FIELD TRIP GUIDEBOOK ON

ENVIRONMENTAL IMPACT OF CLAYS ALONG THE UPPER TEXAS COAST

Clay Minerals Society 28th Annual Meeting
Houston, Texas

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NASA
National Aeronautics and
Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

LPI

FIELD TRIP GUIDEBOOK ON

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For the
Clay Minerals Society 28th Annual Meeting

Hosted with
NASA Johnson Space Center
Lunar and Planetary Institute

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Contents

Preface

The field trip "Environmental Impact of Clays along the Upper Texas Coast" was prepared to provide participants at the 28th Annual Meeting of the Clay Minerals Society an opportunity to see first hand some of the environmental hazards associated with clays in the Houston, Texas area. Because of the very high clay content in area soils and underlying Beaumont Formation clay, Houston is a fitting location to host the Clay Minerals Society. During this one-day field trip, stops will include the examination of (i) expansive soils (Vertisols & Alfisols) in the southern part of Houston, (ii) subsidence and surface faulting east of Downtown Houston (San Jacinto Monument, Goose Creek Oil Field, and Baytown), and (iii) a landfill located southeast of Houston at the Gulf Coast Waste Disposal Authority Campbell Bayou Facility where clay is used as part of the liner material. In addition, a stop will be made at the National Aeronautics and Space Administration's Lyndon B. Space Center where field trip participants will be given the opportunity to observe the heritage of the Nation's space program. Several of the facilities that will be visited include (i) Mission Control Center, (ii) Lunar Sample Building, and (iii) Space Station Freedom and Space Shuttle Mockups.

The assistance of Stephanie Tindell, Renee Dotson, and Steve Hokanson of the Lunar and Planetary Institute in preparing this guidebook is gratefully acknowledged. The field trip has greatly benefitted from the cooperation of the San Jacinto Museum of History, University of Houston-Clear Lake, NASA Lyndon B. Johnson Space Center, and the Gulf Coast Waste Disposal Authority. A special thanks goes to Dave Pevear for his continuous support and encouragement to make this field trip guidebook possible.

We hope that you enjoy your stay in Houston.

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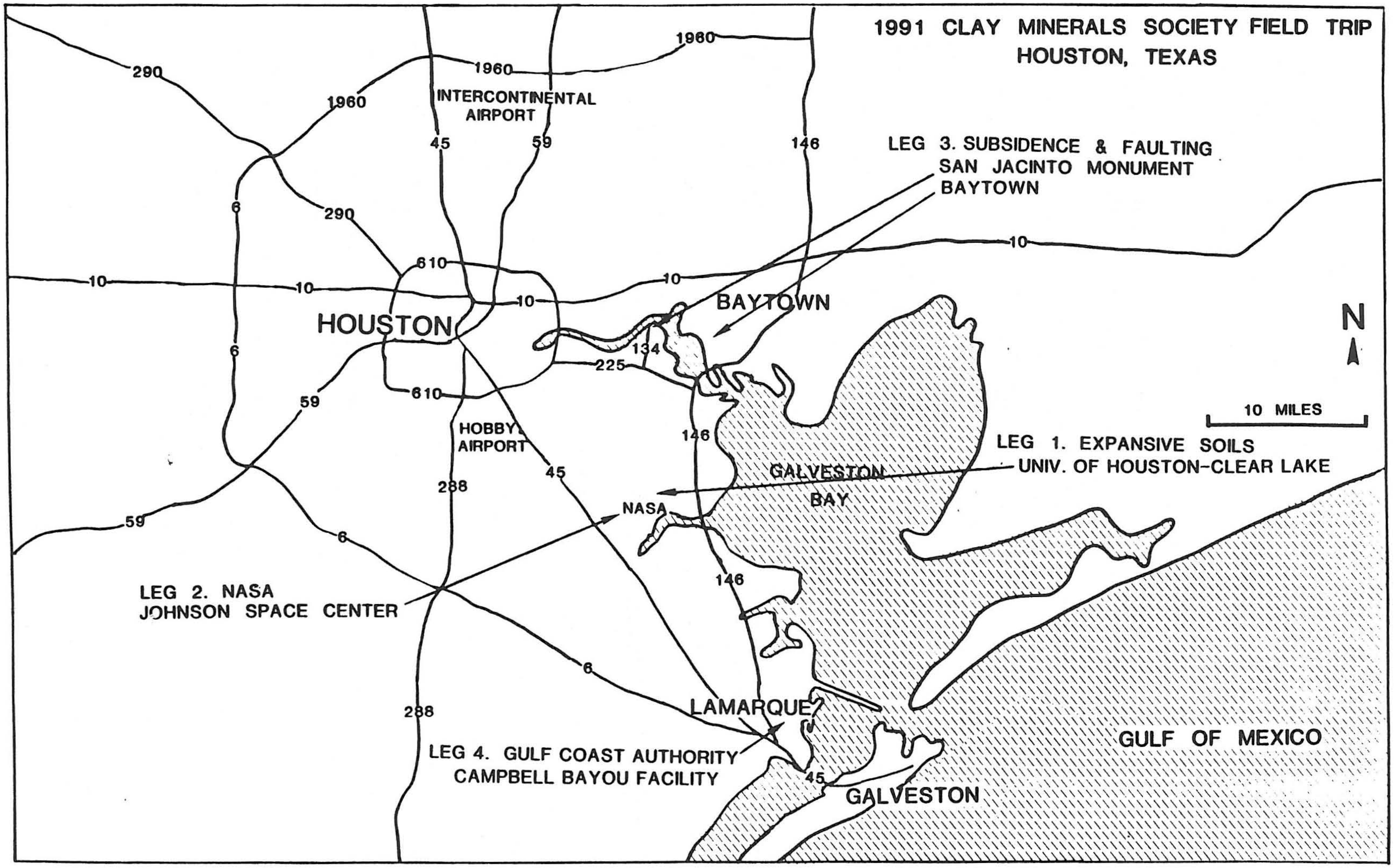


Location of stops for the Clay Minerals Society 28th Annual Meeting mid-conference field trip, Houston, Texas.

ENVIRONMENTAL IMPACT OF CLAYS ALONG THE UPPER TEXAS COAST

Theron D. Garcia
University of Houston-Clear Lake

REGIONAL SETTING

The Houston-Galveston area is located in the northwestern part of the Gulf Coast Basin (Fig. 1). During the Cenozoic Era the Gulf Coast Basin experienced fluctuations in sea level accompanied by transgressive and regressive depositional events. Throughout most of the Tertiary, changes in sea level were relatively mild and lacked the rapid rates of change found in the Quaternary (Winker, 1979). Major fluctuations in sea level have been documented in the Pleistocene and, according to Richmond and Fullerton (1986), the beginning of these major

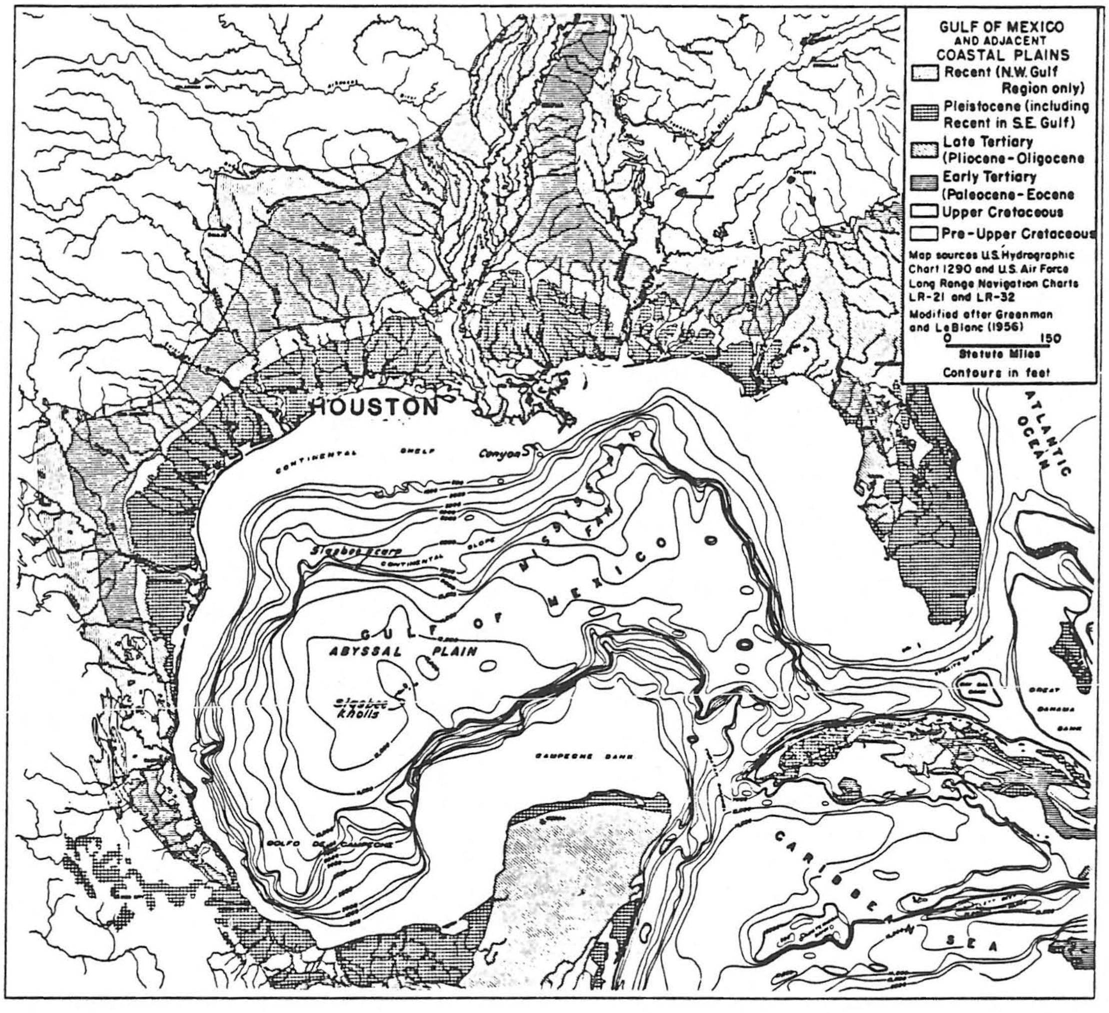


FIGURE 1. Generalized geologic map of the Gulf coastal plains and the principal hydrographic features of the Gulf of Mexico (Bernard et al., 1970).

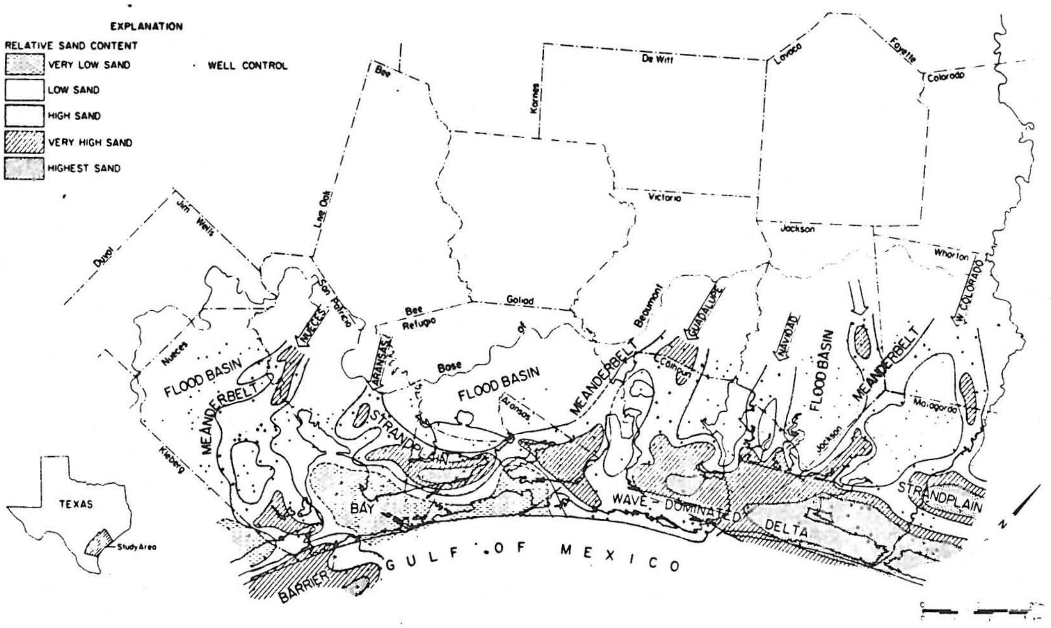


FIGURE 2. Depositional system for the Beaumont Formation (Solis, 1981).

fluctuations can be found in the Pliocene. Multiple fluctuations of sea level throughout the Cenozoic have produced 50,000 feet (15,259 m) of sediment in off-shore Texas and almost 45,000 feet (13,725 m) in off-shore Louisiana. Deposition of these sediments was normally accompanied by growth faulting which, along with subsidence, produced sequences of sediment that thickened seaward (Morton & Nummedal, 1982).

Regardless of the rate of sea level change or magnitude of sea level fluctuations, the depositional styles along the ancient Texas Gulf Coast have remained the same throughout the Cenozoic (Winker, 1979). Rivers crossing the coastal plain deposited silty to sandy meander-belt ridges (levees) and point bars (Van Siclen, 1985). Mud-rich deltas, resulting from the high suspended load of these rivers, prograded into shallow marine water during periods of high sea stand depositing overbank and interdistributary muds (Winker, 1979; Morton & McGowen 1980; Aronow, 1990). Strandplains formed at the seaward edge of delta progradation as transgressing seas reworked previously deposited sands (Morton & McGowen, 1980). During periods of low sea-level stand, the exposed deposits underwent intensive weathering, producing extensive paleosols (Morton and Nummedal, 1982). The modern southeast Texas coastal plain consists mainly of late Pleistocene and Recent alluvial and deltaic plains (Bernard et al., 1970). An example of a depositional system for the Beaumont Formation is illustrated in Figure 2.

The present topographic surface on the Beaumont Formation is directly related to depositional systems present during the high sea-level stand (about +6 meters above present) of the last interglacial stage. Fluvial deltas prograded into shallow marine water

> "and formed broad, low-relief
> surfaces that maintain much of their

> depositional grain. Details preserved on delta surfaces are straight distributary channels, meanderbelt sands, overbank and distributary muds....The seaward extent of delta progradation is marked by strandplains formed by reworked sands deposited on delta-plain surfaces" (Morton and McGowan, 1980, p. 1).

Bernard and LeBlanc (1965) speculated on future sedimentary deposition along the Texas coastal plain:

> "Given sufficient time, approximately 20,000 -25,000 years, and a constant stand of the sea, the future events along this part of the coast should be similar to those of the Last Pleistocene Interglacial stage [Beaumont Formation]. The rivers, if not controlled by man, should prograde their deltas far seaward of the present strand. The Mississippi deltaic plain should eventually cover most of the present shelf off the Louisiana coast and possibly part of the southeast Texas coast before the cycle is terminated by the next falling-sea-level substage."

BEAUMONT FORMATION

The Beaumont Formation of late Pleistocene age is the youngest of a long series of Cenozoic stratigraphic sequences which crop out in subparallel belts along the upper Texas coast. The Beaumont Formation is in contact with Recent sedimentary systems near the coastline. Boundaries between these belts can generally be recognized only by a change in slope relative to adjacent plains (Bernard and LeBlanc, 1965). These investigators noted that successively younger (and seaward) formations dip at progressively smaller gradients. A combination of basin downwarping due to sediment loading (and contemporaneous inland uplift) and higher clay compaction rates oceanward produced the greater slopes evident in older Cenozoic formations (Fig. 3). The

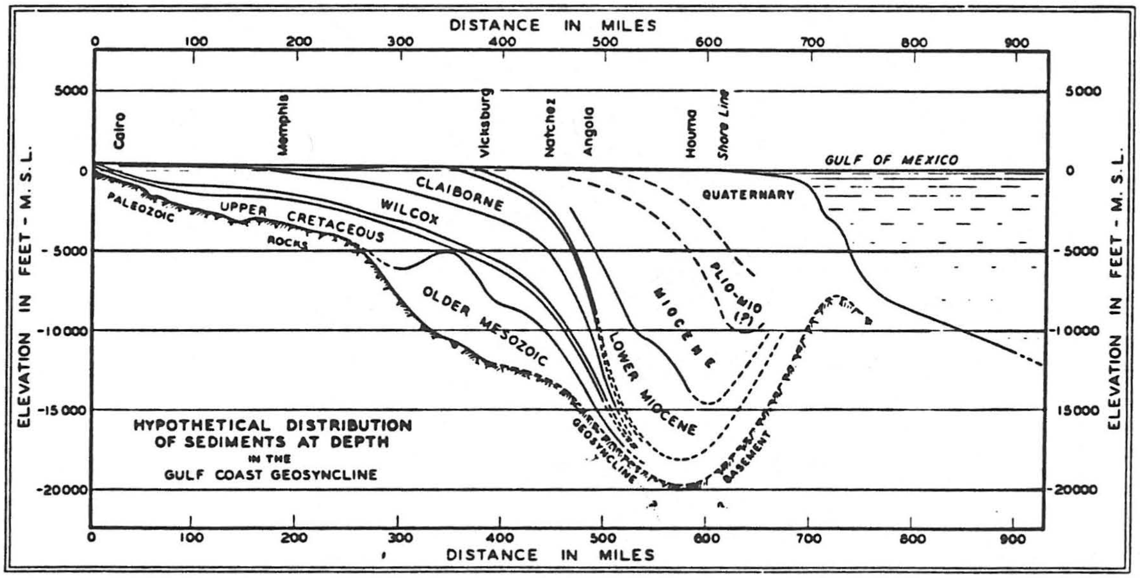


FIGURE 3. Generalized cross section of the Gulf Coast Geosyncline (Bernard et al, 1970).

belt of exposed Beaumont sediments extends from the eastern edge of the Mississippi River in Louisiana (Prairie Formation) to the northern edge of the great South Texas Sand Sheet, south of Corpus Christi (Aronow, 1988). The Beaumont Formation underlies most of Harris County. In the field trip area, the Beaumont outcrop belt is 30 to 40 miles (48.3 to 64.4 m) wide and dips gulfward between 1.5 and 5 feet per mile (0.3 and 0.95 m) (Solis, 1981). Bernard and LeBlanc (1965) approximated the seaward slope of the Beaumont south of Houston at 2.0 feet per mile.

The sediments of the Beaumont Formation were deposited as ancient rivers migrated across the coastal plain depositing silt and sand in meander-belt ridges, point-bars, and distributary channels, and muds (clays) were deposited in overbank and floodbasin deposits (Fig. 4). Sea level during deposition of the Beaumont was slightly higher (+6 m) than the present sea level elevation (Aronow, 1971). Van Siclen (1985) suggested that low meander-belt ridges left by the ancient Brazos River are the most enduring depositional features of the Beaumont Formation in the Houston Area. The silty to sandy meander-belt ridges and distributary patterns of these deltas form topographic highs which are surrounded by the muds of ancient flood basins and interdistributary areas. Similar patterns were produced by the interglacial Nueces and Trinity Rivers (Aronow, 1990). The Beaumont Formation in the Houston-Galveston area, mainly muds representing delta-plain sediments (Kreitler et al., 1977), overlies a sand section known as the Alta

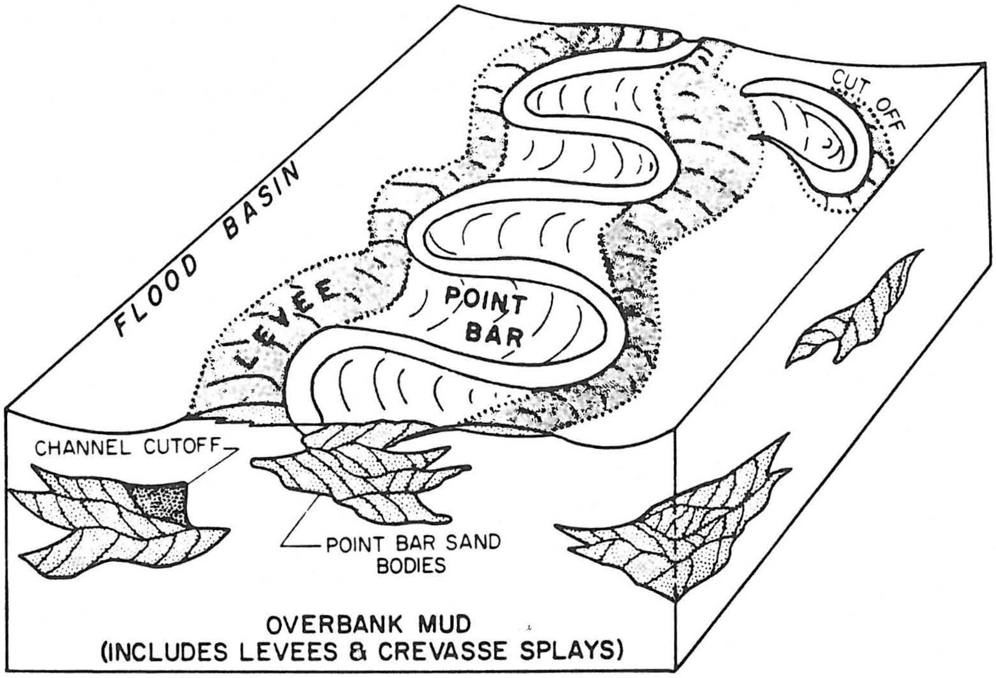


FIGURE 4. Depositional model of an idealized fine-grained meanderbelt fluvial system showing bed forms, sedimentary structures, and multistory geometry (Morton and McGowen, 1980).

