface deformation caused by faulting that affects pavement, reinforcement rods (rebar), and road underbeds as well as the in-situ sediments below. Topsoils are usually absent below pavements because they are typically removed during road building and stockpiled elsewhere for later use in highway landscaping. Saribudak employed standard geophysical equipment to identify and characterize the fault zones, which is relatively straightforward to operate, given appropriate training and experience (more).

Section 8.1 GPR Instrumentation

GPR is the general term applied to techniques that employ radio waves in the 1 to 1,000 megahertz (MHz) frequency range to map man-made features and near-surface in-situ conditions. The typical GPR system consists of a transmitter and receiver antenna(s), and a display unit. The type of antenna chosen determines the depth of penetration of the radio waves (i.e., the higher the frequency of the antenna the less depth of exploration). The electrical conductivity of the soil is a significant factor in selecting the type of antenna as well.

The ability of a GPR system to provide meaningful results depends upon two electrical properties of the sediments present in the subsurface: 1) the electrical conductivity and 2) the relative dielectric constant. Electrical conductivity relates to the ability of a material to conduct electrical current. The electrical conductivity of the subsurface material also determines the depth of penetration of the radio signals. Conductivity is primarily governed by the hydrochemistry of the water present. Generally, the lower the conductivity (the higher resistivity) of the interval, the greater is the depth of the radio-signal penetration.

The dielectric constant is a dimensionless measure of the capacity of a material to store charge when an electric field is applied. The value of the dielectric constant ranges between 1 (for air) and 81 (for water) (see Martinez and Byrnes, 2001). Differences in the dielectric constant of subsurface materials along distinct boundaries, such as between deformed and undisturbed sediments, cause significant reflections in the radio signals, which are recorded and displayed by the system.

During the Saribudak field surveys, the GSSI SIR-2000 GPR system was employed equipped with a 400 MHz antenna, which permits a depth penetration that depends on the conductivity and moisture content of the near-surface soil and underlying sediments. To calibrate the depth penetration and to arrive at the appropriate dielectric constant for the area, Saribudak also used a road crossing over three large culverts (see Figure 53). This area is located on the east side of Highway 249 just north of the Willow Creek Bridge, south of Tomball, Texas (see GPR Profile 4c in Figure 61).

Figure 53 – GPR Depth Calibration Site. Looking North along Highway 249, South of Tomball, Texas
(Near GPR Profile 4. See Figure 61, Profile 4c)

The GPR Profile for the depth test is shown in Figure 54. The depth from the top of the road to the top of each culvert was physically measured in the field as: 2.2 feet, 1.8 feet, and 1.3 feet respectively, from left to right. The white arrows indicate the GPR-indicated top to each of the three culverts, which confirm the depths measured in the field and our selection of the appropriate dielectric constants employed in these investigations.

Note that the radio signals darken in Figure 54 at about 4.4 feet below the surface where the bottom of the culverts would be located, which is about the depth of the standing water in the ditch in front of the culverts (see Figure 53). This boundary may represent the top of the capillary fringe or water table in this area, although the energy returns have degraded significantly, but the 'ring down" signals remain apparent.

Therefore, in this project, the near-surface zone consisted primarily of clay (Beaumont Clay) and sands (Lissie Sand), the former of which was assumed to have a dielectric value of 17 and the latter was confirmed to have a value of 12, which were then employed in our depth calculations (Martinez and Byrnes, 2001). See Figure 17 for the Beaumont Clay-Lissie Sand outcrop boundary.

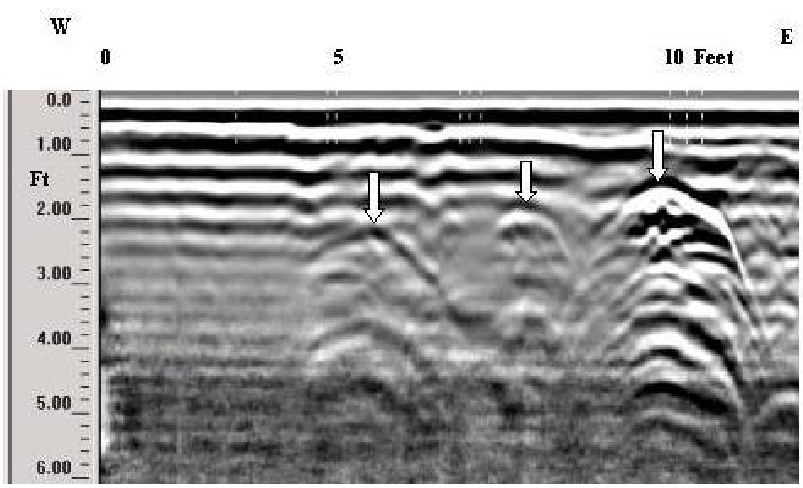


Figure 54 – GPR Depth Test Profile over Three Culverts
(For Location, See Profile 4c, Figure 60)

Saribudak used *Radan* GPR processing and interpretation software for the GPR data. Initially, he used high-frequency pass filters in an attempt to improve the quality of the GPR data where the fault information was present. However, the filtering process did not produce a significant interpretive improvement in the GPR data so all GPR data presented here are unfiltered.

Section 8.2 GPR Data Collection & Interpretation

There are difficulties encountered in interpreting GPR data. Radzevicius, *et al*., (2000) provide some guidance in minimizing antenna "ring down" and other induced artifacts that may be present in GPR data. Olhoeft (1999) provides a summary of the applications and frustrations in using the GPR method.

Section 8.3 GPR Field Surveys

Saribudak and the senior author of this report (as an observer), conducted the GPR surveys between December 12, 2002 and February 14, 2003. The presentation of the GPR data is in gray color (Linescan mode) to provide direct visual recognition of any subsurface deformation, when present. Single white dashed-lines shown at the top of the GPR profiles indicate a horizontal distance marked during the survey.