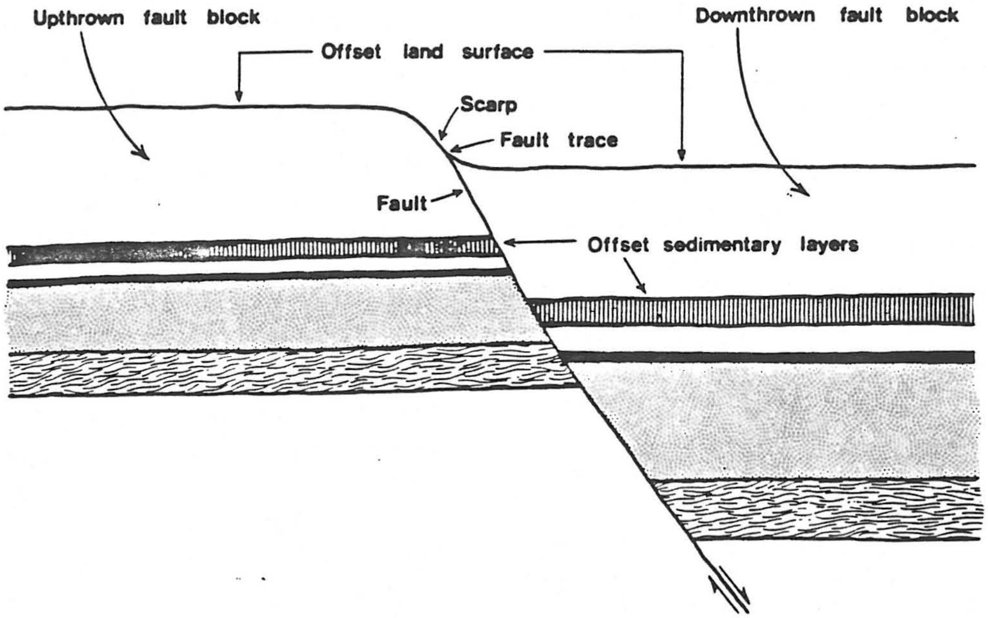


FIGURE 5. Vertical section through a hypothetical fault in the Houston area. Land surface was originally level, but has since been displaced by movement along the fault. Note thickening of sedimentary layers on the downthrown side. This indicates that faulting occurred repeatedly over a long period of time, while the sediments were being deposited. Such faults are common in the Texas Gulf Coast.

Loma Sand (Wood and Gabrysch, 1965). The muds typically contain high percentages of smectite (Gabrysch and Bonnet, 1975), forming Vertisols (Aronow, 1976). Gustavson (1975) estimated that 15 to 20 percent of the Coastal Plain surface is covered by smectite-rich, expansive soils.

Winker (1979) stated that, in Texas, Beaumont deposits are generally less than 100 feet (30 m) thick. Solis (1981) however, suggested the Beaumont is about 500 feet (152.5 m) in the northwestern region of the Gulf Coast Basin. The thickness of the Beaumont in the Louisiana Coastal plain is considerably thicker than the Beaumont in the Texas Coastal plain, ranging from several hundred feet in Texas to three thousand feet (1000 m) in Louisiana (Russell, 1940). Differences in thickness in the Beaumont indicate a shift of main depocenters from Texas, where deposition was greatest in the Eocene to Oligocene, to Louisiana which experienced much greater depositional rates in the Miocene, Pliocene and Pleistocene (Solis, 1981). The depocenter of Pleistocene sediments was located offshore from the Texas/Louisiana border according to Woodbury et al. (1973).

Growth faults originating in Tertiary sediments often penetrate the Beaumont, sometimes producing topographical features (Fig. 5). Verbeek et al. (1979) defined a growth fault as,

> "A fault along which movement occurs as sediments are deposited on and above the fault scarp. Continued movement and sedimentation over an extended

> period of time causes the oldest and lowermost sediments to be offset the most and causes the amount of offset to decrease upward within younger deposits."

Verbeek and Clanton (1981) suggested that these faults are everywhere subparallel to the coastline. The downthrown side is generally coastward. Growth faults, according to Kreitler (1976b), are commonly associated with high-mud delta systems where they form between the delta-front sands and the thick, prodelta muds. Bruce (1972) and Fisher et al. (1972) suggested that gulfward creep of the Cenozoic sediments enhances the formation of growth faults. Over 7,000 miles of lineations representing, in part, surface expressions of deep-seated growth faults occur in the Texas Coastal Zone (Fig. 6) (Kreitler, 1976a). No strain builds up in these poorly consolidated sediments; therefore, no seismic activity occurs along these faults.

Faults resulting from the emplacement of salt domes also cut the Beaumont Formation in local areas. Many active faults in the Houston area are located near producing oil or gas fields (Verbeek and Clanton, 1981).

The Beaumont, then, was deposited in a fluvial-deltaic depositional system during the last interglacial high stand of the sea. Relict features of this depositional system, including meander-belt ridges and point bars, distributary channels, overbank, interdistributary and flood basin deposits are present on the surface in the Houston area (Fig. 7). Vertisols have formed on the smectite-rich muds of these deposits. Topographic features on the Beaumont include meander-belt ridges and fault scarps. According to Aronow (1990, p. 3),

> "Modern analogues [of the Beaumont] are the combined Holocene floodplains of the Colorado and Brazos Rivers, and

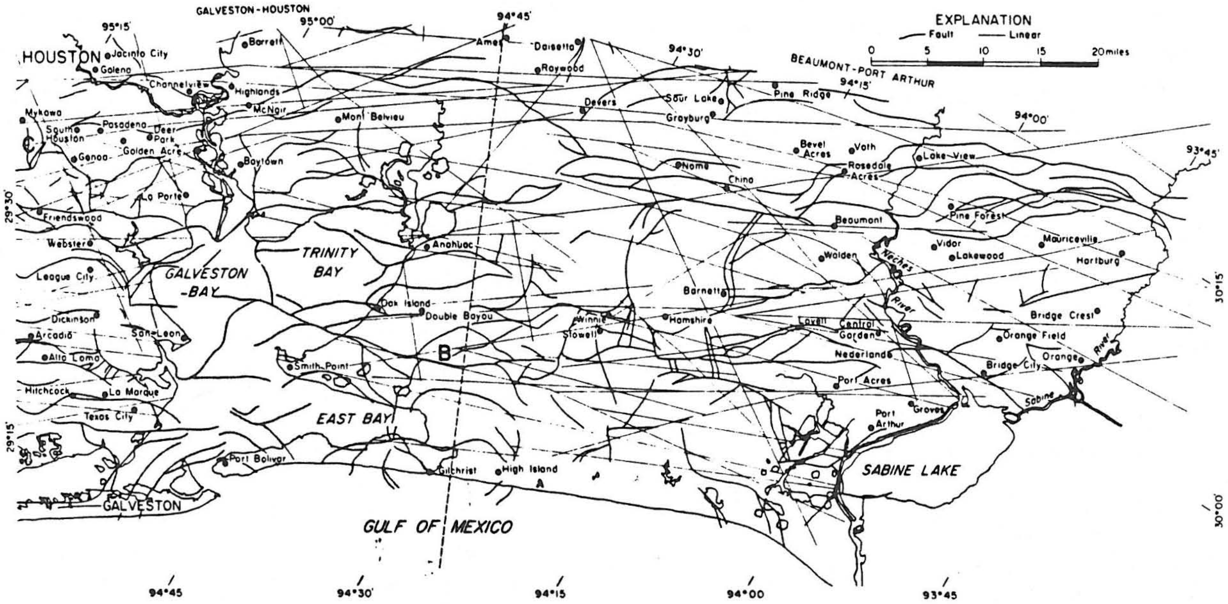


FIGURE 6. Lineations and surface traces of faults extrapolated from the Frio Formation (Oligocene), Galveston Bay to the Neches River (Kreitler, 1976b).

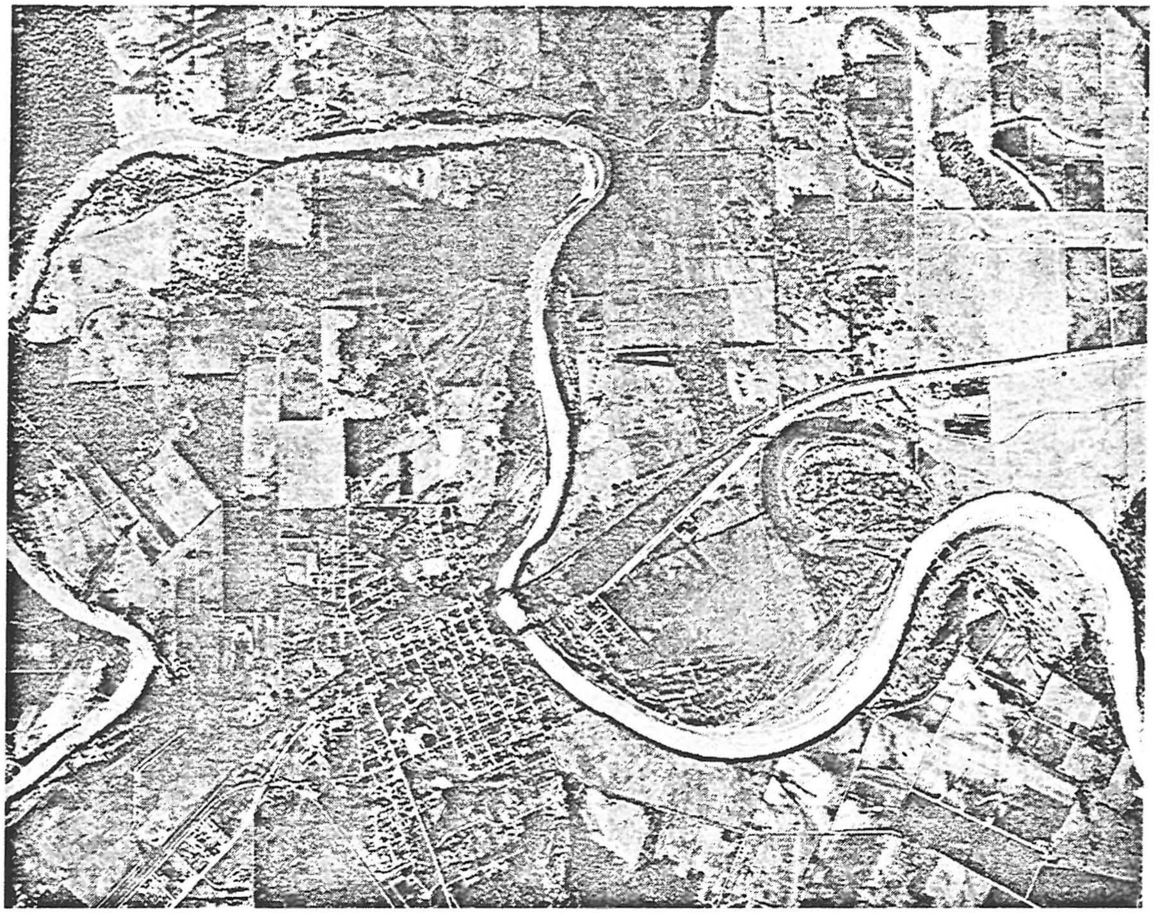


FIGURE 7. Recent Brazos River point bar near Richmond, Texas just west of Houston.

the Holocene alluvial plain of the Rio Grande with its well-preserved numerous resacas (abandoned channels)."

ENVIRONMENTAL HAZARDS ASSOCIATED WITH THE BEAUMONT

The Houston-Galveston area is subject to many environmental hazards as a result of being sited on the Beaumont Formation. Subsidence, faulting, expansive soils and increased risk of flooding are natural hazards that are readily recognized in the Houston-Galveston area. The human presence in the Texas Coastal plain has, however, accelerated the rate at which these natural processes proceed.

Subsidence

Natural subsidence occurs along the Texas Coastal plain due to: 1) dewatering and compaction of clay-rich sediments (Morton & McGowen, 1980); 2) slow basinward migration of the Cenozoic sedimentary clastic wedge (Elsbury et al., 1981; Delflache, 1980); and 3) tectonic subsidence due to structural warping related to the isostatic adjustment of sediment loading (Morton & Nummedal, 1982).

Although natural subsidence is important on a geological time scale, increased subsidence rates from ground water withdrawal (Gabrysch and Bonnet, 1975,) and hydrocarbon production (Holzer and Bluntzer, 1984) have importance in local areas and produce a much greater effect than natural subsidence (Morton & McGowen, 1980; Ratzlaff, 1982). The pumping of large amounts of water for municipal, industrial, and agricultural uses has caused the ground water level in the region's two major aquifers, the Chicot and Evangeline, to decline hundreds of feet (Fig. 8) (Gabrysch and Bonnet, 1975). These aquifers, along with other minor aquifers, represent some of the most prolific sources of fresh water in the United States (Solis, 1981; McGuiness, 1963). In the Houston-Galveston area, as much as 500 million gal/day was pumped from these aquifers at average rates of 1,600 gal/min. Weaver and Sheets (1962) noted that until 1940 all water supplies in the Houston area were from wells.

The Gulf Coast aquifer has been described as a complex, gulfward-dipping series of sands and shales (Solis, 1981). In hydrologic terms, Muller and Price (1979) and Gabrysch (1991) describe it as a leaky, artesian system. Leaky artesian conditions occur when aquifers which dip at an angle are overlain by confining beds or aquitards (the Beaumont in this case). These aquitards impede but do not prevent vertical flow. Heavy pumping from a leaky artesian system decreases the hydrostatic pressure in the water-bearing sands, thus setting up a pressure gradient. Water from

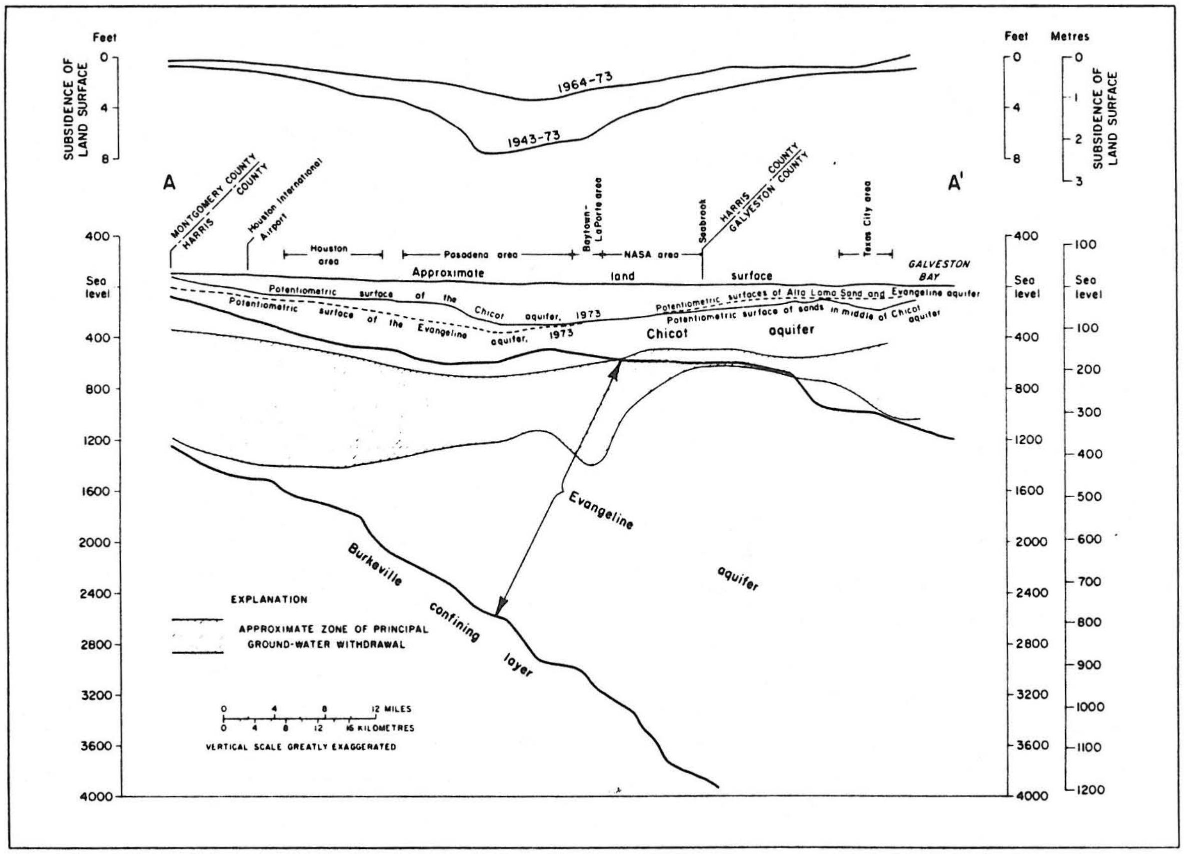


FIGURE 8. Hydrologic profile showing aquifers, principal zones of ground water withdrawal, altitudes of the potentiometric surfaces, and land-surface subsidence (Gabrysch and Bonnet, 1975).

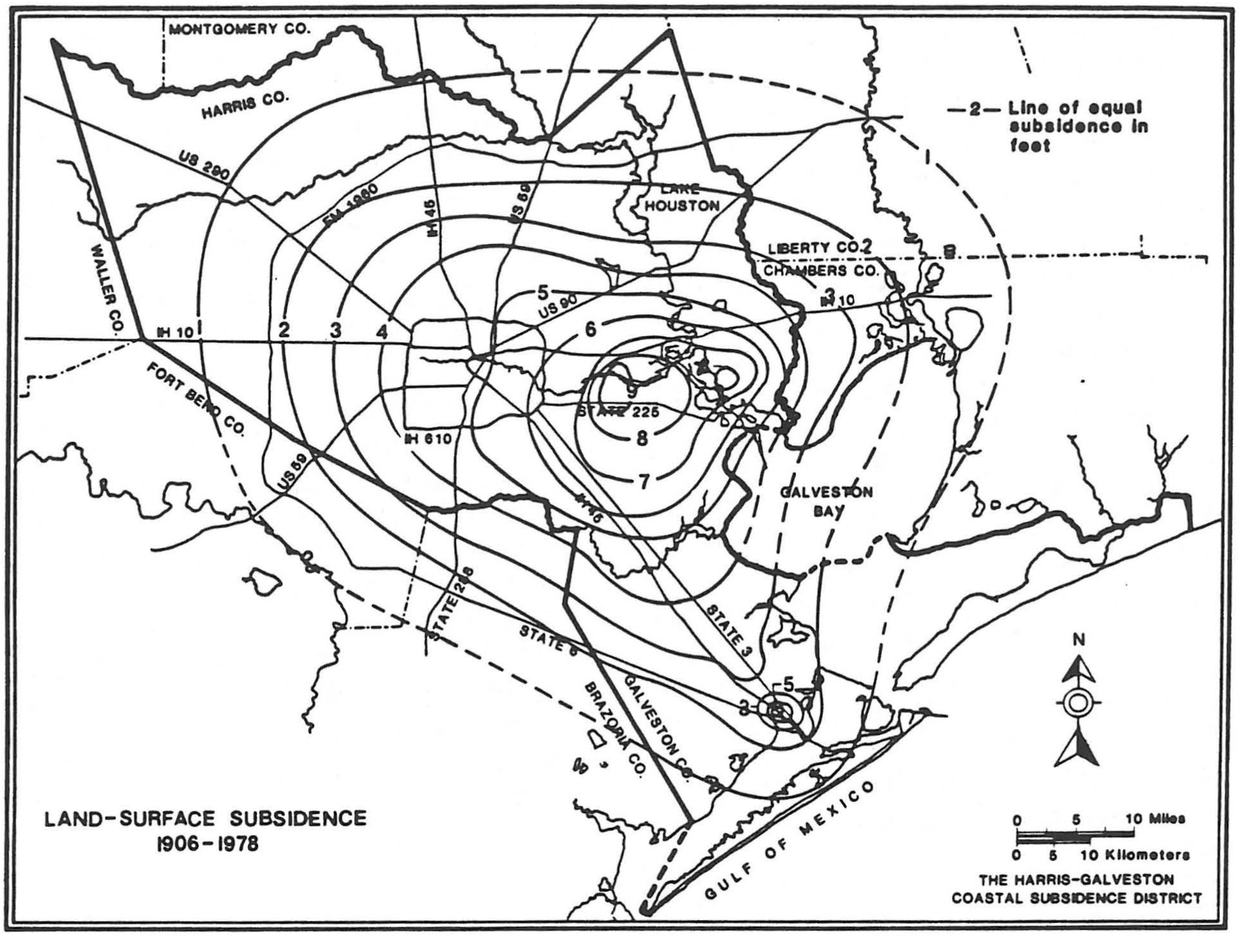


FIGURE 9. Land-surface subsidence in the Houston, Texas area from 1906 to 1978 (Harris-Galveston Coastal Subsidence District, 1981).

adjacent higher pressured clays then migrates into the sands. Upon loss of interstitial water, the clays collapse and compact, thereby losing volume. This reduction in the volume of clay results in subsidence at the surface (Muller and Price, 1979). Jorgensen (1975, p. 49) stated that,

> "the volume of water derived from compaction of clay is very nearly equal to the volume of subsidence in the Houston district because nearly all subsidence is related to ground water pumpage from the Chicot and Evangeline aquifers."

Winslow and Wood (1959) determined that approximately 22 percent of the ground water pumped from the these aquifers in the Houston vicinity was derived from clays. Gabrysch and Bonnet (1975) estimated that 55 percent of the subsidence in southern Harris County results from compaction within the Chicot Aquifer.

By 1975 more than 9 feet of subsidence had occurred along the Houston Ship Channel area (Fig. 9). The Clear Lake area, including the Johnson Space Center, had lost over 4 feet of elevation and nearly all of the Houston-Galveston area had sunk at least 1 foot. The Harris and Galveston Coastal

Subsidence District was created in 1975 to control the use of ground water in the two-county district. From 1978 to 1987 the eastern area of Harris County (including the Ship Channel area) experienced less than 0.5 foot of subsidence while a portion of northwest Harris County subsided in excess of 2 feet. The reduction in subsidence in eastern Harris County has been brought about by conversion to surface water provided by the Trinity and San Jacinto Rivers. During the mid 1970s, total groundwater pumpage in the Houston-Galveston area approached 500 million gal/day. In 1989 total pumpage was less than 360 million gal/day. This decrease in groundwater pumpage has occurred in spite of the industrial and population growth of the area. By 1973, water-level declines in the Chicot Aquifer had reached 300 feet in the Ship Channel area. Since 1977, however, water level increases of as much as 180 feet have been recorded in wells in the Ship Channel area.

Major environmental impacts of subsidence include 1) loss of elevation, 2) activation of growth faults, and 3) activation of faults associated with the formation of salt domes.

Loss of elevation in a low-lying coastal region creates problems of saltwater flooding due to coastal storms, unusually high tides or high winds.

> "...[E]ach incremental loss of elevation subjects more coastal land along bays and estuaries to complete inundation from marine waters and intermittent inundation from both hurricane surges and unusually high tides" (Kreitler, 1976a, p. 1).

In 1961, Hurricane Carla flooded 123 square miles of the Houston-Galveston area. Kreitler (1976a) estimated that 25 percent more land would be flooded in 1976 if a similar hurricane were to hit the coast (Fig. 10). The inundation of this additional land would be due to the subsidence which occurred between 1961 and 1976. The author further predicted that an additional 10 feet of subsidence would inundate 50% more land than Carla did in 1961 (Fig. 11).

Serious drainage problems associated with freshwater flooding occur in the Houston-Galveston area where loss of elevation landward from the coast occurs. The Houston-Galveston area is covered by impermeable clays which produce high runoff rates, drained by tidally-influenced bayous which sometimes experience landward flow and according to Solis (1981) the gradient is as low as 1.5 feet/mile. Subsidence in such an area accentuates the flooding potential.

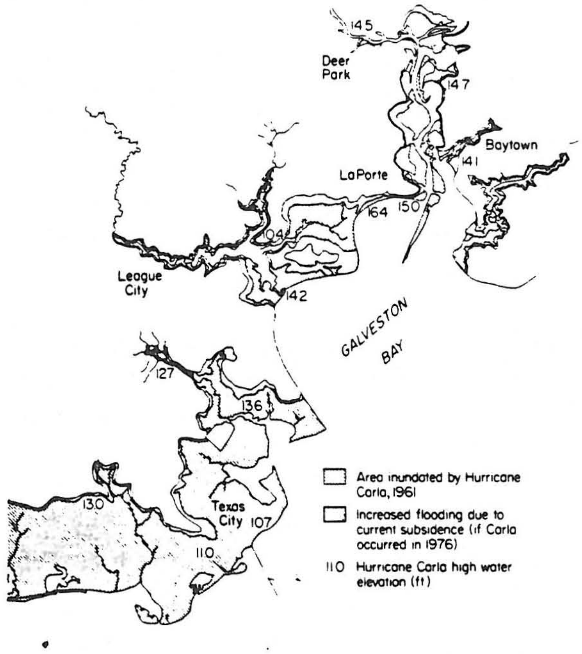


FIGURE 10. Land inundated by Hurricane Carla in 1961 and the land that would be inundated by a Carla-sized hurricane in 1976 (Kreitler, 1976a).

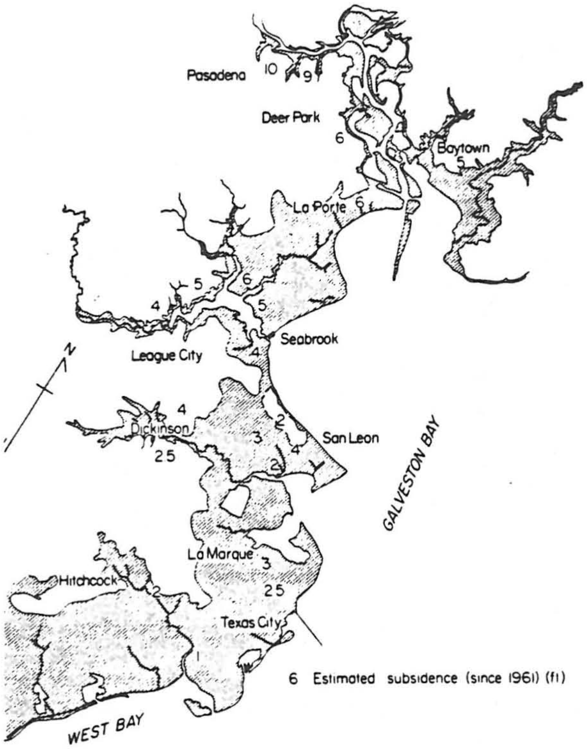


FIGURE 11. Land that would be inundated by a Carla-sized hurricane if an additional 10 feet of subsidence occurred since 1961 (Kreitler, 1976a).

In addition to both marine and freshwater flooding hazards, ground water pumping and the accompanying subsidence has been tied to the activation of regional Tertiary growth faults and local faults associated with salt domes (Brown et al., 1974).

Faulting

More than 60 years ago, Pratt and Johnson (1926) described fault activity associated with oil production at the Goose Creek oil field in Baytown. However, it has only been the last 20 years or so that faults in the Houston-Galveston area have been recognized by the public as an important geologic hazard (Everett and Reid, 1981).

Today, extensive active faults are damaging subsurface utilities (Clanton and Amsbury, 1975), pavements and buildings (Elsbury and Van Siclen, 1983), runways and railroad lines (Clanton and Verbeek , 1981; Elsbury et al., 1981) and other man made structures within the Houston-Galveston area (Fig. 12). Contemporary rates of movement on many of these faults is in the range of 0.5 to 2.0 cm/yr (Verbeek and Clanton, 1978). Everett and Reid (1981) suggested the rates of movement on many of the faults in Houston exceed 1.5 inches per year. Vertical displacements of as much as 0.8 in/year have been measured along sections of the Long Point Fault (Elsbury et al., 1981). Kreitler (1976a) noted that at least 150 miles of active faults with topographic escarpments are present in the Houston-Galveston area. According to Elsbury and Van Siclen (1983), however, Harris County alone is crossed by 205 miles (330 km) of known active or potentially active surface faults.

As previously discussed, subsidence has been implicated in the activation of both growth faults and local faults associated with salt domes. Kreitler (1976b) observed that, in turn, faults can work to compartmentalize subsidence, thus forming structurally controlled subsidence basins. The author cited the Texas City area which has experienced over 5 feet of subsidence as an example. Subsidence in this case, according to Kreitler, has been confined on two sides by fault control. On the northern side, an extrapolated subsurface fault with no topographic escarpment controls the lateral migration of subsidence. The southern side is controlled by a fault with a mappable scarp. This fault prevents the migration of subsidence in Texas City to the Galveston area.

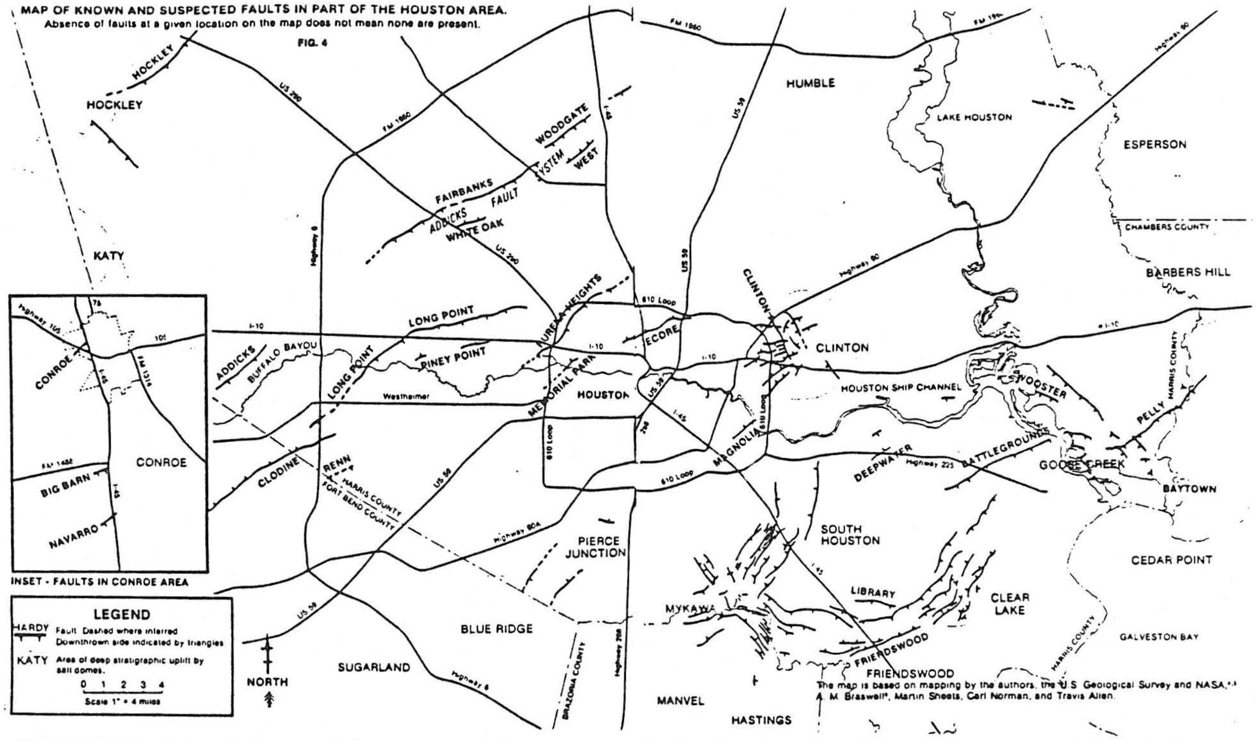


FIGURE 12. Map of known and suspected faults in the Houston area (Verbeek and Clanton, 1981).

Expansive Soils

Soils in the southern half of Harris County are predominantly Vertisols that have formed on the Beaumont Formation. Cracked foundation slabs, buckled pavement, undulating road surfaces, broken curbs and tilted utility poles are evidence of the expansive nature of these soils (Gustavson, 1975). Millions of dollars are spent each year in attempts to remediate damages resulting from expansive soils.

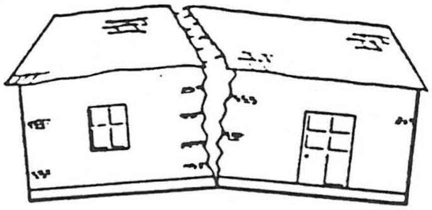
According to Olive et al. (1989) environmental/engineering problems in areas underlain by expansive soils are caused by volume changes in swelling clays resulting from human activities that modify the local environment. Such activities include construction of slab foundations (Mathewson et al., 1975; Mustafayev, 1988), basements (Chen and Huang, 1988), airport runways, canal linings and pavements (Christodoulias and Gasios, 1988; Livneh and Ishai, 1988) and emplacement of utility lines in the subsurface. According to Williams (1965), damage is the result of differential vertical movement in the clay as moisture levels in the clay adjust to new environmental conditions. Expansive soil movements are greatest near the ground surface and generally diminish to nothing between 5 and 30 feet underground (Jones and Holtz, 1973). In addition to vertical displacement at the surface, cyclic expansion and contraction of the soil and localized heaving also produce damage in manmade structures (Lamar and Laier, 1988; Gustavson, 1975).

Mathewson et al. (1975, p. 276) stated,

> "The average total yearly loss from earthquakes, hurricanes, tornadoes, and floods is only half that from expansive soils."

According to a National Science Foundation (1978) study only riverine floods surpass the average annual losses due to expansive soils. Jones and Holtz (1973) have set the annual losses at approximately $2.3 billion. These investigators stated that, within the United States, annual loss to single-family homes due to structural damage from expansive soils has been approximately $300 million. Loss due to expansive soils was estimated by Griggs and Gilchrist (1983) to be $7.2 billion annually. Chen (1988) stated that the projected annual loss, by the year 2000, in the United States due to expansive soils will exceed $4.5 billion. Regardless of the precise figure, the costs associated with remediating damages incurred as a result of expansive soils is several billions of dollars annually.

Precautions homeowners can take to minimize damage from expansive soils include: 1) maintaining proper drainage to prevent ponding of water near the house; 2) preventing desiccation of soil by trees (Perpich et al., 1965); and 3) maintaining moist soil conditions around and under the foundation at all times. Watering the foundation of a home in the Houston area takes precedence over watering vegetation. Loss of moisture around the periphery during the dry season will cause shrinkage and contraction, resulting in cracking and settlement of the edges of the slab. Conscientious homeowners commonly lay soaker hoses around the foundation in an attempt to keep the perimeter of the slab from drying and shrinking (Mathewson et al., 1975).



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LEG 1

EXPANSIVE SOILS IN HARRIS COUNTY, TEXAS: LAKE CHARLES AND MIDLAND SERIES

Douglas W. Ming
NASA Johnson Space Center

HARRIS COUNTY, TEXAS

The city of Houston resides in Harris County, which is located in the southeastern part of the state (Fig. 1-1). The population of the county is over 2 million and the county covers 1,765 square miles. The majority of the county is urban land.

The climate of Harris County is predominantly marine. Prevailing winds are from the southeast and south, except in the winter when high pressure systems

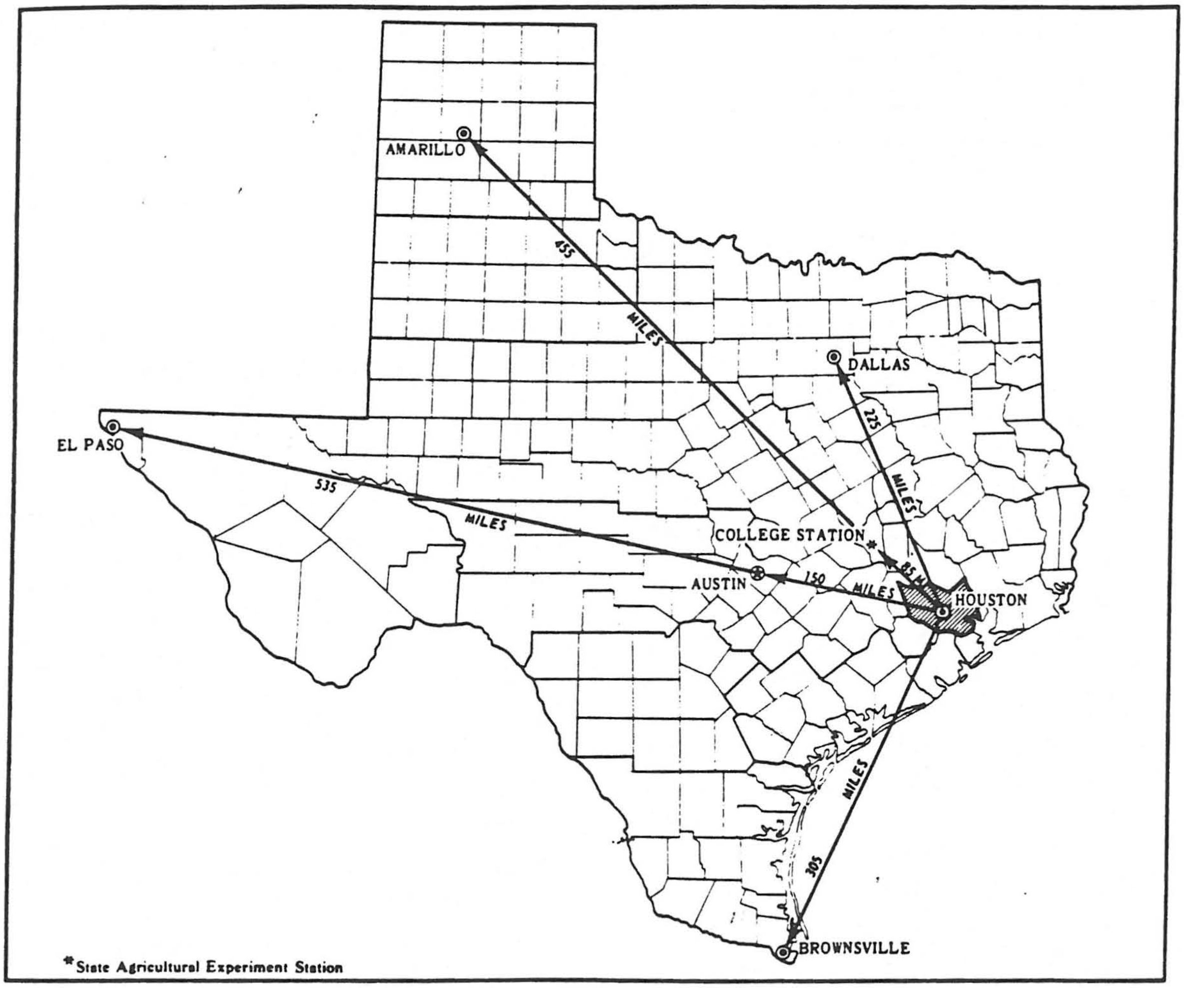

FIGURE 1-1. Location of Harris County in Texas.

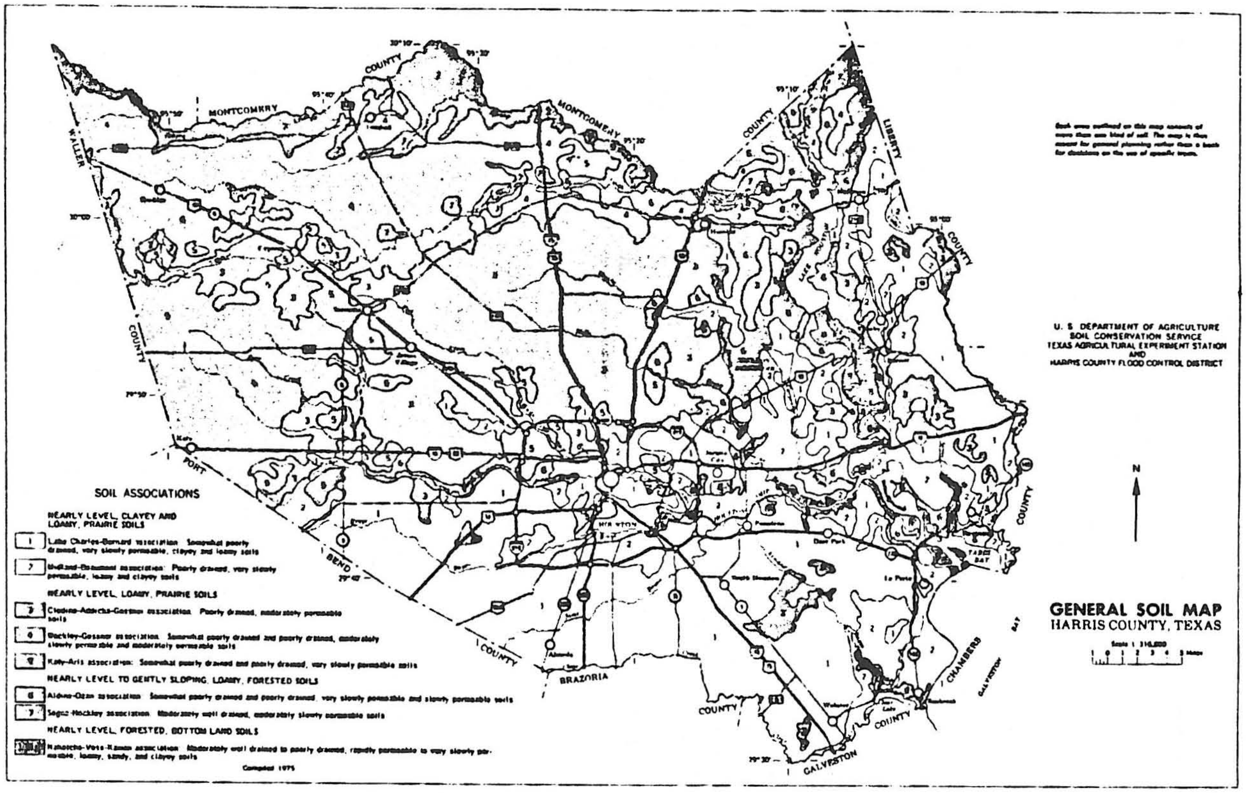

FIGURE 1-2. General soils map of Harris County, Texas.

move down from the north and bring prevailing northerly winds. The climate of the county is influenced by the close proximity of the Gulf of Mexico, which results in fairly mild winters and abundant rainfall (mean average of 46 inches annually). Summers are warm and humid.