Double white dashed-lines indicate cracks in pavement or other features discussed in the text. The converted depth scale is given along the side of the profiles. Because of the typical low relief in the area, the ground surface shown in the profiles have not been corrected for topography. We have indicated the location of a scarp at the top of the profile presented, if present. In the Saribudak surveys, the most useful data comes from intervals within or just below the road-construction materials.

Section 8.3.1 GPR Profile 1: Iowa Colony Site

Located on Route 288 south of Houston over pavement, this profile clearly shows the Iowa Colony fault system. One of its faults is downthrown away from the coast (see Figure 17 GPR Profile Location). As shown in Figure 55, the recently patched pavement has already cracked but another fault also appears to intersect the pavement's underbed approximately 50 feet south of the patch (Figure 56). The length of the profile was approximately 200 feet. There is no apparent scarp on either side of the road.

Interpretation of GPR Data for Iowa Colony Profile 1

The zone of deformation along Profile 1 is at least 35 feet wide. The road patch obscures the data below the patch and may hide faulted structures below the path. A series of ring-down artifacts, shown near the right side of Figure 56, highlights a void at their apex at a depth of approximately 1.5 feet below the surface. A fault boundary zone and its relative movement are evident in the figure near the left side.

Numerous deformed and faulted beds are also present toward the middle of the Profile. Fault lines or other interpretations were not included to avoid obscuring the signal data. The use of transparent overlays would be appropriate when detailed interpretations are required.

Of particular note in this profile is the width of the deformed zone is about 50 feet, with multiple bed dislocations suggested in Figure 56. The standard geotechnical "Clearance Zones" of 50 feet to guide construction may need to be expanded because evidence showing deformation at the surface may extend some distance in the subsurface.

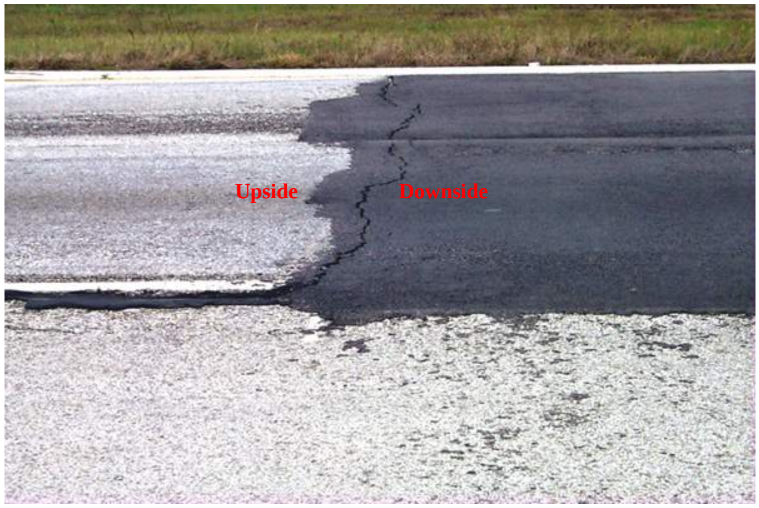


Figure 55 – GPR Profile 1: Iowa Colony Site Looking West across the Northbound Lane (2005) **(Note recent patch with more recent crack)**

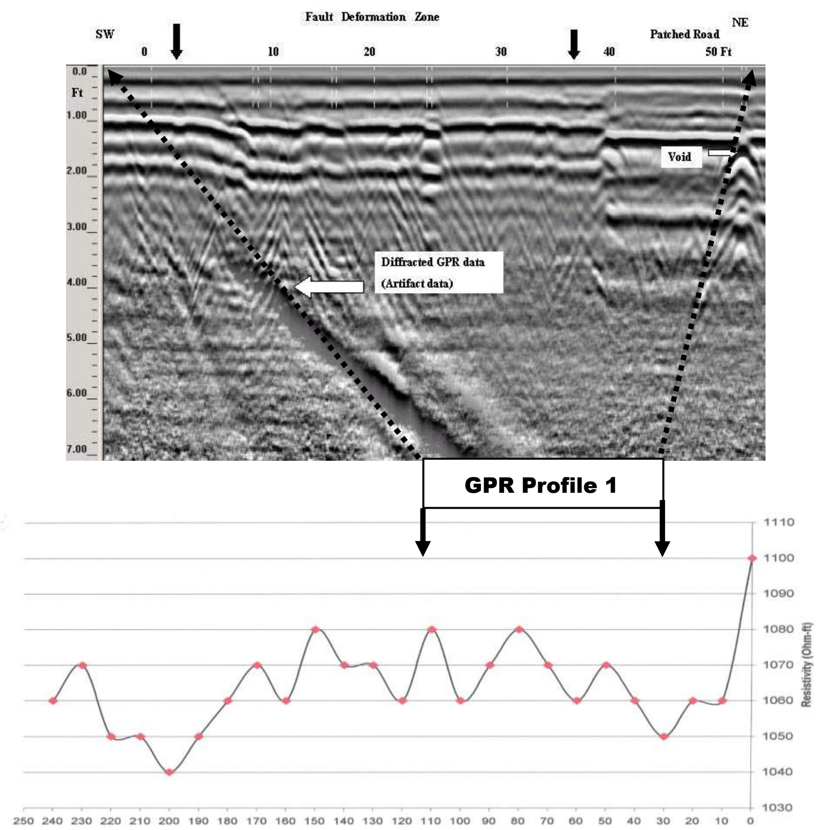


Figure 56 – GPR Profile 1 and Resistivity Survey: Iowa Colony Fault Zone

Saribudak also conducted a resistivity survey parallel to the GPR Profile on the east side of Highway 288 approximately 20 feet from the edge of the highway pavement in moist grass cover. The black arrows show the segment of the resistivity survey that extends along a segment of 50 feet of the GPR profile. As Hamann and Tronicke (2014) and others point out, in order to accurately image subsurface structures such as geological layering or manmade objects with GPR, information regarding GPR velocity and its variations is crucial. For example, migration routines require an accurate velocity model to move dipping reflections to their correct position, unravel crossing events, and collapse diffractions.