The soils of the county have been grouped into four general landscapes: (i) nearly level, clayey and loamy, prairie soils; (ii) nearly level, loamy, prairie soils; (iii) nearly level to gently sloping, loamy, forested soils; and (iv) nearly level, forested, bottom land soils (Soil Conservation Service, 1976). The landscape group of greatest concern for its environmental hazards due to clays is the nearly level, clayey and loamy, prairie soils. The two expansive soils (Lake Charles and Midland) that we will look at on this field trip fall into this category (Fig. 1-2). This group makes up about 39 percent of the county. They have a clayey or loamy surface layer and clayey underlying layers. The soils that have clayey surfaces layers (predominantly Vertisols) have large cracks on the surface when dry. The clayey underlayer has a high shrink-swell potential.

The soils on the nearly level, clayey and loamy, prairie landscapes have severe limitations for urban use. Nevertheless, a large portion of these soils in the county lie within the city of Houston. These soils are covered by buildings, streets, and large industrial complexes. The greatest management concern for these soils is the high shrink-swell potential. Cracked foundation slabs, buckled pavement, broken curbs, and tilted utility poles are common in the

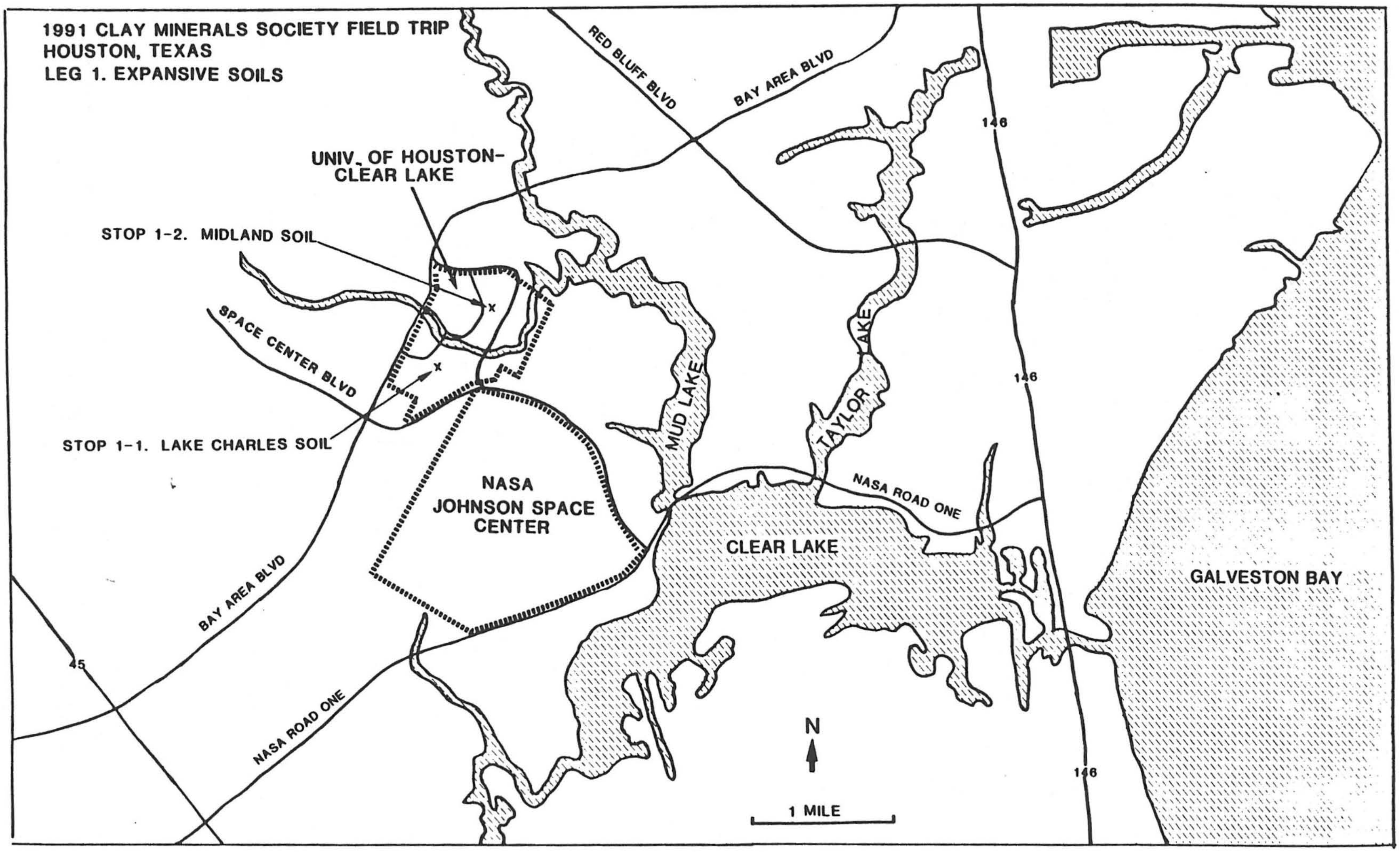

FIGURE 1-3. Location of Lake Charles and Midland soil profiles in southern Harris County.

southern part of the county where these soils are found. It is also difficult to establish gardens and lawns because of the high clay content of these soils.

STOP 1-1 Lake Charles Clay

The Lake Charles series soil is located on the grounds of the University of Houston-Clear Lake (Fig. 1-3). The soil is a Vertisol and classified as Typic Pelludert (Table 1-1). The Lake Charles series consists of deep, nearly level to gently sloping, clayey soils on upland prairies. Because they are Vertisols, these soils are clayey throughout the profile and have wide cracks when dry. These soils are also characterized by intersecting slickensides within the profile. Undisturbed areas of these soils have gilgai microrelief. These soils are somewhat poorly drained and runoff is slow. Because of their high clay content, these soils have very low permeability.

The mineralogy of the coarse fractions of the Lake Charles soil is predominantly quartz with minor amounts of feldspar. The lower horizons contain calcium carbonate which reflect the calcareous parent material in which these soils have formed (Fig. 1-4). The clay fraction of the Lake Charles soil is predominantly smectite with minor amounts of mica and kaolinite present (see Figs. 1-5 & 1-6). There is very little variation in clay mineralogy within the profile.

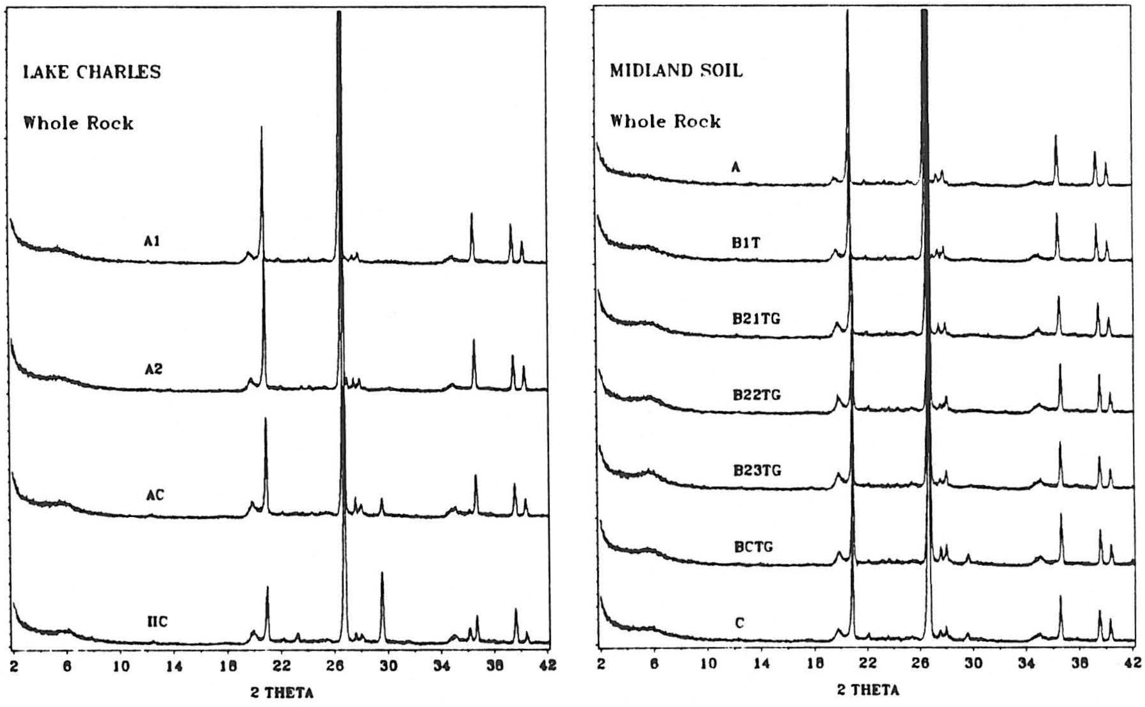

FIGURE 1-4. X-ray diffractograms of whole soils for the Lake Charles and Midland soils (Cu-Kα radiation). The coarse fractions of these soils is predominantly quartz with minor amounts of feldspar. Carbonates are present in the lower horizons.

TABLE 1-1. Profile description for the Lake Charles soil.

SOIL SERIES: Lake Charles clay

CLASSIFICATION: Fine, montmorillonitic, thermic Typic Pelludert

LOCATION: Harris County, Texas; from the junction of Bay Area Boulevard and University Drive in far Southeast Houston, 0.1 miles southeast on University Drive, 0.1 miles southwest on paved road, 0.2 miles southeast through parking lot G of the Arbor Building on the campus of the University of Houston-Clear Lake, 250 feet south of parking lot in a clearing in wooded area.

DRAIN. & PERM.: Poorly drained; very slow runoff; very slow permeability.

GEOLOGIC UNIT: Beaumont Formation, Tertiary

SAMPLED: July 20, 1987

SAMPLED BY: D. Ming, T. Garcia

REMARKS: Soil is located on level broad upland area. Elevation is about 15 feet.

HORIZON	**DEPTH** (cm)	**PEDON DESCRIPTION**
A11c	0-53	Dark gray (10YR 4/1) clay; black (10YR 2/1) moist; moderate fine blocky and subangular blocky structure; very hard, very firm; few fine and medium roots; shiny pressure faces; many thin continuous clay films; few fine brown, black, and red concretions; slightly acid; diffuse wavy boundary.
A12c	53-117	Dark gray (10YR 4/1) clay; very dark gray (10YR 3/1) moist; common large wedge-shaped peds have long axis tilted 15 to 50 degrees from the horizontal and bordered by large intersecting slickensides parting to moderate medium blocky and subangular blocky structure; extremely hard, very firm; shiny pressure faces; many fine black, brown, and red concretions; slightly acid; diffuse wavy boundary.
ACc	117-137	light gray (2.5Y 7/2) clay; gray (2.5Y 6/2) moist; common medium distinct brown, yellowish brown, and mottles; common large wedge-shaped peds have long axis tilted 15 to 50 degrees from the horizontal and bordered by large intersecting slickensides parting to moderate medium blocky structure; extremely hard, very firm; shin pressure faces; many fine and medium black and brown concretions; common fine pitted strongly cemented $CaCO_3$ concretions; mildly alkaline; diffuse wavy boundary.
2C	137-160	Reddish yellow (7.5YR 6/6) clay; strong brown (7.5YR 5/6) moist; few dark gray (10YR 4/1) vertical streaks to 2 cm wide that are apparently filled cracks; structureless massive; extremely hard; very firm; many fine to coarse pitted strongly cemented $CaCO_3$ concretions; alkaline and calcareous.

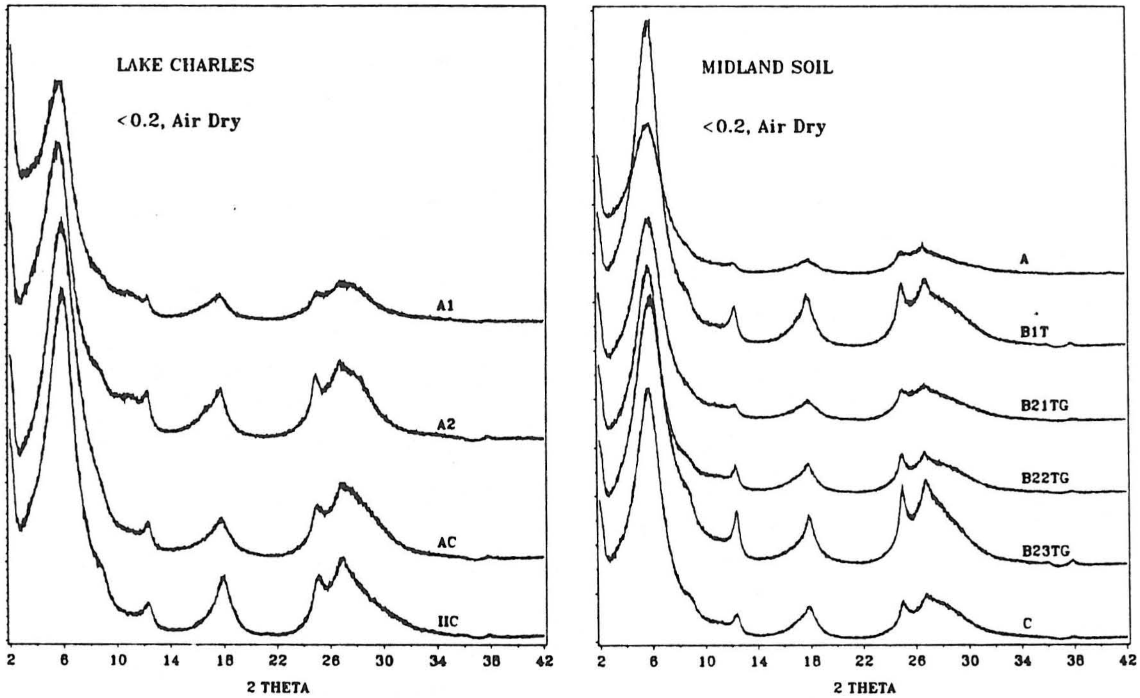

FIGURE 1-5. X-ray diffractograms for the < 0.2 µm Mg-saturated clay fractions for the Lake Charles and Midland soils (Cu-Kα radiation).

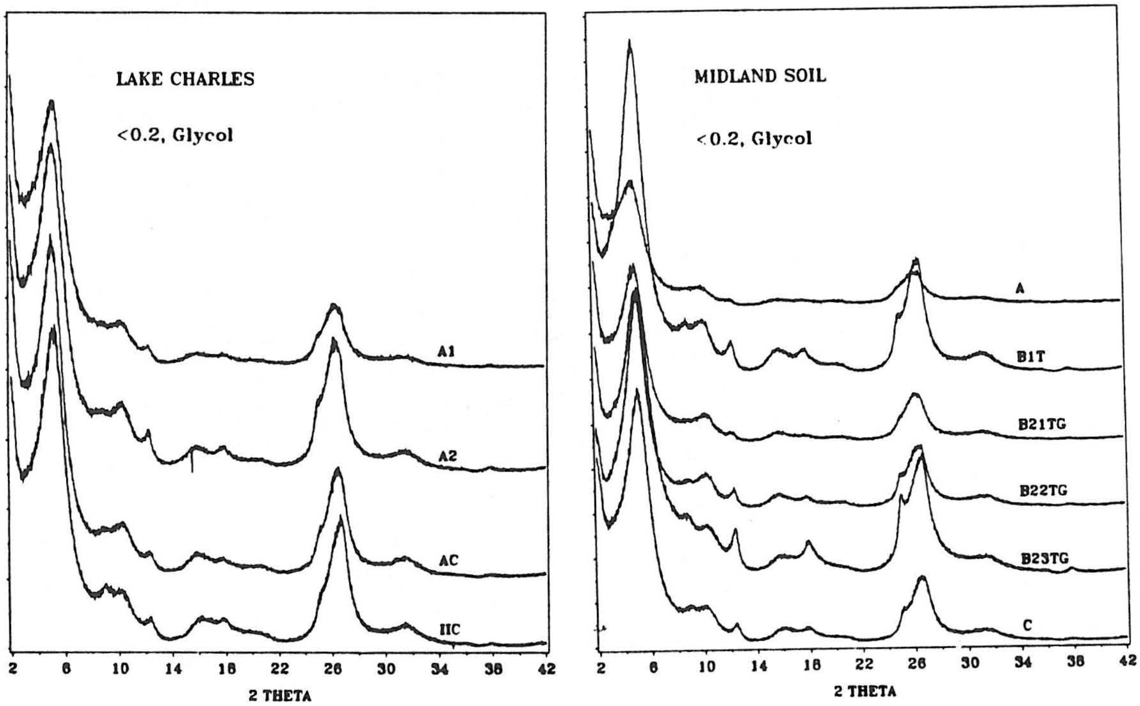

FIGURE 1-6. X-ray diffractograms for the < 0.2 µm Mg-glycol clay fractions for the Lake Charles and Midland soils (Cu-Kα radiation). The clay fraction is predominantly smectite with minor amounts of kaolinite and mica present.

STOP 1-2 Midland Clay

The site of the Midland series soil is also located on the grounds of the University of Houston-Clear Lake (Fig. 1-3). The soil is an Alfisol and is classified as a Typic Ochraqualf (Table 1-2). Similar to the Lake Charles soil, the Midland soil has a high clay content; however, the Midland has a loamy surface horizon and a very well developed argillic horizon. The argillic horizon does have some distinct slickensides that do not intersect. These soils are also poorly drained and have very slow surface runoff. Permeability is very slow. Because of the high clay content in the argillic horizon, these soils have high shrink/swell characteristics and therefore, this series has severe limitations for urban development.

The mineralogy of the coarse fraction of the Midland soil is nearly identical to that of the Lake Charles soil (Fig. 1-4). The coarse mineralogy is dominated by quartz with minor amounts of feldspar. Small amounts of carbonates are present in the BC and C horizons. The clay mineralogy is predominantly smectite with minor amounts kaolinite and mica present (Figs. 1-5 & 1-6). The Midland soil has very little variation in mineralogy throughout the profile.

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TABLE 1-2. Profile description for the Midland soil.

SOIL SERIES:	Midland variant
CLASSIFICATION:	Fine, montmorillonitic, thermic Typic Ochraqualf
LOCATION:	Harris County, Texas; from the junction of Bay Area Boulevard and University Drive in far Southeast Houston, 0.5 miles southeast on University Drive, 0.5 miles northeast on Bayou Road, 0.1 miles east on paved road, 0.3 miles southeast on dirt road; 40 feet north of dirt road in a clearing in wooded area.
DRIAN. & PERM.:	Poorly drained; very slow runoff; very slow permeability.
GEOLOGIC UNIT:	Beaumont Formation, Tertiary.
SAMPLED:	August 5, 1987
SAMPLED BY:	D. Ming, T. Garcia
REMARKS:	Soil is located on level broad upland area. Elevation is about 15 feet.