As in earlier work by Kreitler and McKalips (1978), an interpretation of the significance of a single resistivity plot would be tenuous without further, more detailed GPR and resistivity surveys, the latter of which tend to give ambiguous results (Figure 56).

Section 8.3.2 GPR Profile 2: Quail Valley Site

This GPR profile (see Figure 17 - GPR Profile Location) was conducted over asphalt underlain by concrete pavement, and was located in the Quail Valley area near the Meadowcreek Subdivision, Fort Bend County, just west of the Blue Ridge Salt Dome (Hager and Stiles, 1925). This dome was the site of a collapse in the 1940s. One night late in 1949, a 24-inch shaft, drilled to recover salt from below 245 feet, collapsed forming a crater measuring 100 feet across. Buildings as well as the shaft were lost, but without injury to mine personnel (Boehm, 1950, and Coates, *et al*., 1981).

Minor, but significant, recent movement of the surface and underlying sediments was apparent also in the area to the west of the salt dome, as indicated by the failure of two of the area's high-capacity water wells, cracks and dislocations in roadways, misaligned utility poles, unusually high incidences of water and sewer line repairs reported by local MUDs, and cracking of brick veneers and walls in some homes of the area.

The length of the GPR profile was approximately 250 feet, with profiles perpendicular to the main profile (see Figure 57). There is a very low scarp running NNE in the grass yards south of the road. Note the offset of repaired pavement indicating movement, now covered by an asphalt patch.

Figure 57 – GPR Profile 2: Quail Valley, Looking West Along the Profile
(circa 2005)

Interpretation of GPR Data for Quail Valley Profile 2

The presence of surface damage to a brick wall of a home and a nearby offset to pavement segments, plus other damage in the general locality, such as MUD water well failures, utility pole and brick wall misalignments, prompted us to conduct GPR surveys in this area. Extensional or graben features among "ring down" interference are evident in Figure 58. Using the line of rebar cross sections (showing as a line of black dots along the top of the figure) as guides, a slumped area (small graben) becomes apparent that extends over a distance 20 feet near the western edge of the profile (see Figure 58).

Small-scale slumping, caused by movement of microshear planes are often associated with high-plasticity, fine-grained sediments. These features are generally known as slickensides and are often observed in fine-grained samples obtained during shallow drilling in Gulf Coast sediments. Their behavior under loading conditions, as well as under conditions of excess pore pressure, may be evidence of local stress created by growth faulting and subsidence in the area, as discussed previously (Kaufman and Weaver, 1967; Foott and Ladd, 1981; and Holzer, *et al.*, 1983). Other extensional structural features, such as graben-within-graben structures are evident as well, and are indicated in Figure 58 over a horizontal distance of approximately 70 feet.

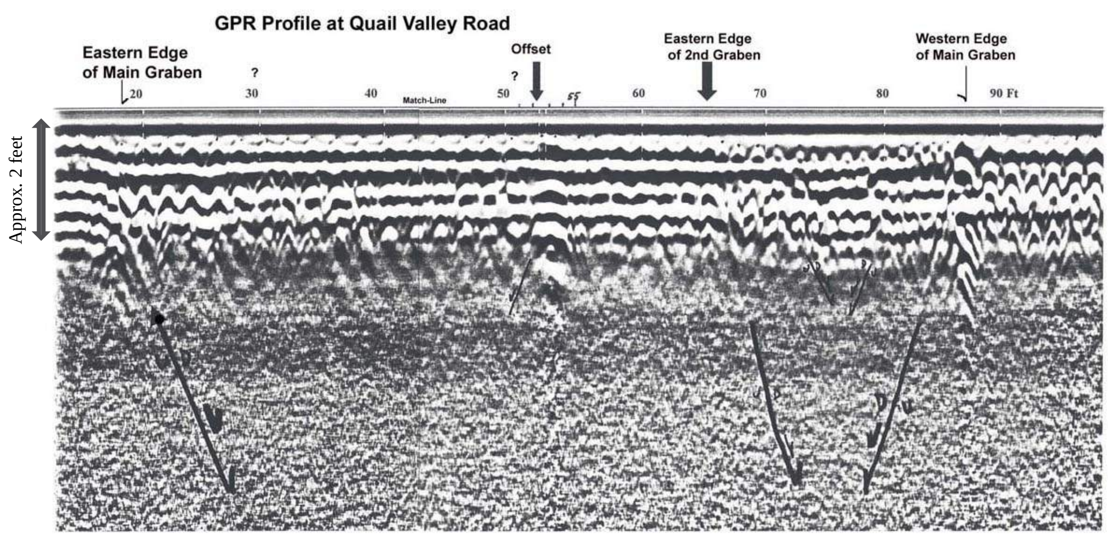


Figure 58 – Profile Results of GPR Profile 2, Quail Valley, Looking South

Section 8.3.3 GPR Profile 3: Eureka Heights Site

Located along 31st Street, the area is a well-known surface expression of the Eureka Heights fault (see Figure 17 GPR Profile Location). It has been active over the past decade as residents have made numerous attempts to level foundations and the City of Houston has continued to patch the street (see Figure 59). A rise in the road surface is apparent. This fault extends southwestward intersecting the NW section of the 610 Freeway (see Figure 47).

Figure 59 – GPR Profile 3: Eureka Heights, Street View
(31st Street in Eureka Heights, Houston, Texas)

Interpretation of GPR Data for Eureka Heights Profile 3

The fault boundary is apparent. Rebar is not obvious in this profile (lack of ring down from spaced points near the top of the section). Two areas of ring down are apparent. The major one is located among radio data of the fault zone and may be a utility conduit or a water main. The second site of ringing is to the left of the fault zone shown in Figure 60 at about the same depth. A zone of high moisture is apparent at depth at this site, suggesting that either a leaking water line is present in the area and/or the top of the capillary fringe likely has been encountered. It should be noted as well that the horizontal-scale spacing shown on Figure 60 varies because of software issues in downloading data from the GPR used in our investigations.

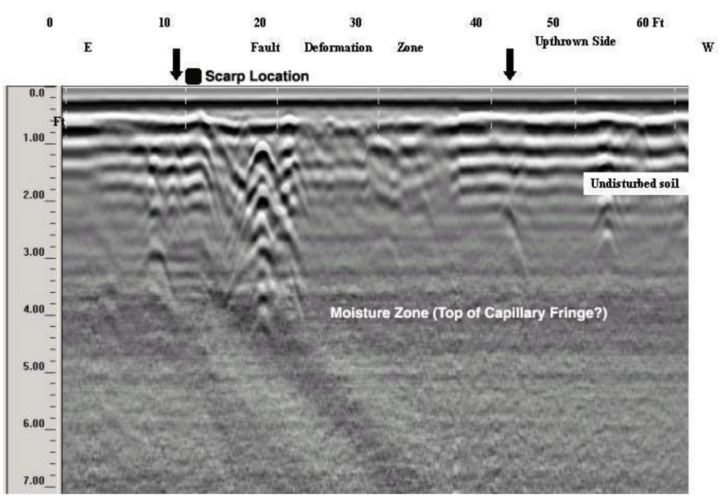


Figure 60 – GPR Profile 3: West 31st Street, Eureka Heights, Houston, Texas

Section 8.3.4 GPR Profiles 4a and 4b: Willow Creek Site

These GPR profiles covered almost 1,000 feet and revealed an extensive fault zone that we now call the Willow Creek fault system, with the northern-most fault exhibiting down-to-the-coast movement and antithetic faults to the south (see Figure 61). Turner, Collie, and Braden, Inc., (1966) showed three faults extrapolated from the subsurface. Later, Kreitler (1977b) also indicated an area of surface traces (see his Figure 5, p. 206) that appear to be the same area investigated here. The fault zone is also evident on the 7.5-minute topographical map (see Figure 61). Willow Creek drainage appears to have been controlled by these faults. Also, two pipelines apparently transporting crude oil cross the faults just west of Route 249. Figure 33 shows one of the pipelines (see Figure 17 for the location of GPR Profile).

The northern-most fault of this system crosses Highway 249 near the northern end of the Willow Creek Bridge. Recent movement is evident in Figure 61 (and Profile 4a). Evidence on the highway for the southern fault zone is shown in Figure 62 (and Profile 4b). The only movement observed is apparent in Figure 60 where the retaining wall segment has moved and where the highway pavement has cracked and has been repaired numerous times (Figure 64). Down-to-the-north faulting is indicated at this location.

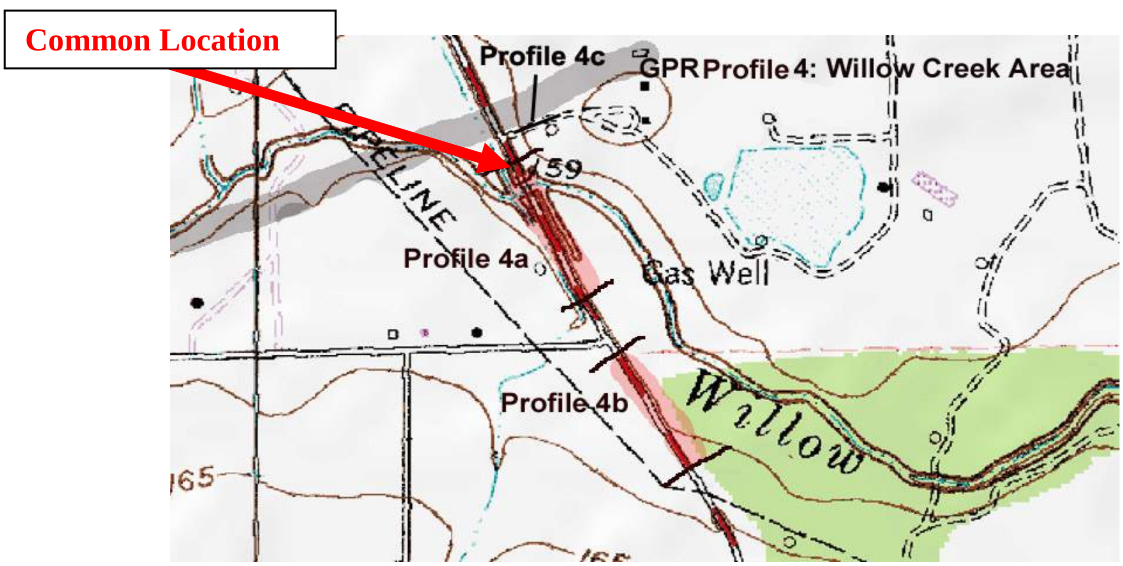


Figure 61 – Topographic Location of GPR Profile 4
(Highway 249 Runs Through Middle of this Figure)

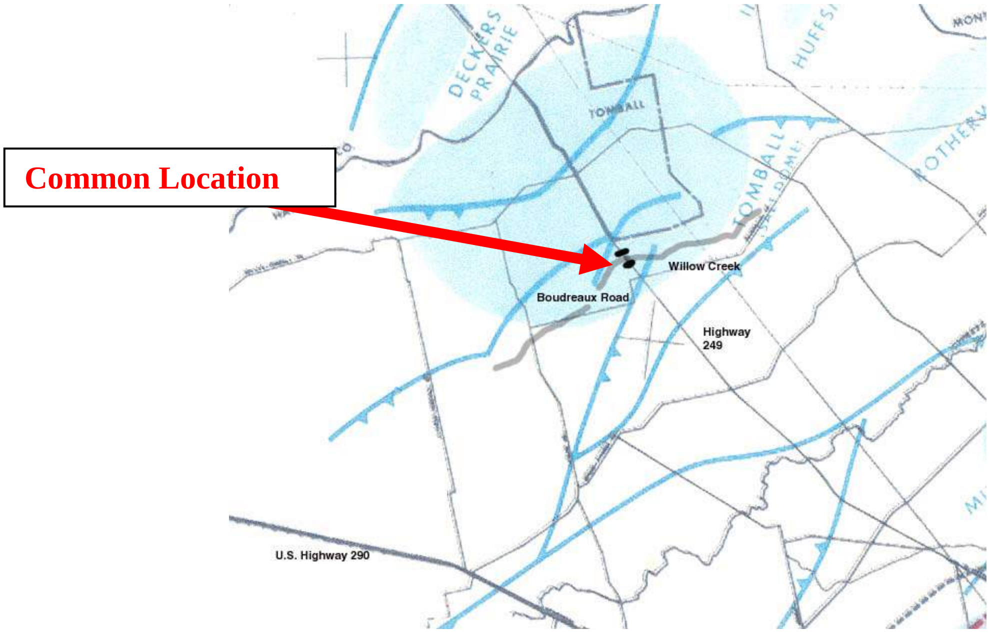


Figure 62 – Mapped Location of GPR Profile 4
(Highway 249 Runs Through Middle of this Figure)