HORIZON	DEPTH (cm)	PEDON DESCRIPTION
A	0-18	Dark grayish brown (10YR 4/2) silty clay loam; very dark grayish brown (10YR 3/2) moist; weak medium subangular blocky structure; very hard, friable; fine distinct dark brown mottles; many fine and medium roots; moderately acid; smooth clear boundary.
BAc	18-51	Dark gray (10YR 4/1) silty clay; very dark gray (10YR 3/1) moist; weak medium and coarse subangular blocky structure; very hard, firm; common fine and medium roots; few fine brown and black concretions; slightly acid; gradual smooth boundary.
Btgc1	51-64	Grayish brown (10YR 5/2) clay; dark grayish brown (10YR 4/2) moist; moderate medium subangular blocky structure; extremely hard, very firm; few fine roots; few fine brown and black concretions; common distinct reddish brown mottles; common thin continuous clay films; slightly alkaline, noncalcareous; gradual smooth boundary.
Btgc2	64-79	Gray (10YR 5/1) clay; dark gray (10YR 4/1) moist; moderate medium subangular blocky structure; extremely hard, very firm; few fine roots; few fine black and brown concretions; common distinct reddish brown mottles; common thin continuous clay films; slightly alkaline, noncalcareous; gradual smooth boundary.
Btgc3	79-94	Light brownish gray (10YR 6/2) clay; grayish brown (10YR 5/2) moist; moderate medium subangular blocky structure; extremely hard, very firm; few fine roots; few fine black and brown concretions; common fine distinct dark brown mottles; common thin continuous clay films; distinct slickensides 10 cm across that do not interest; few dark gray (10YR 4/1) vertical streaks to 2 cm wide that are apparently filled cracks; few fine strongly cemented $CaCO_3$ concretions; slightly alkaline, noncalcareous matrix; gradual wavy boundary.
BCtgc	94-114	Light gray (10YR 7/2) clay loam; light brownish gray (10YR 6/2) moist; weak coarse angular blocky structure; extremely hard, very firm; few black and brown concretions; common medium gray mottles; few dark gray (10YR 4/1) vertical streaks to 2 cm wide that are apparently filled cracks; distinct slickensides 10 cm across that do not interest, common fine and medium strongly cemented $CaCO_3$ concretions; slightly alkaline, calcareous; gradual wavy boundary.
C	114-145	Light gray (10YR 7/1) clay loam; light gray (10YR 7/2) moist; structureless massive; very hard, very firm; many fine to coarse pitted strongly cemented $CaCO_3$ concretions; calcareous; slightly alkaline.

LEG 2

NASA
LYNDON B. JOHNSON SPACE CENTER*

BACKGROUND

In May 1961, President John F. Kennedy challenged the Nation to an ambitious space program that would put a man on the Moon before the end of the decade. NASA's Space Task Group at Langley Research Center, Virginia, needed more room to do the job of turning the dream into reality. By July, NASA had drawn up the criteria for a new space center. The site had to provide these essentials: availability to water transport, a convenient military base, a commercial jet airport, an established university specializing in science and space-related research, a major telecommunications network, a pool of contractor and industrial support, adequate water and energy supplies, a mild climate year round, a culturally active community, and at least four square kilometers to build on.

After an investigation of many prospective locations around the United States, a 1620-acre site near Houston, Texas, was selected. In September 1961, it was announced that the Manned Spacecraft Center should be built on prairie land 25 miles southeast of downtown Houston, Texas, near Ellington Air Force Base, and on the shore of Clear Lake, an inlet of Galveston Bay. Much of the land had been donated to NASA by Rice University.

Personnel of the Space Task Group began moving to the Houston area where they worked in temporary facilities while construction of the new center progressed. On July 4, 1962, Houston threw the biggest parade and barbecue in its history to honor the arrival of the seven original astronauts. The Manned Spacecraft Center officially opened in September 1963, and was renamed in honor of the late President Lyndon B. Johnson in February 1973.

The facilities are designed and built to house the wide variety of technical and scientific disciplines required for the Center's mission. JSC is organizationally divided into several directorates, with each directorate responsible for a specific function, such as, spacecraft development, astronaut training, or space flight planning, for example. The system is flexible and the directorates are frequently realigned to keep pace with the changing directions and dimensions of manned space flight. Some of the original JSC directorates have reorganized, merged, or split into separate groups; new directorates are created as needed. Directorates are responsible to the Center Director who, in turn, is responsible to the Office of Space Flight at NASA Headquarters in Washington, D.C.

Today, more than 95 astronauts are among the 3500 Federal employees at JSC. Another 10000 contractor personnel work at or near JSC to support Center operations Fig. 2-1).

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*NASA Facts, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas

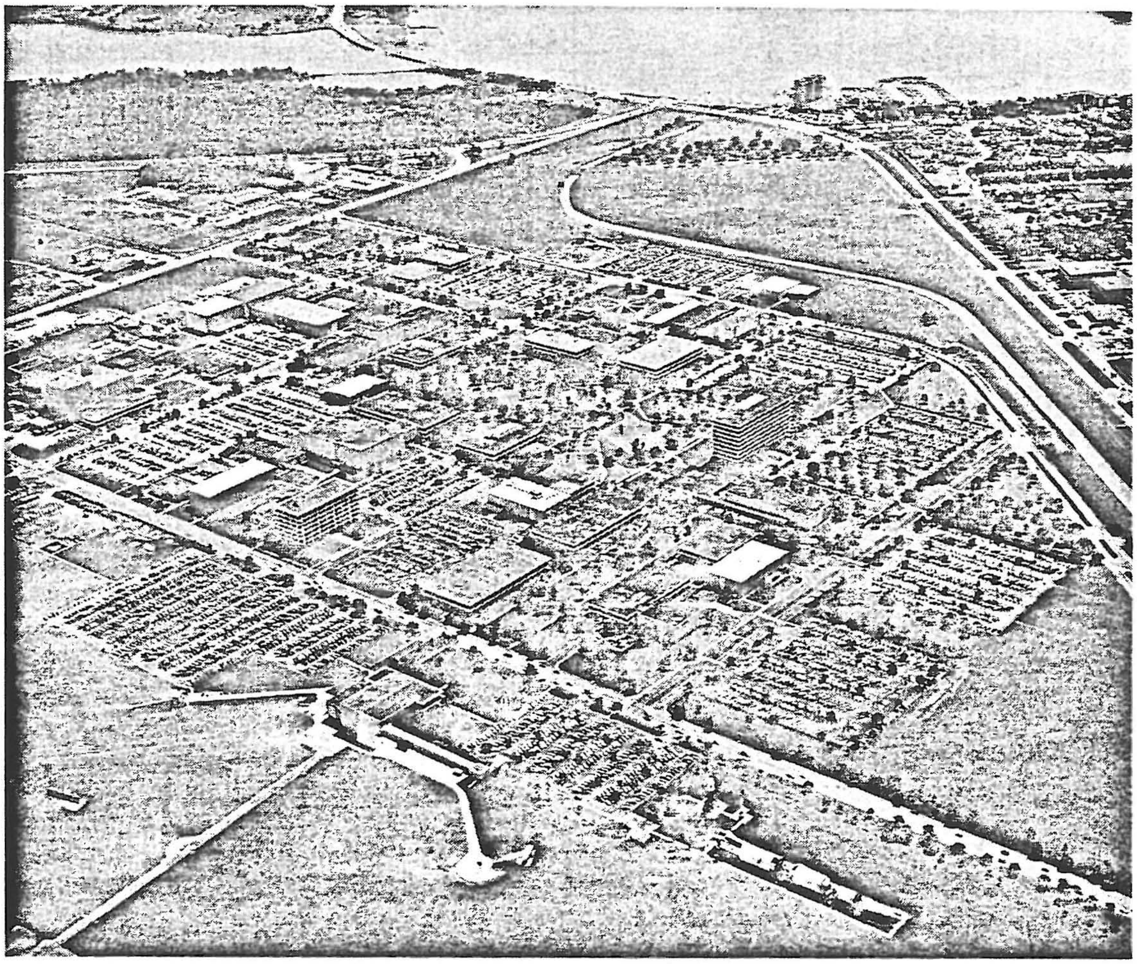

FIGURE 2-1. Aerial view of the Lyndon B. Johnson Space Center located on the shore of Clear Lake in far southeast Houston, Texas (NASA Photo S89-41404).

MISSION

As the focal point for America's manned space flight programs, the JSC mission includes:

- -design, development, and testing of spacecraft and associated systems for manned space flights;
- -a major role in the development of a permanently manned space station;
- -selection and training of astronauts and mission specialists and training of payload specialists;
- -participation in the areas of medical, scientific, and engineering experiments.

As part of its responsibility for the Space Transportation System (STS), JSC operates a Customer Integration Office for managing the integration of the customer's payload into the STS. The customer may be NASA, the Department of Defense, or commercial organizations. A payload integration manager is assigned to each customer to serve as a single point of contact between the customer and the STS for technical integration.

JSC maintains aircraft at nearby Ellington Field for astronaut training, research programs, and administrative travel. The space center also operates the White Sands Test Facilities at Las Cruces, New Mexico, where propulsion systems tests are conducted.

The scope of the Space Shuttle program is a worldwide project. Hundreds of contractor and subcontractor firms throughout the United States and Canada provide Space Shuttle hardware and software. Space Agencies in Europe develop certain experiments and equipment. Other NASA centers with Space Shuttle responsibilities include the John F. Kennedy Space Center in Florida for launch and recovery facilities, and Marshall Space Flight Center in Alabama for main engines, booster rockets, and external tanks.

FACILITIES

Of the over 100 buildings that comprise JSC, many contain equipment unique to spacecraft and manned space flight programs. Several of these buildings will be visited during the field trip.

STOP 2-1. Mission Control Center (Building 30)

Mission Control Center is a three-story building at JSC. In it are some of the most sophisticated communication, computer, data reduction, and data display equipment available. During Space Shuttle flights, operations are supported 24 hours daily by teams of engineers and technicians with a wide scope of specialized skills. Mission Control is supported by an emergency power building which houses generators and air-conditioning equipment for use if regular power fails.

In the event of some unforeseeable but catastrophic failure that prevents the Houston control center from continuing its support of the flight, an emergency facility at the White Sands Ground Terminal in New Mexico is activated. The emergency center provides only limited capability, incorporating just enough equipment to let the controllers support the flight to its conclusion. The key mission command and control position is the Flight Director, who is responsible for conduct of the overall mission and real-time decision making. The Ascent/Entry Flight Director directs the ascent and entry portions of the flight. The On-orbit Flight Directors are responsible for the phases of the mission such as payload deployment, experiment operations, and other mission objectives.

Focal points of the Mission Control Center are the Flight Control Rooms (Fig. 2-2). Here flight controllers get information from television-like screens on the consoles and rear-projected displays that fill the wall at the front of the room. One Flight Control Room is on the second floor and one is on the third floor. Only the third floor Flight Control Room is used for missions carrying Department of Defense payloads.

Either Flight Control Room can be used for mission control, or they can be used simultaneously to control separate flights. At times, one team of flight controllers may conduct an actual flight in one Flight Control Room while a second team is going through a simulation mission for a future operation.

The Flight Control Rooms occupy only a small portion of the Mission Control Center. A cadre of support

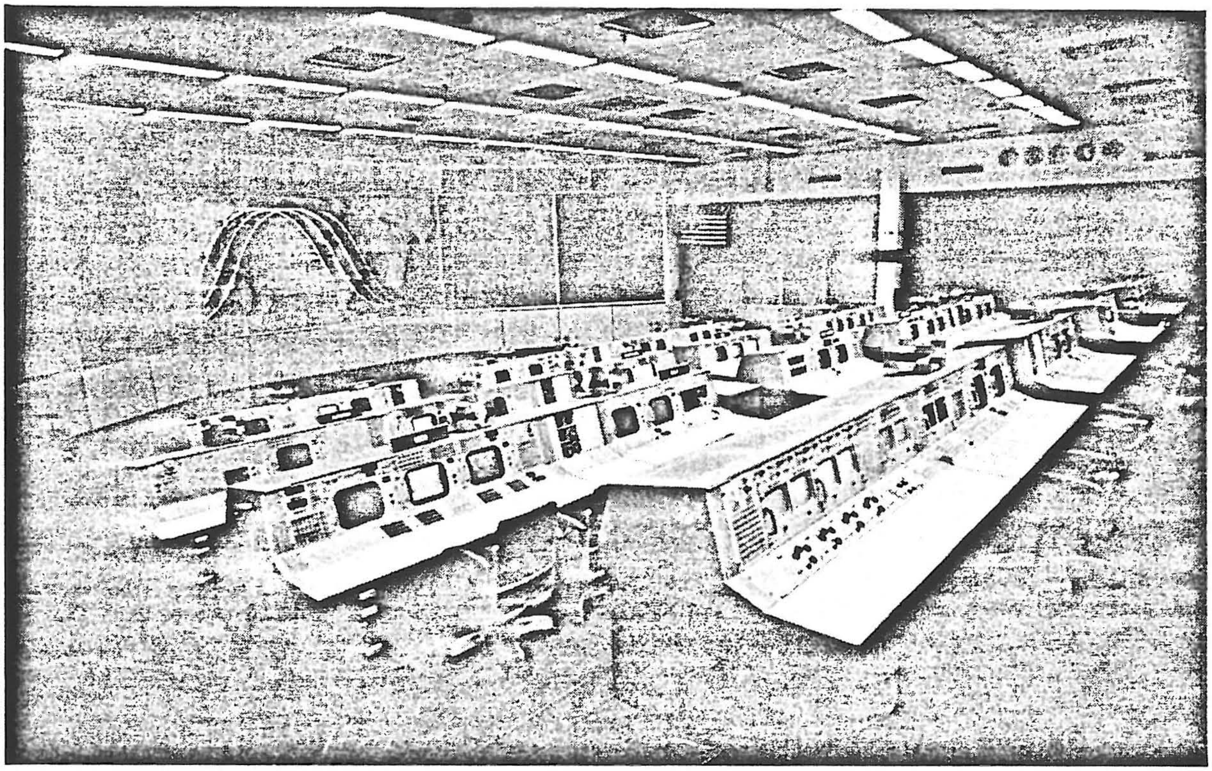

FIGURE 2-2. Flight Control Room located inside the Mission Control Building at the Johnson Space Center (NASA Photo S79-26821).

personnel are located in nearby support rooms where data on the mission are monitored and analyzed in detail. Multipurpose Support Groups representing separate support disciplines perform planning and support functions. Each room houses personnel that support the lead discipline controller, who is located in the Flight Control Room. These groups provide technical expertise for planning and real-time operations, responding quickly to any in-flight contingency.

Operating in conjunction with the JSC Mission Control Center are the customer support rooms. Here the owners of payloads, or other scientific experiments carried in the cargo bay of the Orbiter, can monitor and manage their payloads. It is a command post, communications center, and management interface area for payload customers and their support staffs who are headquartered here throughout a mission. All decisions about payload operations are made in coordination with the customer in the customer support rooms.

Free-flying payloads that are deployed, retrieved, or serviced in Earth orbit by the Orbiter are monitored by Payload Operation Control Centers at other locations such as the Goddard Space Flight Center in Greenbelt, Maryland. Payloads with distant destinations, such as those exploring other planets, are controlled from the Payload Operation Control Center at the Jet Propulsion Laboratory, Pasadena, California.

STOP 2-2. Lunar Sample Building (Building 31N)

Between 1969 and 1972, six Apollo spacecraft brought back 382 kg (842 pounds) of lunar rocks, core samples, pebbles, sand, and dust from the lunar surface. The six space flights returned 2000 separate samples from six different exploration sites on the lunar surface. The Lunar Sample Building is the chief repository for the Apollo samples. Protection and preservation of the Apollo collection is one important purpose for the Lunar Sample Building. Equally important, however, is making the collection available for scientific study and education because it is these activities that give the samples their true value (Fig. 2-3). As methods of research continue to improve and as knowledge is gained, previously unformulated questions arise that require new studies. Enough of the samples must be preserved so that material will remain available in unaltered condition to make such new studies possible.

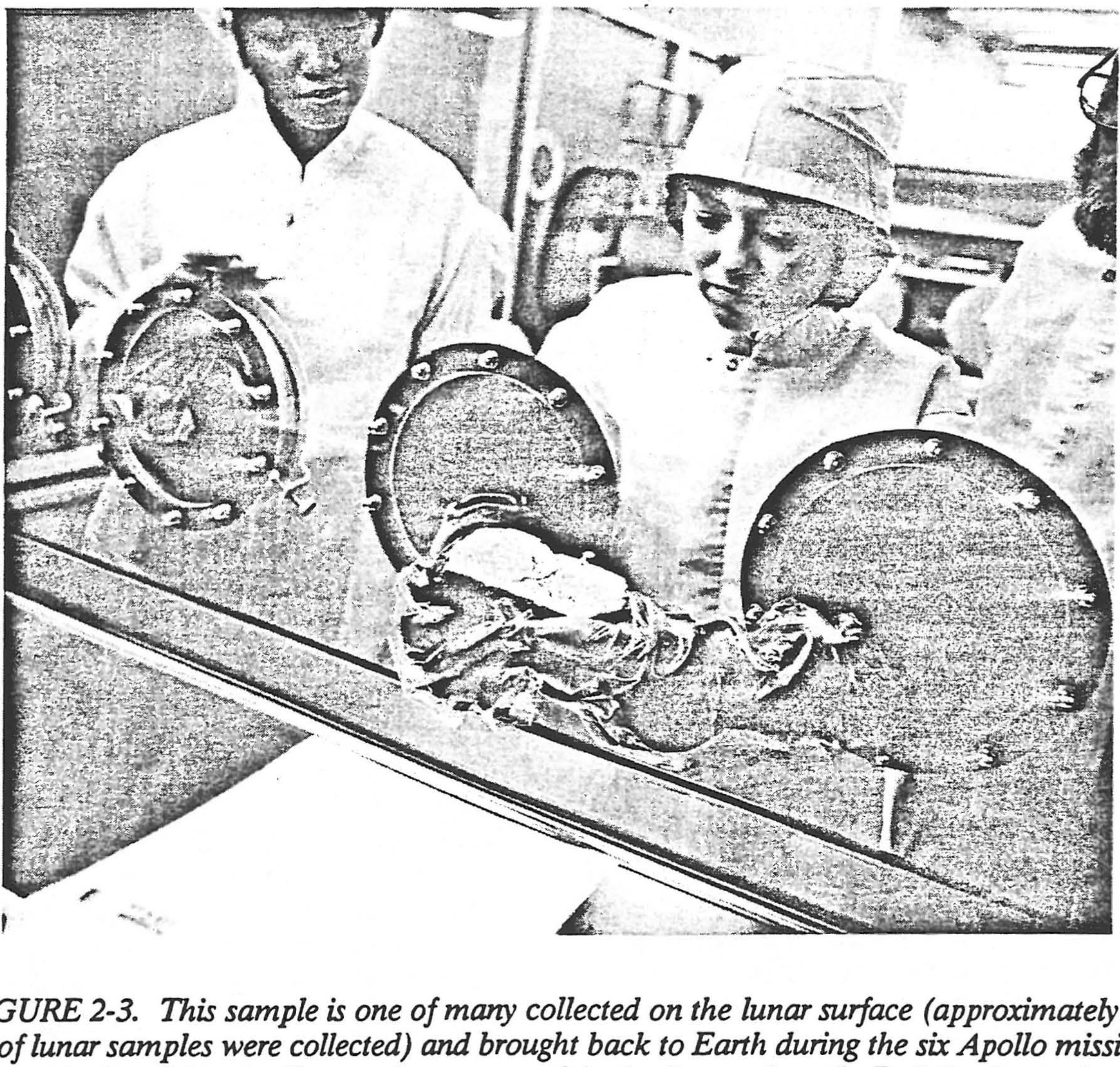

FIGURE 2-3. This sample is one of many collected on the lunar surface (approximately 382 kg of lunar samples were collected) and brought back to Earth during the six Apollo missions. The majority of the Apollo samples are stored in the Lunar Sample Building located at the Johnson Space Center (NASA Photo S82-26777).

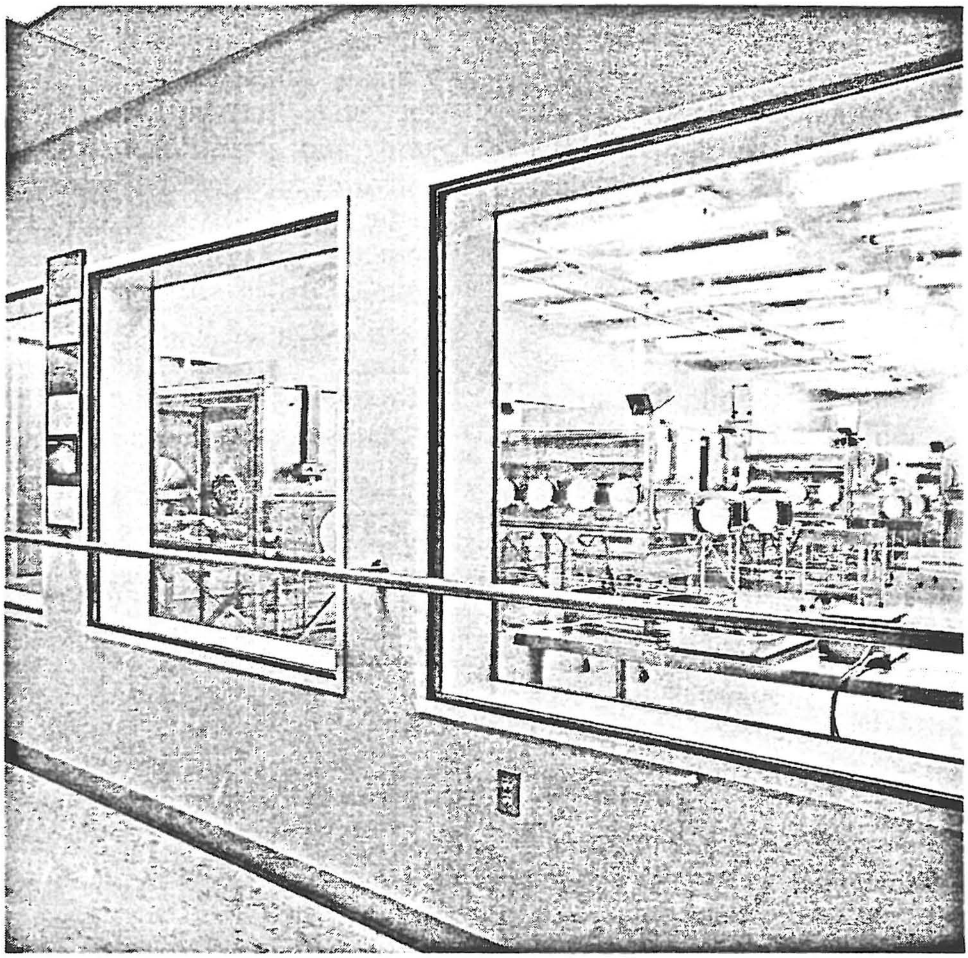

FIGURE 2-4. The lunar Sample Building is the chief repository for the Apollo samples (NASA Photo S83-42819).

The Lunar Sample Building consists of storage vaults for the samples, laboratories for sample preparation and study, a vault for all sample data and records, and the machinery to supply nitrogen to the cabinets and to maintain the clean environments of the sample laboratories and vaults (Fig. 2-4). The vaults are designed to protect the collection of samples against theft, and from damage by natural hazards such as tornados and hurricanes. Thick walls of reinforced concrete are lined on the inside by welded steel plates to keep out moisture. The heavy vault doors remain closed except for removal or storage of samples. All pipes and openings into the vaults close automatically if there is any disturbance in the building such as fire or intrusion. Two vaults are used, one to store samples that have never been out of the sample laboratories, and the other for those that have been returned by investigators after their analysis. In that way, "pristine" samples can never become mixed with "used" samples.

Adjacent to the sample laboratory is a special experiment room, for tests and measurements on particularly large or rare lunar specimens. Visiting scientists working with these specimens can take advantage of the Lunar Sample Building's unique environmental controls, as well as the assistance of people experienced in the care of lunar materials. In the past, visiting scientists have measured the heat conduction through unopened core tubes to determine the rate of cooling of the Moon's interior and have measured the light reflected from soils and rocks. The values for the reflected spectra can be compared with similar measurements by telescopes from Earth and thus compositions of lunar areas that we have not sampled can be estimated.

On the first floor below the sample vaults is the data vault where the records on the samples are assembled, stored, and used. Also, the many photographs needed to record the work done on the lunar samples are stored there. In addition, the first floor contains simulation laboratories in which procedures and techniques can be tested before they are used on actual lunar samples, and in which new techniques can be developed for use with samples yet to be collected from other parts of the solar system, such as Mars, comets, or asteroids.

STOP 2-3. Space Shuttle and Space Station Freedom Mockups (Building 9A & B)

In the Space Shuttle and Orbiter Mockup and Integration Facility, astronauts train in full-scale space shuttle mockups (Fig. 2-5). The Orbiter Crew Compartment Trainer is a high fidelity

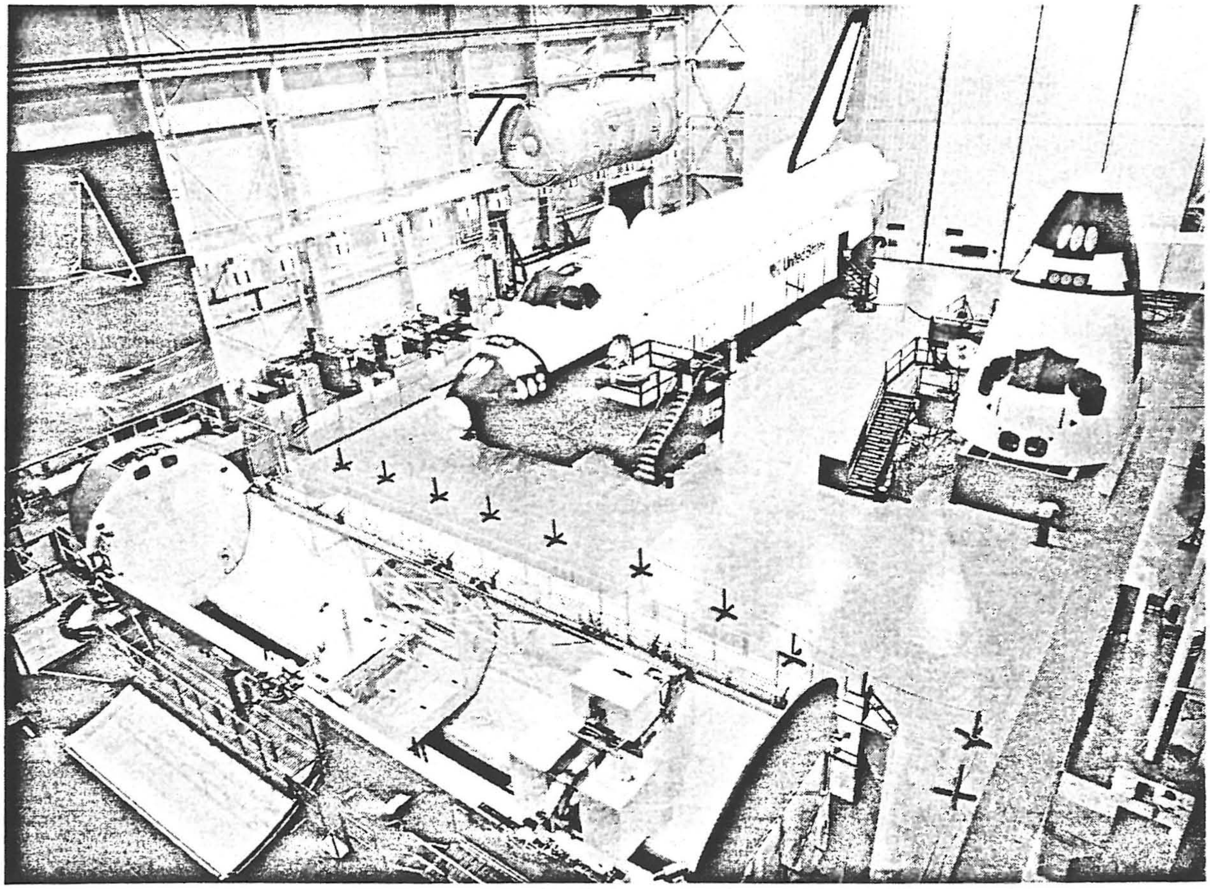

FIGURE 2-5. The Shuttle Mockup and Integration Laboratory is a facility frequently used by astronauts in training and by planners of in-space activities (S81-34843).

representation of the interior of the Orbiter crew station. It is used primarily for in-orbit crew training and engineering evaluations. The Orbiter Full Fuselage trainer includes a high-fidelity crew station and payload bay. The facility supports numerous engineering evaluations and crew training sessions. The Manipulator Development Facility provides a realistic simulation of the Remote Manipulator System for development of payload operation, procedures, and hardware.

The Space Station Mockup and Trainer Facility contains a full-scale mockup of the modules and nodes that will comprise Space Station Freedom. The mockup will contain the crew habitation quarters, the laboratory, the Japanese and European Space Agency modules, a logistics module that will house surplus food and equipment, and a crew escape and return vehicle. Four connecting resource nodes will serve as airlocks between docking vessels and the modules in addition to housing command and control equipment.

STOP 2-4. Visitor Center (Building 2) and Gift Shop (Building 3)-Optional Stop

Actual and replica rockets, spacecraft, space suits, and memorabilia from every facet of the Nation's space program fill the Visitor Center (Fig. 2-6). A gift shop is located in Building 3 where visitors may purchase gifts and NASA mementos.

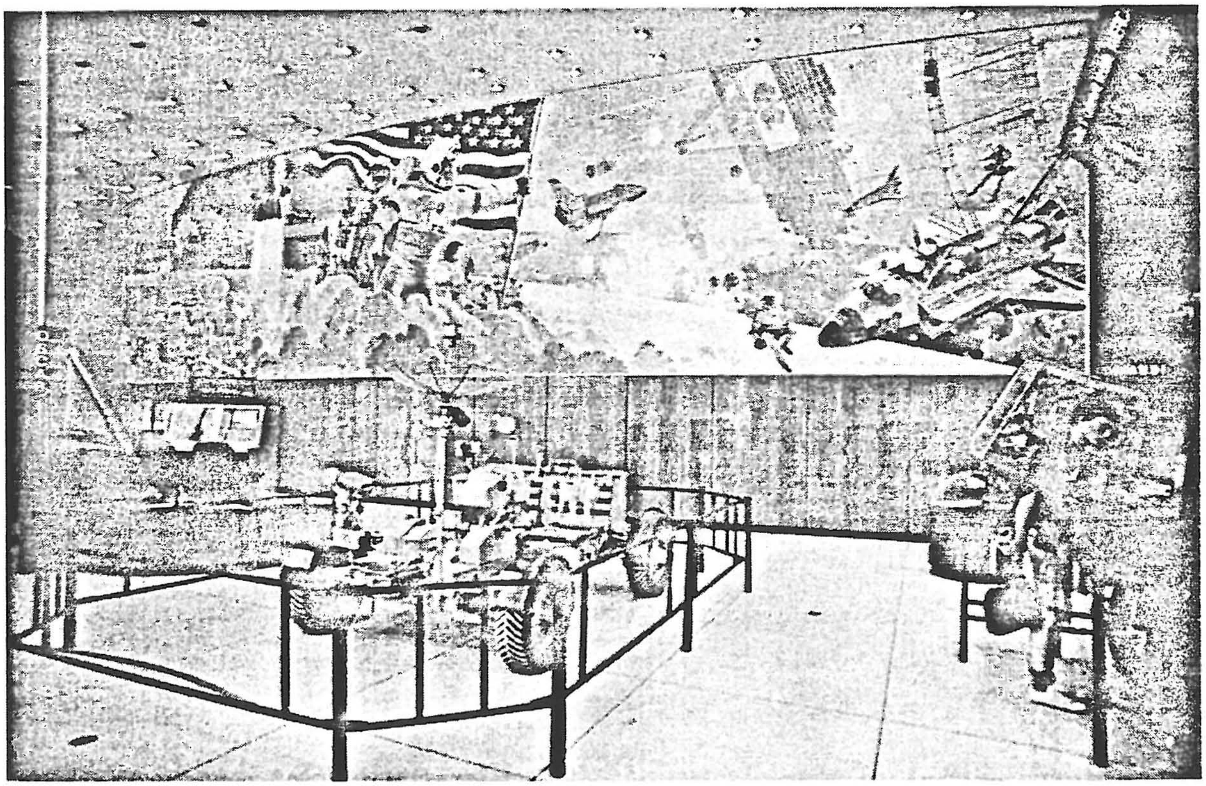

FIGURE 2-6. This is just one example of the variety of actual and replica rockets, spacecraft, space suits, and other memorabilia from the Nation's space program on display in the Visitor Center at the Johnson Space Center (S79-35665).

LEG 3

SUBSIDENCE AND SURFACE FAULTING AT SAN JACINTO MONUMENT, GOOSE CREEK OIL FIELD, AND BAYTOWN, TEXAS

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University of Houston-Clear Lake

INTRODUCTION

Subsidence and surface faulting are two of the major environmental concerns of the upper Texas Coast caused by the high clay contents in the Beaumont Formation. This Leg of the field trip will examine some of the most dramatic evidence of subsidence and surface faulting in the Houston area. Locations of the Stops are illustrated in Figure 3-1.

STOP 3-1. San Jacinto Monument State Park

The San Jacinto Battleground was the site of the decisive battle of April 21, 1836 in which the Texan army led by General Sam Houston (camped on the west side of Texas Highway 134) defeated the Mexican army led by the President of Mexico, Santa Anna (camped to the east) and won Texas' independence from Mexico. Originally, the battleground was a State park of 450 acres. However, subsidence on the order of 8-9 feet in the park since the monument was constructed in 1937-38 has caused almost 30% of the original acreage to be lost due to inundation.

We will take the elevator to the top of the Monument. From this vantage point we can contrast the land/water distribution in Figure 3-2 (1964) and the present day view. To the north, the view from the Monument also affords an excellent view of the canal that brings freshwater from the Trinity River to the ship channel area. The water is pumped under the ship channel via nine-foot diameter conduits. These large pipes run subsurface across the Park grounds in a northeast-southwesterly direction to deliver water to the industrial and municipal centers along the channel and as far as the west end of Galveston Island.

Through the 1970s, maximum subsidence in the metropolitan area had centered along the ship channel in Pasadena and the Monument area, and at the Exxon Refinery and Goose Creek Oil Field in Baytown. With the exception of the oil field, the subsidence in this area has been caused by excessive withdrawal of ground water from the Chicot and Evangeline aquifers for industrial and municipal purposes. According to Weaver and Sheets (1962), prior to 1940, all water supplies in the Houston area were from wells. Subsidence in the area had been less than 1 foot until the early '40s when the war effort increased industrial output along the channel. Nine feet of subsidence was recorded in this same area from the early 1940s to 1980 (Holschuh, 1991).

Understanding the local, regional, and national importance of the Houston Ship Channel is essential to understanding the threat subsidence posed to this area. The Port of Houston

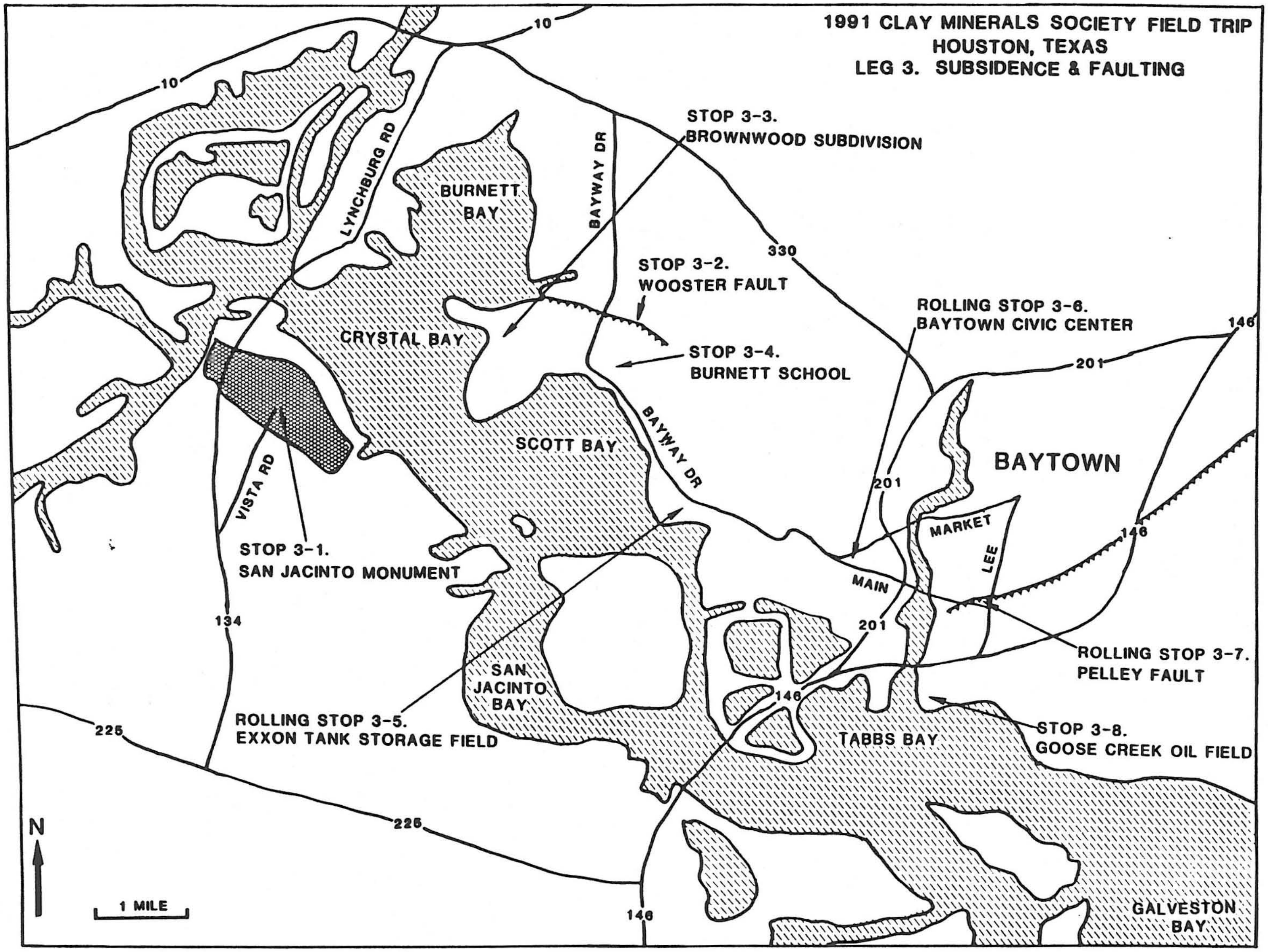

FIGURE 3-1. *Locations of Field Trip stops to examine subsidence and faulting near Baytown, Texas.*

FIGURE 3-2. Aerial view of the San Jacinto Monument area in 1964.

is accessible to the Gulf of Mexico through this man-made channel. The Houston Ship Channel is a 25 mile (40 km) long complex of diversified industries and shipping facilities valued at over 15 billion dollars. Local revenue generated from activity along the ship channel has been estimated to be about 3 billion dollars annually (Holschuh, 1991). Holschuh stated further (1991, p.6) that,

> "[i]t has been estimated that the total capital cost of relocating dock facilities, constructing hurricane levees and rectifying drainage problems due to subsidence would exceed $120,000,000 at just two of the refineries along the Houston Ship Channel (these figures in 1976 dollars)."

According to a publication of the Harris-Galveston Coastal Subsidence District (1981, p.2),

> "In the last four decades alone, the figures have steadily escalated to more than 4,500 square miles of land that have succumbed to one foot or more of subsidence. At present, over 1,000 square miles of Harris and Galveston Counties face the continuing threat of being inundated by flood or hurricane surge. As a result of subsidence, over 20,000 acres in the Houston and Galveston area are now below the waters of Galveston Bay."

The diversion and use of surface water supplies in east Harris County has been a major factor in water level rebound in the Chicot and Evangeline aquifers and the subsequent slowing of subsidence in this area. West Harris County, however, is not yet using surface water and ground water pumpage has caused the bowl of subsidence to now center around Highway 290 near Jersey Village.

In addition to the effects of subsidence evident at the Monument area, there are other environmental concerns present. Since November 1936 when the foundation was laid, the Monument has settled over 12 inches (Fenske and Dawson, 1984.) (Weight of the Monument is estimated at 35,000 tons). According to these investigators, the trend in present data indicates settlement will continue. In 1938 about five inches of settlement was predicted for the Monument with a projection of 7.35 inches in 800 years. Possible explanations for this settlement, according to Fenske and Dawson (1984), include secondary consolidation following disturbance of the soil structure.

The Monument is faced with a native Texas stone known as Cordova Shell. The rock is Cretaceous in age and is quarried near Austin, Texas. This type of stone, unfortunately, is a poor choice for building stone in this area. Moisture, combined with atmospheric pollutants (particularly sulfur dioxide) has formed acid rain which is taking its toll on the limestone.

Upon leaving the Monument area, we will travel roughly parallel to the reflection pool (Park Road 1836). Near the east end of the pool, the road crosses ridge and swale topography. Kreitler (1976b) suggested that this feature is produced by an active fault which crosses the area. Evidence to support this view includes: 1) an apparent lineation visible on a 1956 Edgar Tobin aerial photo; and 2) uneven subsidence which, by 1974, had lowered the eastern end of the pool by five feet and the western end by only three feet.

We will take the Lynchburg Ferry across the Houston Ship Channel. Notice that the road has been built up several times to keep the road passable. The loading docks for the ferry have also been raised several times; eventually abandonment and relocation of older docks was required. The tenuous stretch of land occupied by the ferry landing is kept above sea level solely by human efforts.

Upon exiting the ferry we will travel parallel to the water impoundment facility (Lynchburg reservoir) which stores surface water for use by industry and municipalities. The reservoir has a capacity of about 1.5 billion gallons (5.7 million m^3). The canal which diverts water from the Trinity River is also visible to the west, running parallel to the road. Near Trinity, Texas, water from the Trinity River is lifted 50 feet by pumps and discharged into the 22 mile long canal which brings the water to the Lynchburg reservoir and pump station. From there the water is pumped under the ship channel to be distributed to industries and municipalities along and south of the channel. To the east, fence posts in the bay denote boundaries of former pasture land (summarized from Holshuh, 1991).