Figure 63 – Recent Movement in Retaining Wall at North End of Willow Creek Bridge
New Repair Shown in Road at Bridge Edge. Looking East Across Highway 249.

Figure 64 – Recent Crack along GPR Profile 4: Willow Creek Area
Likely Caused by Dislocations Shown in Figure 62 as Profile 4b. Looking East across the Highway.

Interpretation of GPR Data for Willow Creek Profiles 4a and b

The zone of deformation over the fault system along these profiles is extensive. For the profiles we conducted, the zone begins just north of the bridge (Figure 61: Profile 4a) and extends south for some distance beyond Profile 4b. One explanation for this wide zone might be that Highway 249 may have been constructed along a well-worn track where the Willow Creek fault has been offset, and where the zone runs along the strike of this offset. Another explanation might be that two fault zones are present and the area between the two is deformed as a result.

Clearly, additional work is needed at this site to clarify and define the conditions present in the subsurface. In Figure 65, aka Profile 4a, this shows an extensive zone of deformation, the tell-tale patterns of rebar associated with an asphalt patch, voids or piping, and blind zones below the bridge at the right of the figure. The location of the southern-most fault is unclear because Profile 4b ends just beyond the deformed zone(s). In Figure 65, however, the profile extends to the end of the zone (at the right arrow). The dislocated beds and associated structures across the zones are numerous and distinct. Some areas of the profile exhibit nearly vertical movement of beds while other areas suggest chaotic conditions of disrupted beds.

If GPR profiles are not conducted normal to the strike of the fault, because they often follow roadways, the profile may show chaotic structures, as illustrated in Figure 66. Also, any calculations conducted to estimate the fault-dip angle based on non-perpendicular profiles, would be erroneous. Therefore, such calculations should only be attempted if there is some assurance that the profile is aligned normal to the fault strike. Of particular note here is that the total width of the deformed zone associated with the Willow Creek fault system, as well as other fault zones, may be wider than the length of the GPR profiles.

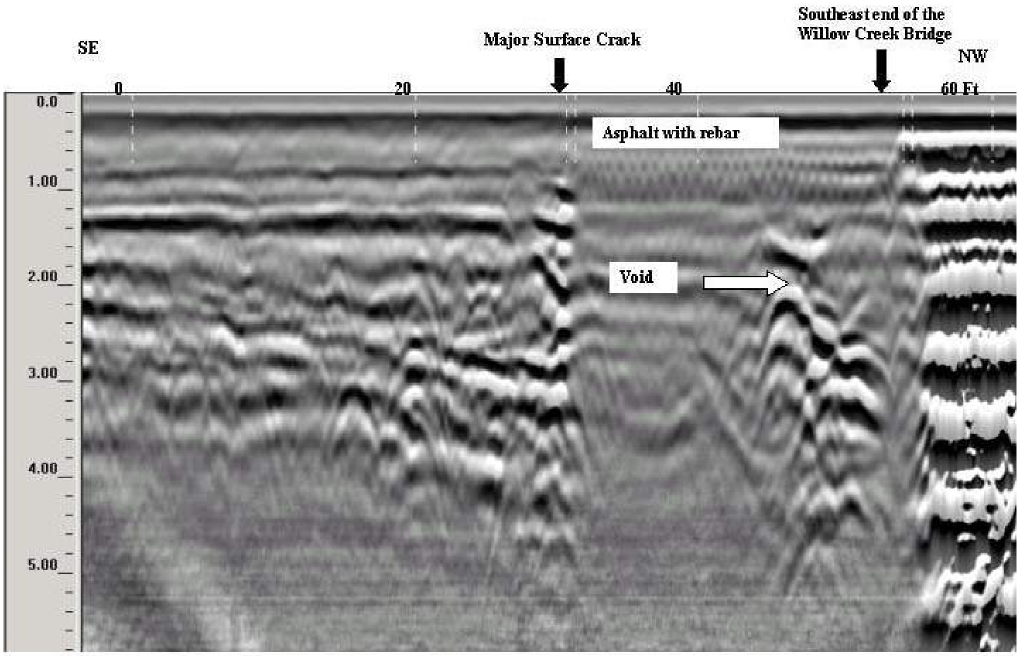


Figure 65 – GPR Profile 4a: Major Surface Cracks Indicated
Location Also Shown in Figure 61