Follow the road from the ferry through Lynchburg. Turn right (east) on Decker Drive (Spur 330). At the intersection of Decker Drive and Bayway Drive, turn south on Bayway traveling 1.7 miles from the intersection to Rolling Stop 3-2.

ROLLING STOP 3-2. Wooster Fault

This fault appears to be related to the Goose Creek Oil Field. Surface vertical displacement along this fault is

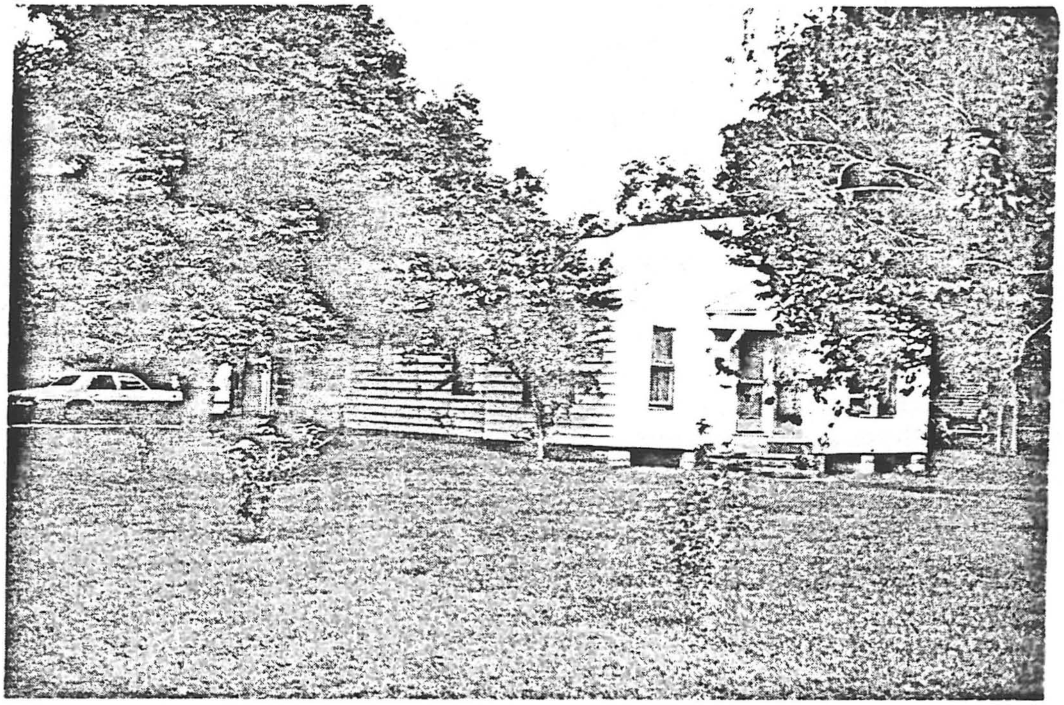

FIGURE 3-3. Residence that straddles the Wooster fault in Baytown.

about four feet. Continue a short distance south on Bayway to North Street. We will turn east on North Street, traveling on the downthrown side of the fault. The scarp of the fault is visible to the north as the scarp cuts the streets perpendicular to North Street. At the end of North Street we will turn north. The Wooster Fault now lies directly to the north of North Street. Go one block, turn left (west) and follow the fault to the next intersection. The house on the northeast corner has been continually shimmed up under the front portion to prevent the house from being torn apart by the fault (Fig. 3-3). These efforts to overcome the effects of the fault have not been entirely successful.

Until 1989, the northwest corner of this intersection was the site of a home. Unfortunately, no efforts to compensate for the fault were undertaken at this site and the house eventually became uninhabitable as the doors and windows refused to open and the roof began to break up.

The Wooster Fault disappears into the bayous to the west. Eastward, it continues into the Exxon Refinery area where it forms one of the surface faults across the north flank of the Goose Creek Oil Field (Sheets, undated). The surface fault on Hogg Island is on the south flank of the field, and together the two faults form an east-west graben.

Return to Bayway Drive and continue south to Cabeniss. Turn right on Cabeniss to Brownwood Street. Turn onto Brownwood and follow it into the Brownwood Subdivision and Stop 3-3. (Route may differ due to possible impassible roads in the subdivision).

STOP 3-3. Brownwood Subdivision

The history of Brownwood Subdivision is a dramatic example of how humans have operated in a way that has accelerated natural subsidence and have reaped the consequences of these actions. Over the years the homes in this subdivision were periodically flooded by storm surges, high tides, and high winds (Fig. 3-4). Extensive flood and storm damage occurred in this subdivision during Hurricane Carla in 1961. By the late 1960s, many Brownwood homeowners had either turned their homes into rental properties, abandoned them, or moved them to higher ground.

This subdivision is located on the downdropped side of the Wooster Fault which has undoubtedly contributed to the rapid subsidence of the area. Differential subsidence across a fault is to be expected and much of the environmental hazard associated with faults occurs on the downthrown side.

A total of over 8 feet of subsidence has occurred since 1938 when building first began in the Brownwood Subdivision. Elevation at that time was about 10 feet (3.3 m) above sea level. At times in the past the rate of subsidence in this area was measured in inches per year. By 1961 when Hurricane Carla hit the Houston area the subdivision had lost 4 feet of elevation. Homeowners fought periodic flooding due to high tides, high winds, and storm surges until 1983 when

FIGURE 3-4. Submerged house in the Brownwood subdivision, Baytown, Texas.

Hurricane Alicia hit the area. Hurricane Alicia virtually wiped out the remaining inhabited homes in this once affluent subdivision. Speculation on further use of this area includes a park, golf course, nature preserve, etc., certainly more appropriate uses of the land than a subdivision.

The perimeter road on which we are driving has been built up several times to act as a levee to protect the interior homes from tidal waters. The road is now at an elevation of 4.6 feet. Five pumps were installed in 1961 following Hurricane Carla to pump out impounded waters that collected behind the perimeter road. Hurricane Alicia destroyed three pumps located on the perimeter road.

The Government declared Brownwood unfit for human habitation in 1983-84 and the area was closed to all except permitted investigators and residents salvaging their belongings. Three hundred homes and numerous vacant lots were affected by the ruling. Federal offers to the owners for their property averaged about $2,000. The owners also collected an average of $45,000 on their insurance. The federally acquired property was turned over to the City of Baytown with the stipulation that the land be used for open space. Demolition contractors dug pits behind the remains of the homes and buried some 230 houses, along with their foundation slabs and fallen trees (Sadik-Macdonald et al., 1988).

The progressive subsidence of Brownwood is clearly demonstrated by comparing the aerial photo in Figure 3-5 with the present view. In the 1940s, a

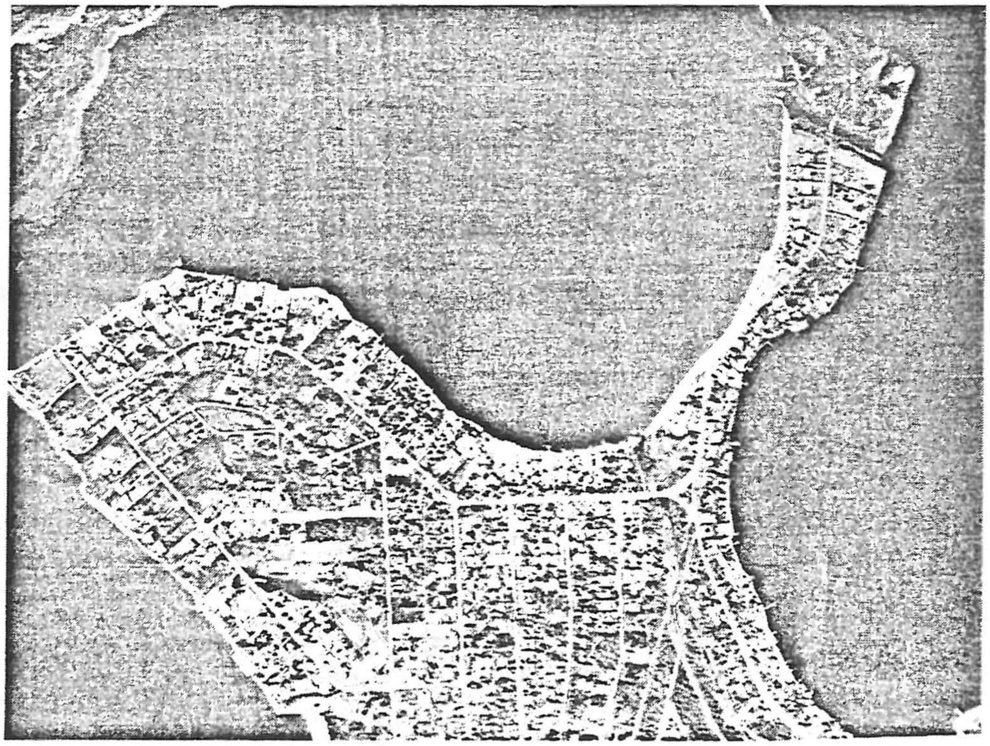

FIGURE 3-5. Aerial view of the Brownwood subdivision in 1964.

FIGURE 3-6. Land subsidence away from the wellhead located near the Burnett School in Baytown, Texas.

strip of land separated the Houston Ship Channel from Crystal Bay. In 1964, parts of the strip of land were inundated with water. By the 1980s, the intervening land had been almost completely submerged. Also of note is the position of the perimeter road in the subdivision relative to the shoreline.

Exit Brownwood Subdivision, turn right (south) on Bayway Drive. Take next left (east) on Arbor Street and next right into the parking lot of Burnett School to Stop 3-4.

STOP 3-4. Burnett School/Baytown Alternative High School Wellhead Casing

This area is also on the downthrown side of the Wooster Fault. Differential compaction across the fault produces a greater loss of elevation on the downthrown side. Located in the pasture across the fence is an old utility district supply well. The base of the well casing, 500 feet below the surface, has experienced much less subsidence, relatively speaking, than the land surrounding the wellhead causing the wellhead to protrude several feet above ground level (Fig. 3-6) (Holschuh, 1991; Sadik-Macdonald, 1988).

The gymnasium of Burnett School is being held together by steel rods and reinforcing corner braces. The structural failure of the school is not directly related to subsidence which is a general lowering of elevation over a rather large surface area. Most likely the failure is due to activity in the expansive soils which underlie the area. Structural problems (of a geologic nature) in the Houston-Galveston area are generally related to faults or expansive soils.

Continue south on Bayway Drive 1.5 miles to Rolling Stop 3-5.

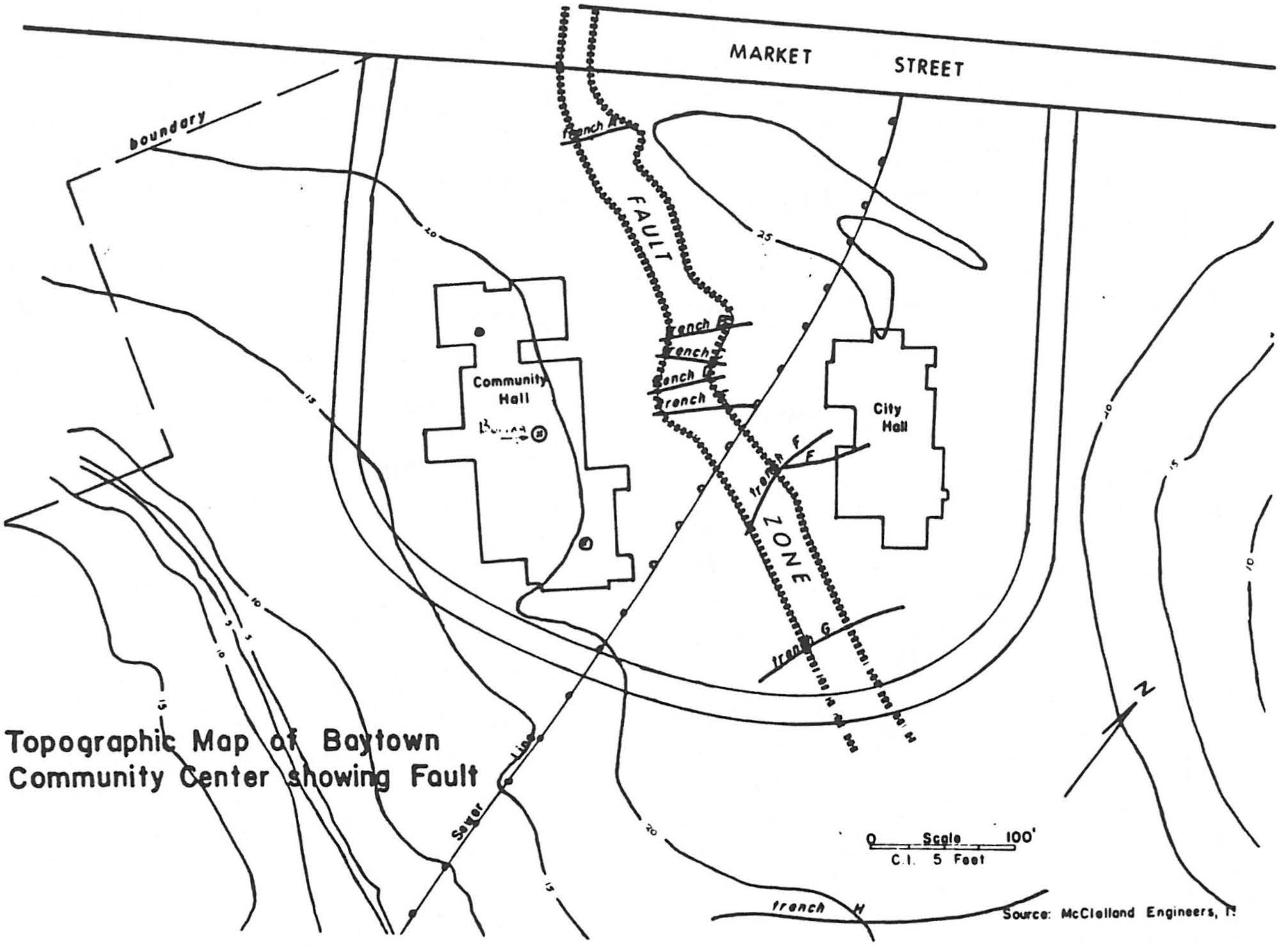

FIGURE 3-7. Topographic map of the Baytown Community Center showing a fault running between the Community Hall and the City Hall.

ROLLING STOP 3-5. Exxon Tank Storage Field

This is not the Wooster Fault but another well-recognized fault crossing Bayway. Movement along this fault has been slow but steady. This is the same fault we will see at rolling stops 3-6 and 3-7. The fault is visible in the broken curbs that have recently been repaired.

Go straight ahead following Wisconsin Street. At Market Street turn right (east). Continue to the Baytown Civic Center and Rolling Stop 3-6.

ROLLING STOP 3-6. Baytown Community Center

This is an example of the proper way to engineer around an active surface fault. An active fault runs between these two buildings. The fault was recognized before the center was built and development of the center was planned so that no major structures were located on the fault (Fig. 3-7).

The scarp of the fault offsets the ground surface from 7 to 14 inches and the width of the fault zone is 15 to 100 feet. About 1500 feet west of this site, at Airhart Drive, movement is estimated to be about one inch per year. McClelland Engineers conducted the investigation of the fault and recommended that no structures be built within a 150 foot wide zone centered on the fault (AAPG-HGS Field trip, 1988).

Follow Market Street to Lee Drive. Turn right on Lee Drive to Rolling Stop 3-7.

ROLLING STOP 3-7. Pelley Fault (Optional Stop)

After turning right on Lee Drive watch for a large fault after the second set of railroad tracks. Just before the fault, turn right on Nazro Street. The fault can be seen running parallel to Nazro Street to the south. Turn left on Yupon Street and proceed over the fault. In the early to mid 1900s, this area comprised the community of Pelly. In 1916, large-scale oil production began in the Goose Creek Oil Field and large cracks appeared in the ground. The south side of the fault (downthrown to the oil field) dropped 16 inches or more within a few days of the start up of pumping in the field. In 1918 this fault moved abruptly about 16 inches creating a very small earthquake (Pratt and Johnson, 1923). The fault has continued to move steadily, causing damage to streets, houses and businesses in the area.

Turn left on Main Street and then right on Lee Drive. Continue south on Lee Drive and proceed across Highway 146 to Stop 3-8.

STOP 3-8. Goose Creek Oil Field (Optional Stop)

This oil field was developed on the Goose Creek salt dome. Cumulative production (1916-1985) is 136 million barrels of oil (AAPG-HGS guidebook, 1988). Note the partially submerged facilities in the middle of the estuary and south and east in Tabbs Bay (Fig. 3-8). When the field was established in 1916 by Humble, the present estuary was mostly dry and the marshy Gaillard Peninsula extended into Tabbs Bay. In 1918 production had reached 9 million barrels of oil per year and it was becoming increasingly clear that Gaillard Peninsula and other nearby lowlands were being submerged (AAPG-HGS guidebook, 1988). Ten years of extensive pumping from this field produced three feet of subsidence along an east-west axis coinciding with the area of heaviest production. Pratt and Johnson (1926) estimated that the

> "aggregate volume of oil, gas (at 1,000 lbs/in^2 pressure), water, and sand removed from Goose Creek since 1917 will exceed 100 million barrels, or about 500 million cubic feet".

When the low-lying producing areas became submerged, the State of Texas ruled that the field was now in State water bottom land and the State sued Humble, claiming title to the field and its oil and gas production. The State also sought to recover from Humble the value of the oil and gas removed from the premises subsequent to the time when the land became submerged. Not only did Humble stand to lose in the State suit but the landowners would be deprived of their now submerged land. The case went to court and Humble won the suit because in Texas at that time, no man (Humble) could operate in such a way as to deprive another man (landowners) of his due property (Pratt and Johnson, 1926). By 1978, total subsidence at the field was nine feet in comparison with six

FIGURE 3-8. Submerged oil wells in the Goose Creek Oil Field near Baytown, Texas. These wells were once located on dry ground until subsidence in the oil field left them in their current, partially-submerged state.

feet maximum subsidence in Baytown.

Faulting accompanied early development of the field. In fact, the only earthquake in the Houston area felt by humans occurred in this area during the early development of the field (Pratt and Johnson, 1926). According to these authors (p.578-581),

> "...cracks appeared in the ground running beneath houses, across streets, and through lawns and gardens. These cracks persisted, and recurrent movement along them resulted in dropping the surface of the ground on the side of the cracks toward the oil field. The changes in elevation resulting from these movements amounted to 16 inches or more in places. The movements were accompanied by slight earthquakes which shook the houses, displaced dishes, spilled water, and disturbed the inhabitants generally".

After leaving the Goose Creek Oil Field, turn left on Highway 146 and continue south 34.1 miles to the Campbell Bayou Facility (see map, Fig. 4-3).

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LEG 4
GULF COAST WASTE DISPOSAL AUTHORITY CAMPBELL BAYOU FACILITY

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GULF COAST WASTE DISPOSAL AUTHORITY

The Gulf Coast Waste Disposal Authority (GCA) was created in February, 1970, by the Sixty-first Legislature of the State of Texas to own and operate waste treatment facilities. Its original mission was the treatment of wastewater. During the late 1960's, the Houston Ship Channel had become known as "one of the most polluted waterways in the world". Industries and municipalities along the Channel were then discharging some 425,000 pounds per day of biochemical oxygen demand (BOD) into the water, turning it black and nearly eliminating all marine life. The Ship Channel waters eventually entered Galveston Bay and, many experts believed, threatened the bay's very existence. Farsighted business and political leaders recognized these dangers and called for governmental controls. Hence the creation of the GCA.

GCA immediately began to revolutionalize the wastewater treatment industry. They pioneered regional wastewater treatment by signing five different industries to their Washburn Tunnel Facility. This milestone proved that separate industries could join together for regional treatment of their wastewaters.

Later GCA expanded to solid (i.e. other-than-liquid) wastes. One of GCA's solid waste treatment facilities, the Campbell Bayou Facility, will be the last stop on this field trip.

STOP 4-1. GCA's Campbell Bayou Facility

The Campbell Bayou Facility is located at the junction of Interstate 45 and Texas Highway 146 just south of LaMarque, Texas (Fig. 4-1). The facility is a 200-acre tract of land permitted by the Texas Water Commission as a Class I industrial solid and hazardous waste landfill. The facility receives hazardous and non-hazardous waste from four local industries.