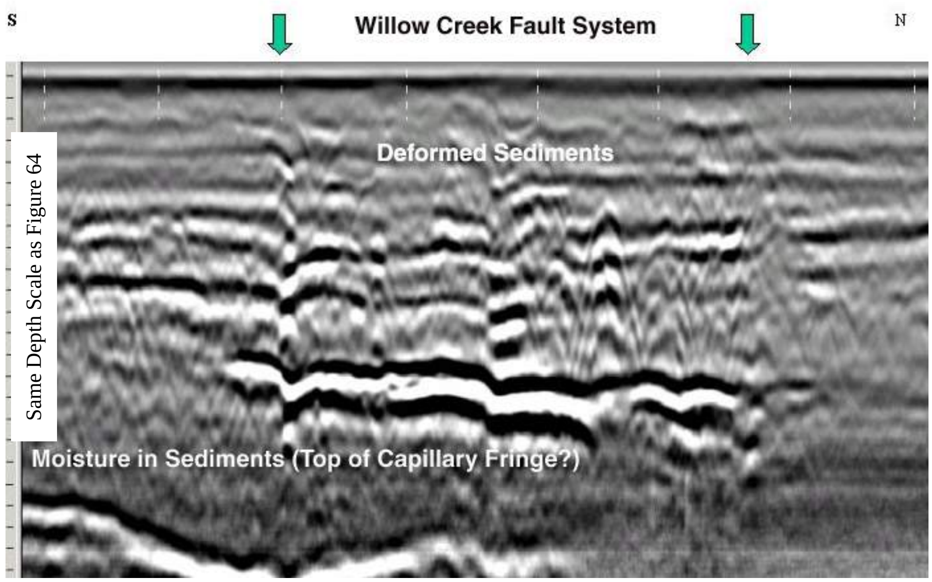


Figure 66 – GPR Profile 4b: Shows Multiple Vertical Displacements
Along a Wide Zone of Deformation Within A Thick Fill Zone. Location Also Shown in Figure 61

Section 8.3.5 GPR Profile 5: Hazard Street Site

Located on Hazard Street in Hyde Park Main, Houston, Texas, this home shows serious foundation problems (see Figure 17 GPR Profile Location). GPR Profile 5 was conducted down the center of the street over a distance of about 60 feet (see Figure 67).

Figure 67 – GPR Profile 5: Hazard Street House (as of 2003)
North to Right. Looking West (House Demolished in 2005 and Rebuilt)

Interpretation of GPR Data for Hazard Street Profile 5

To assess the likely cause of damage to the house shown in Figure 67, we conducted a GPR profile in the street across the front of the house. Although a typical indication of fault damage, our GPR profile shows that the damage is likely caused by differential settling of the fill below the subject house. No evidence is apparent that a fault and the typical deformation zone are present at this location (see Figure 68). The major crack indicated in Figure 68 below is the same crack shown in Figure 66.

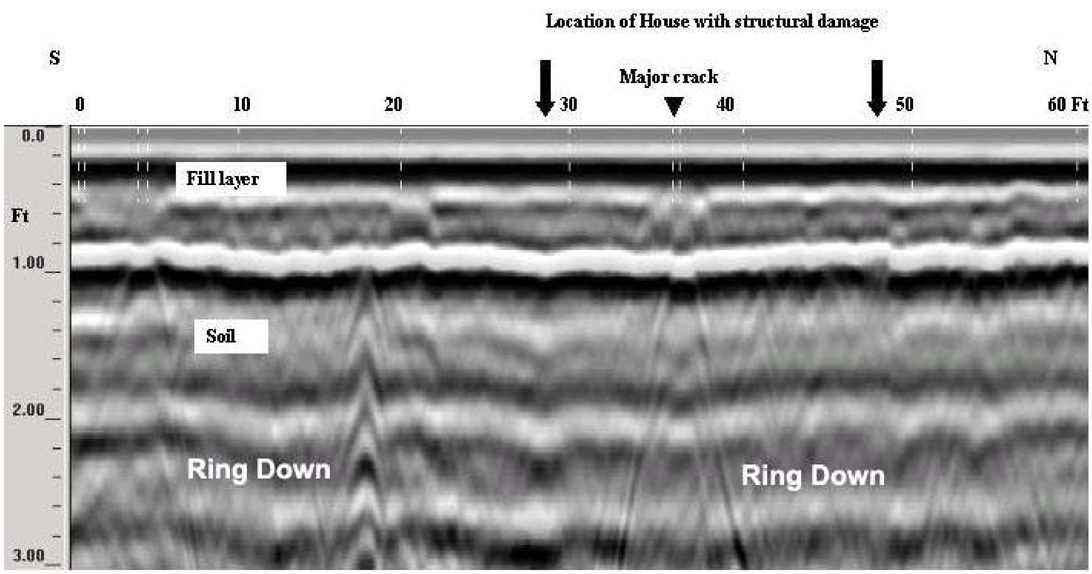


Figure 68 – GPR Profile 5: Structural Damage to House
(see Figure 67)

Section 8.3.6 GPR Profile 6: Long Point Site

GPR Profile 6 was conducted over the rise of the well-known Long Point fault along Moorhead Street at Westview and at OJ Cannon at Long Point Road, Houston, Texas (see Figure 17 for the general GPR Profile Location). The surface displacement of the fault at these locations has produced scarps of approximately 2 feet and more (see Figure 69). Nearby, City of Houston personnel have monitored the movement of the fault and applied special construction sleeves to the large diameter water lines passing through this area. Major leaks were common problems in the area for many years as they are all over the area, many of which are likely related to fault movement.

Figure 69 – GPR Profile 6: Long Point Fault
(Survey in Progress. Looking North.)

Interpretation of GPR Data Long Point Profiles 6a and b

Reinforcement bars and the associated signal "ring down" are evident in Figures 70 and 71. At a depth of approximately two feet below the surface, sediment deformation is indicated on the down side of the fault. Deformation appears to be present on both sides of the indicated fault. Because of the widespread interference likely caused by rebar present in the Figure 70 record, additional surveys would be required to clarify conditions. However, fault zones are indicated in Figure 70 where beds have been deformed and in Figure 71 where "ring-down" interference partly obscures the structural pattern.

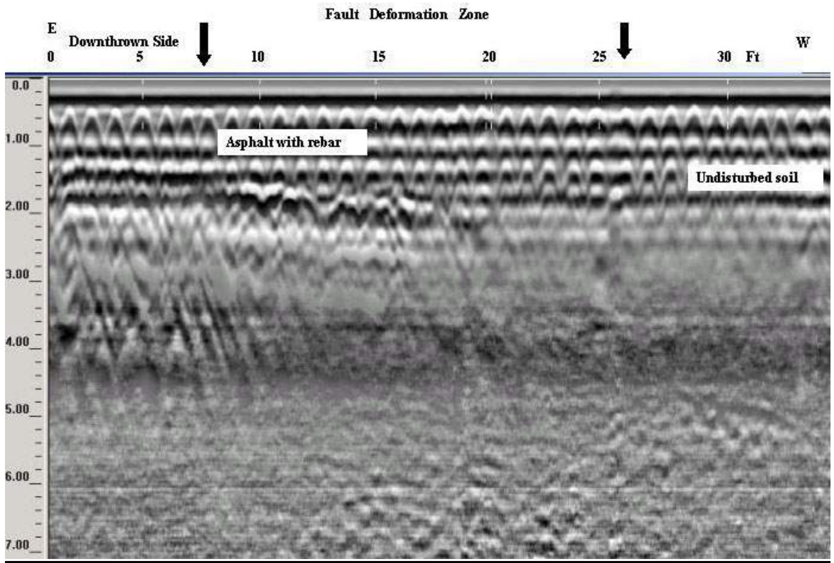


Figure 70 – GPR Profile 6a: Moorhead Street at Westview, Houston, Texas

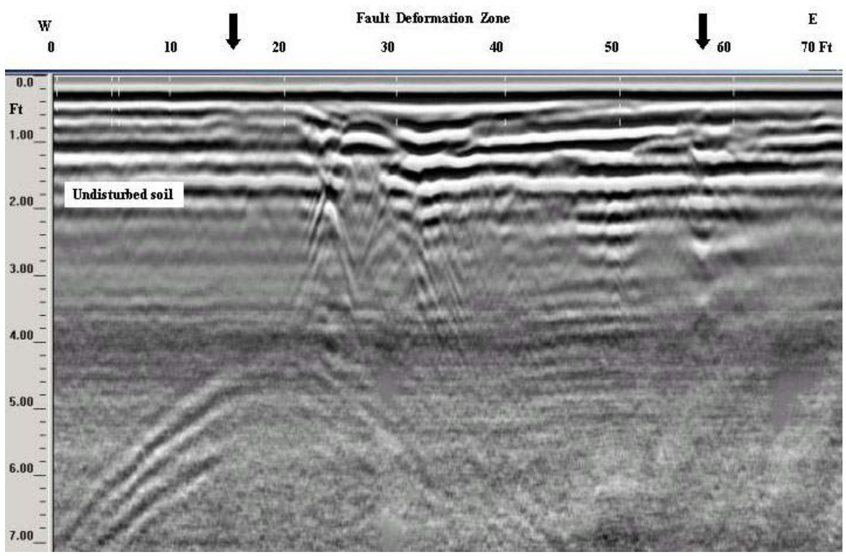


Figure 71 – GPR Profile 6b: OJ Cannon at Long Point Road, Houston, Texas

Section 9.0 Conclusions and Recommendations

There are a number of issues that we have reviewed and evaluated in this report. In coming to our conclusions during these investigations over the years, the process often required that recommendations for solutions be assembled as well. To that end, we have summarized the principal conclusions of our investigations below and have included recommendations where appropriate. There is still much work that remains to be done on the various geologic, hydrogeologic, and geophysical phenomena present in the subsurface in the Houston, Texas area.

The work would be particularly suitable topics of research for graduate geoscience students from the local universities. Where justified by economic concerns involved in real-estate transactions, construction, and other activities, professional geoscientists will address the issues with the available information and new technology provided such as LiDAR as well as information provided by further field investigations. The geotechnical engineering and geoscience disciplines are interdependent in these activities.

A system of categorizing geologic hazards needs to be developed and implemented, e.g., a GeoHazard Rating Scale (GHRS) for relative impact of the geological hazards present in the Houston area. It would seem that sites where pipelines carrying certain hazardous products cross active fault zones and areas on the surface along identified zones of preferred subsurface geologic structures that are known to transmit radionuclides or hydrocarbons, such as in the Jersey Village, southwestern Houston, eastern Humble, Texas area, and south of Tomball, Texas (Figures 18 and 19) could be considered Type I GeoHazards. Type I would require regular monitoring. Drinking water supplies would require special water and air sampling programs designed to monitor for such hazards.

Peripheral fault areas might be defined as Type II GeoHazards because they may likely be affected in the foreseeable future. These would include pipelines carrying certain hazardous products that cross an area where apparent extensions to known faults may be present (see Figures 33 and 34). The data accumulated in applying the GHRS, or another one serving the same purpose, could be published as overlays within the County Flood Plain maps (see Figure 36) prepared with Federal funds, a program managed by the Federal Emergency Management Agency's (FEMA) Federal Insurance Administration and Mitigation Directorate. The Federal Insurance Administration manages the insurance component of the program, and works closely with FEMA's Mitigation Directorate, which oversees the floodplain management aspect of the program (see Dodson & Associates, Inc., 2003).

We also conclude that:

1) Houston sits in the middle of the Houston Salt Basin (see Figure 17) and abundant oil and gas resources have been found and produced from among the deep sediments as a result of structural traps created by growth faulting above salt domes, ridges, and other salt masses that began to rise more than 50 million years ago and are still rising. We have reviewed the causes, kinetics, and associated factors involved in growth faulting that has reached the surface in the Houston and surrounding region and have concluded that the faults are geologic hazards that cause other factors of concern to come into play.

2) Although faults play significant roles in forming oil and gas resources, they can also form unstable ground above and around the periphery of the known salt domes as well as allow dissolved radionuclides and hydrocarbons to migrate along and up favorable fault zones entering the Evangeline Aquifer from below.

3) We recommend that buildings for either domestic or industrial purposes should be prohibited (by insurance costs or by City and County ordinances that define areas of GeoHazards) from being built over and within the area of influence of the known and projected geologic hazards, such as along regional fault zones and around salt domes that have the potential to disrupt the surface. This process would be similar to restrictions placed on construction that is prohibited along streams within the 100-year flood boundary (or flood hazard maps (see Figure 36), or in

areas of underground mine subsidence identified in other parts of this country (see Yokel, 1978).

4) The known fault zones are Types I and II GeoHazards where they are crossed by pipelines (hydrocarbon, chemical and water). Serious potential hazards exist for pipelines carrying hydrocarbons where they cross fault zones, especially along sections of pipelines where poor maintenance of corrosion-control systems may be a problem. Pipe stressed by faulting would pass unnoticed through many neighborhoods. Stressed metal is a common site for galvanic corrosion and corroded pipe eventually leaks or ruptures, especially if the pipeline is pressurized. Special care should be given by pipeline companies and regulatory agencies to identify pipelines carrying hazardous materials and to devote extra effort to manage these critical crossing points along faults that have a history of movement, as well as those that, at present, do not have a documented history of movement (in association with the GeoHazard Rating Scale).

5) The repair records of water supply lines filed by the City of Houston, Harris County MUDs, and other groups should be pooled to provide guidance in locating potentially hazardous areas where fault movement may not be apparent in identifying new faults or extensions of known faults. Leaks involving pipelines are always a potential hazard; adding active faults to the mix can easily have disastrous consequences. We cite the Brenham, Texas natural gas leak and subsequent explosion of a few years ago that devastated the area and was felt by millions in Houston that morning. Undermining Houston streets by leaking water mains (some created indirectly by fault movements) have also caused major sinkholes to appear in roads causing hazards to drivers.

6) The need exists for a qualified, independent committee of licensed geoscience professionals, capable of coordinating with all high-capacity well operators within the City of Houston and MUD personnel in surrounding counties, to periodically assemble and evaluate all data pertinent to managing the operation of the wells and to monitor all water levels (i.e., their cones of pressure relief) throughout the five-county area. To avoid political entanglements, we recommend that the U.S. Geological Survey be tasked to coordinate these activities, as well as other tasks such as developing the GeoHazard System. Cooperation with personnel of the Harris-Galveston Subsidence District would also be essential.

7) If newly recognized fault zones could be identified and characterized early in the future, highway construction practices could be modified to minimize frequent, costly repairs. Industrial facilities could also be designed and built to accommodate the fault zones by either building away from the zones an appropriate distance or by modifying construction practices to accommodate fault movements. We recommend that fault maps should be prepared and updated on a regular basis to permit full disclosure in real-estate transactions (in association with the GeoHazard System) in concert with the development and publication of Federal Flood Plain Maps.

8) Growth faults represent a geologic hazard in and around the Harris County area by introducing radioactive materials and hydrocarbons that represent a threat to human health and the environment. There is strong justification for monitoring the ground-water supplies for these constituents on a periodic basis, as required by state and federal regulations. Because the faults generally move silently and episodically, fault movements may in the process also create new

avenues for migration of radionuclides, hydrocarbons, or other unwanted constituents up from deep sources, or from shallow sources of contaminants contained in closed landfills and old dumps downward to the uppers zones of the Chicot and Evangeline aquifers. Any migration, up or down, would depend on whether the particular fault zone consisted of reasonably permeable sediments. Therefore, we recommend that the appropriate City of Houston personnel, MUD personnel, and private well owners be re-alerted by personnel of the U.S. Geological Survey to this potentially hazardous condition via a new GeoHazard System.

9) Understanding the structural conditions of subsidence and its relationship to faulting needs further study to better manage our high-quality ground-water and available surface-water resources by reassessing water needs of industry and agriculture in light of the future water needs of Houston, Harris County, and surrounding counties. These topics would also appear to be important topics for local academic research in cooperation with the U.S.G.S.

10) An additional task for the U.S. Geological Survey would be to resume systematic mapping and monitoring of fault zones and subsidence in the five-county area, especially where pipelines and other structures cross known fault zones and where radioactive materials and hydrocarbons have been reported in the drinking water along associated structures (in association with developing the GeoHazard System).

11) There are existing methods to identify fault zones but most are expensive and time consuming. Many common forms of surface geophysics can be used in so-called hard-rock areas of the U.S. and in areas of lower precipitation than east Texas and surrounding areas. However, a special application of GPR appears to be more useful in the Houston area than previously considered. The Saribudak survey conducted during our investigations has demonstrated that meaningful data can be obtained by using GPR to identify faults where they disturb the ground surface and to characterize the zone of subsurface disturbance on both sides of the fault.

12) GPR is also a useful, preliminary tool to demonstrate that faulting is not the likely cause of damage resulting from movements of the ground surface or foundations or other structural damage to homes or buildings. We have found through the use of GPR that construction-fill practices can have a significant effect on the stability of house slabs or other footings even years after installation.

13) A new fault system is evident at the surface and is located just south of the town of Tomball, Texas, herein named the Willow Creek fault system, on the basis that more than one fault seems to be present at the site. Subsequent work by Saribudak (2014) has confirmed this disturbance.

14) The Meadowcreek and Quail Valley areas are located in areas of periodic movement caused by the radial fault system associated with movements within the structures in and around the Blue Ridge Salt Dome just east about two miles from the above areas.

15) GPR data should be acquired and interpreted by qualified professional geoscientists licensed in the State of Texas, or equivalent, to avoid unnecessary liability (see Hughes, 1981; and Coogan, 1981).

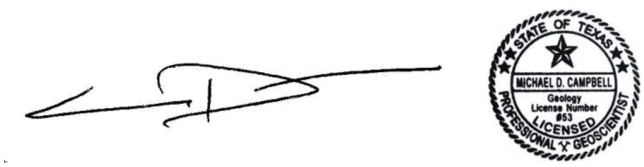
16) New information will be available via the Internet on growth faults and subsidence in the Houston, Texas area and elsewhere in the world as more historical reports and publications come online and as new studies are published by the U.S. Geological Survey, local universities, and other professional evaluations by consultants.

The authors consider this document to be dynamic in nature in that new information may encourage us to make revisions to the guide from time to time. The reader should note the Version of the document shown on the lower right of the front cover page, and should download any new versions that become available in the link provided.

Therefore, the authors reserve the right to revise this report in the future as new information becomes available or as they deem appropriate.

Signed in Houston, Texas this 16th day of December, 2014.

Sincerely,



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