A landfill is essentially a burial pit that confines residues from materials that cannot be reused, incinerated, or otherwise disposed. One of the primary requirements for a landfill is that the natural geologic repository have a permeability (i.e. hydraulic conductivity) of 10^{-7} cm/s or less. The Campbell Bayou Facility is well located; it sits atop the Beaumont Formation clay, which is

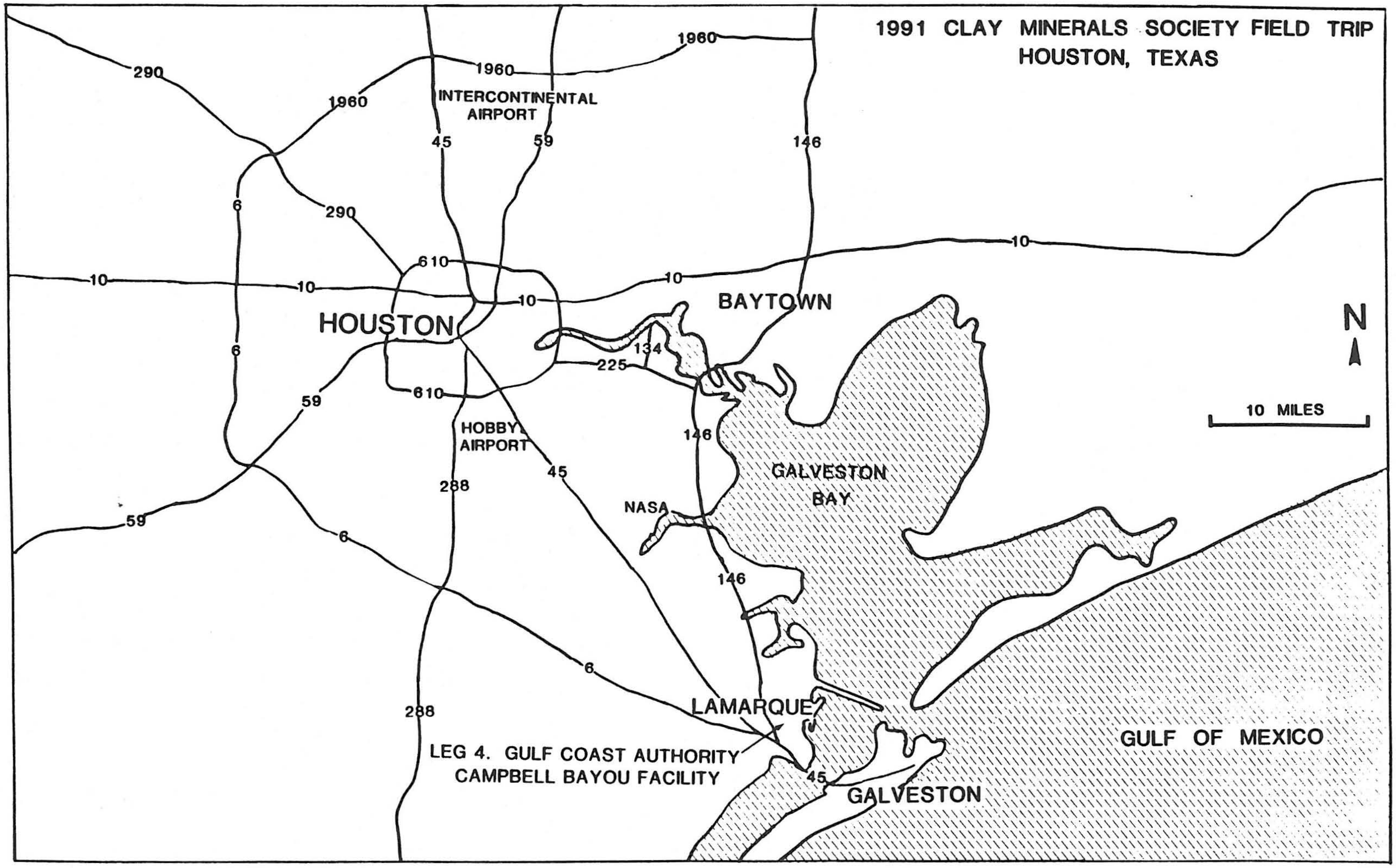

FIGURE 4-1. *Location of GCA's Campbell Bayou Facility.*

known for its very low permeability. Even if the natural geologic medium meets this requirement, however, regulations generally require that landfills be lined with some material to prevent migration of the waste into the substrate and thus protect the groundwater from contamination. The most commonly used material for landfill liners is clay, combined with a synthetic liner material.

The landfill itself is divided into sections called "cells". Having various cells in a landfill allows for the separation of incompatible wastes. Each active cell at the GCA facility is lined with a combination of high-density polyethylene (HDPE), clay, synthetic drainage net, and geotextile fabric (Fig. 4-2). The hazardous waste cells have two layers of this combination liner; the non-hazardous cells have one layer. Submergeable pumps remove hazardous and non-hazardous leachate as well as groundwater from the cells. Hazardous waste waters are biotreated off site. All other waters are treated at a GCA wastewater treatment plant. Construction photographs of a cell appear in Figures 4-3 and 4-4.

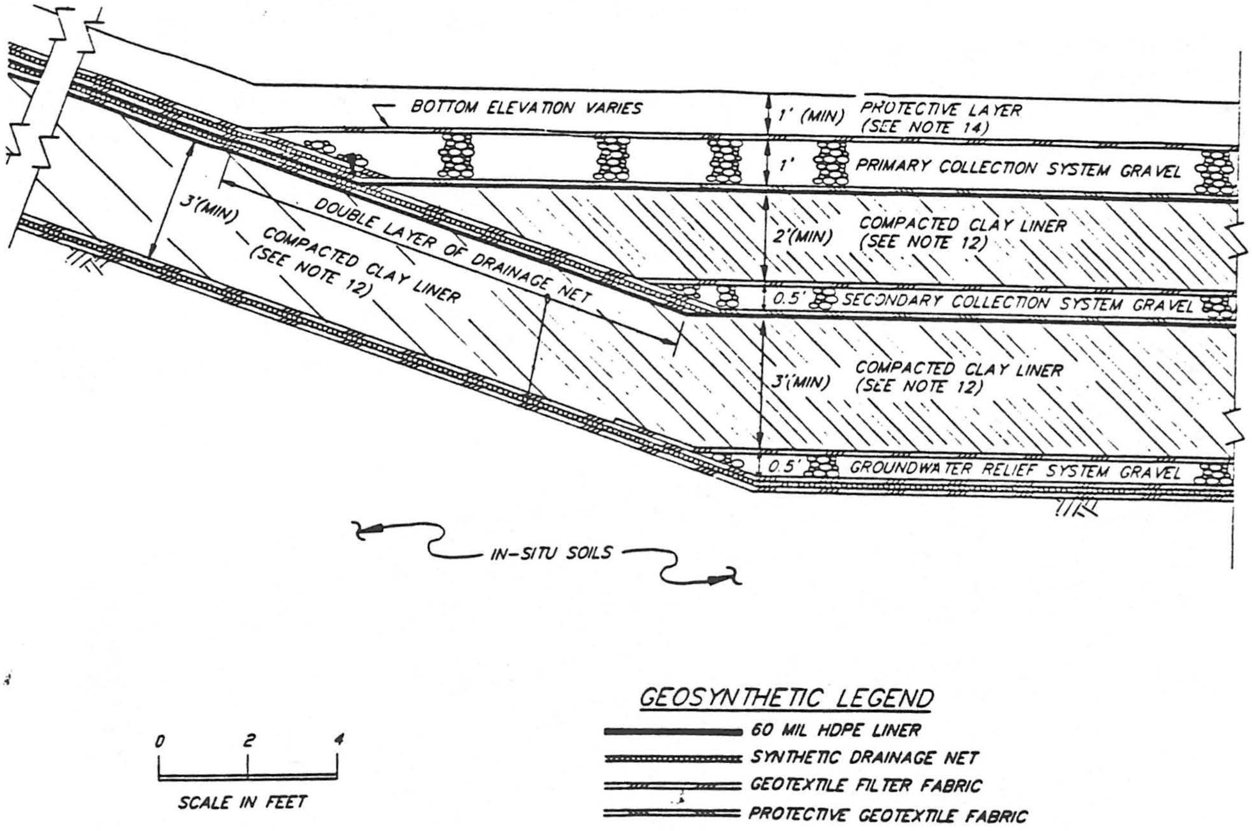

FIGURE 4-2. The GCA landfill is lined with a combination of high-density polyethylene (HDPE), clay, synthetic drainage net, and geotextile fabric. Submergeable pumps remove leachate and groundwater from collection systems in the liner.

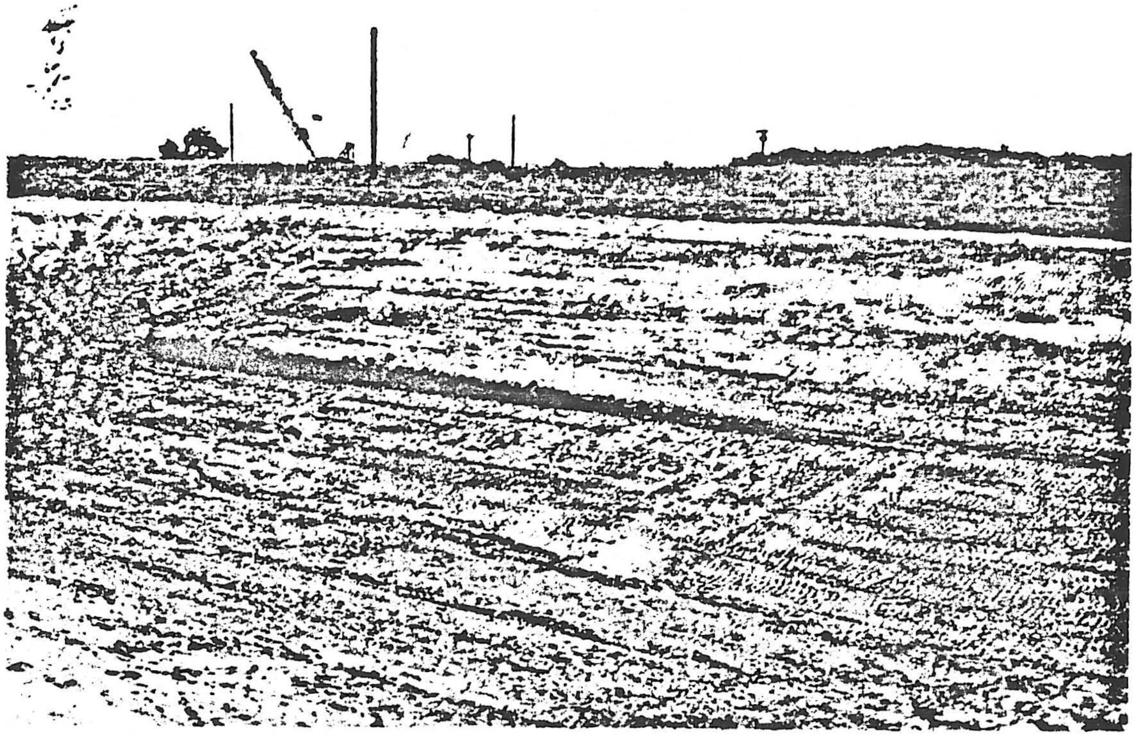

FIGURE 4-3. A cell at the GCA landfill. The in-situ strata is composed of approximately 1 m of topsoil, underlain by 3 or 4 m of yellowish marine clay. Below this lies the reddish Beaumont Formation clay.

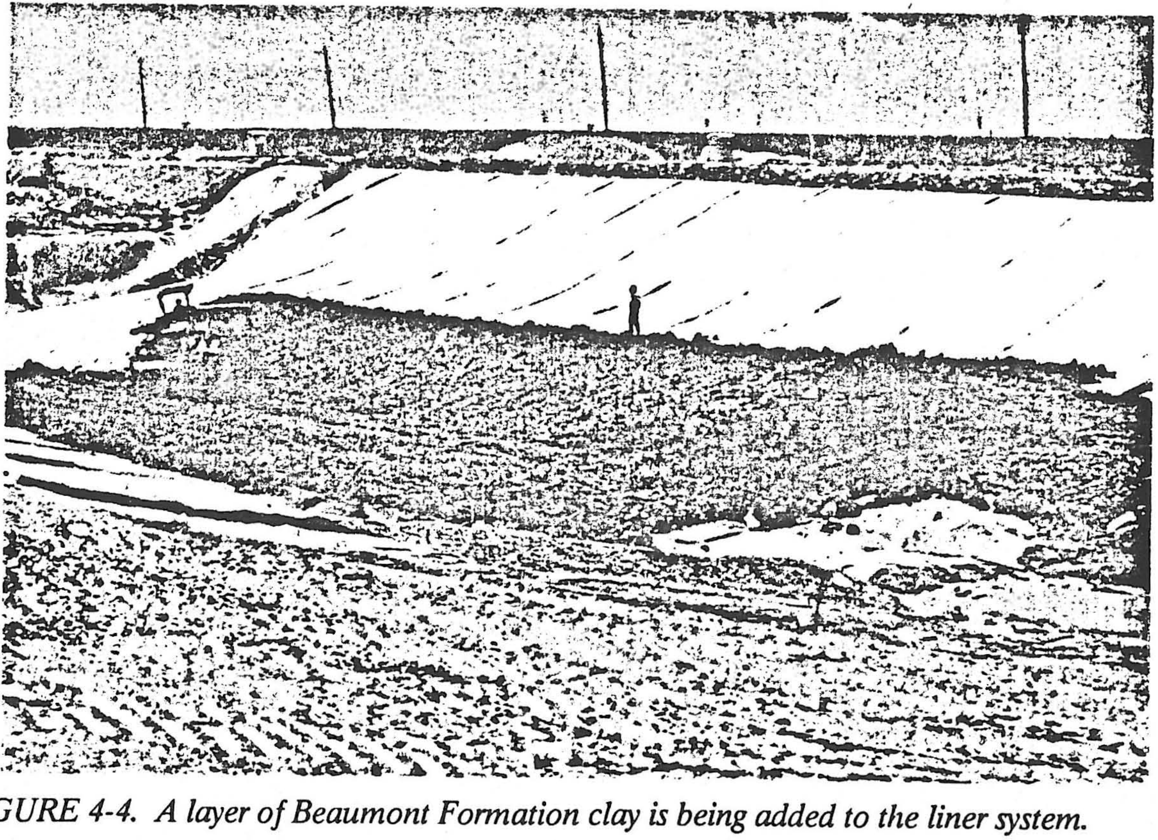

FIGURE 4-4. A layer of Beaumont Formation clay is being added to the liner system.

The ground surface at the Campbell Bayou Facility is covered by approximately one meter of topsoil underlain by 3 or 4 m of yellowish marine clay. Below this lies a reddish clay of the Beaumont Formation to depths of 50 m or more. The mineralogy of the Beaumont Formation clay from this site has been described by Tuck (1991).

Approximately 81% by weight of the Beaumont Formation material at this site is clay sized (<2 μm); over 18% is silt-sized particles (2 μm to 50 μm); and the remainder is greater than silt-sized (Table 4-1). The large percentage of clay particles in this soil very likely accounts for its low permeability. X-ray diffractograms run for each of the sand and silt fractions revealed that the sand fraction was composed of quartz and some plagioclase feldspar. The silt fraction contained some mica and kaolinite as well as quartz and plagioclase feldspar (Fig. 4-5). The clay fractions (2 μm to 0.2 μm and < 0.2 μm) contain predominantly smectite with smaller amounts of mica, kaolinite, and quartz (Figs. 4-6 & 4-7).

TABLE 4-1. Particle size distribution of Beaumont Formation clay from GCA's Campbell Bayou Facility (Tuck, 1991).

Particle Diameter μm	Percent wt. %
>50	0.7
50 to 20	2.2
20 to 2	16.1
2 to 0.2	25.3
<0.2	55.7

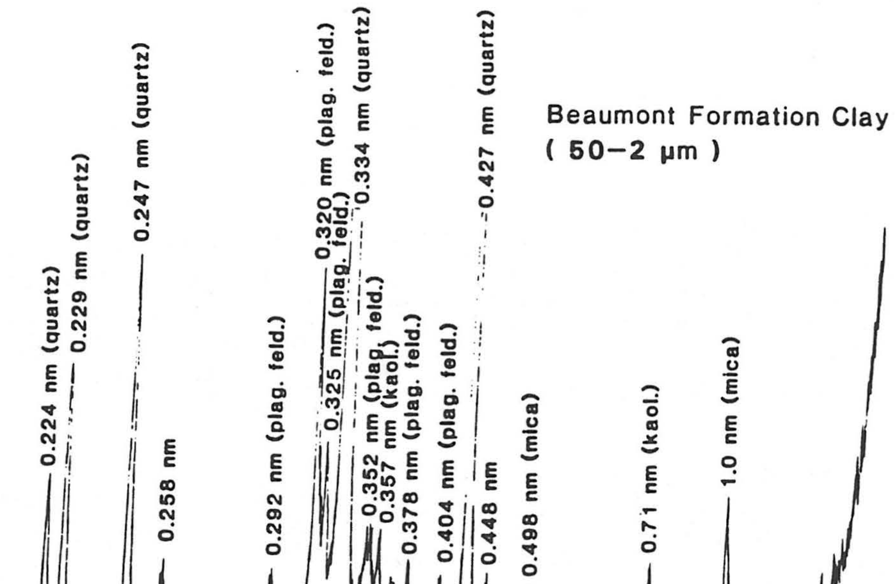

FIGURE 4-5. X-ray diffractogram of the silt-sized particles of the Beaumont Formation clay from GCA's Campbell Bayou Facility. The 50 μm to 2 μm fraction of the Beaumont clay material contained quartz, plagioclase feldspar, mica, and kaolinite (Tuck, 1991).

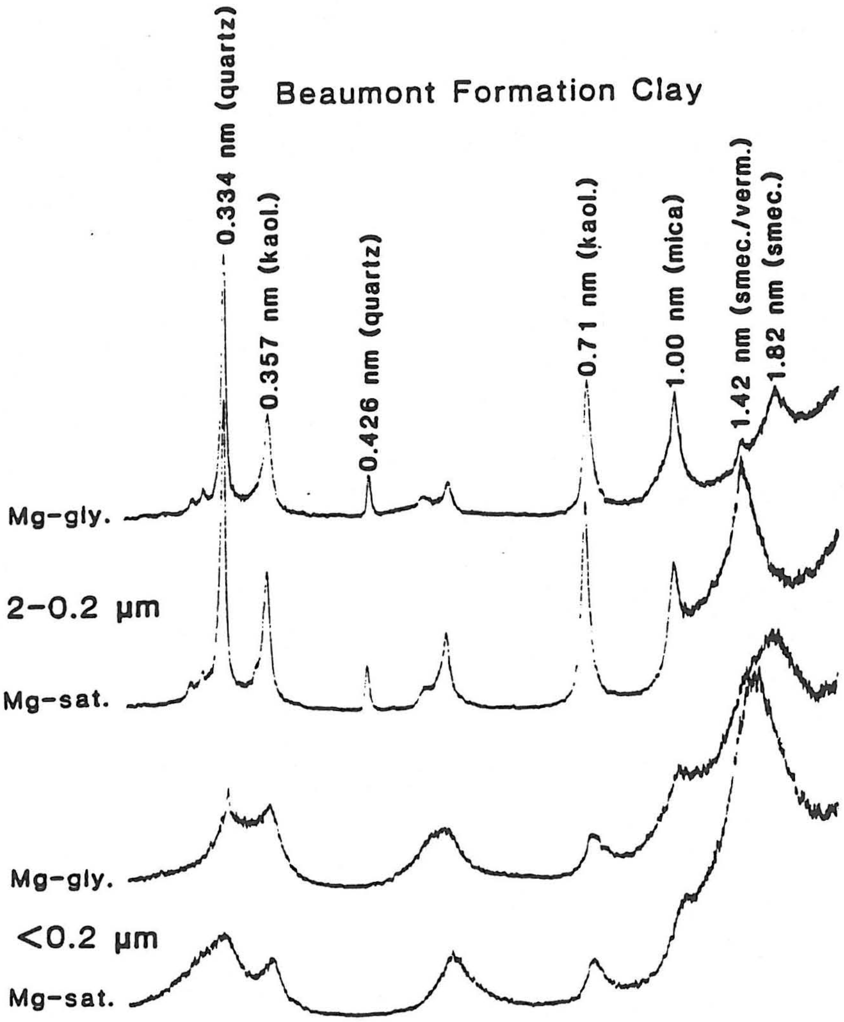

FIGURE 4-6. X-ray diffractograms of Mg-saturated clay-sized fractions of the Beaumont Formation clay from GCA's Campbell Bayou Facility. For the Mg-saturated and glycerated fractions, the 2.0 μm to 0.2 μm diffractogram revealed smectite, kaolinite, mica, and quartz peaks. The diffractogram of the < 0.2 μm fraction showed a large smectite peak, with lesser peaks for kaolinite, mica, and quartz. The peak located at 1.42 nm expanded in both clay fractions when glycerated to 1.82 nm, indicating smectite (Tuck, 1991).

The cation exchange capacities (CECs) of the 2 μm to 0.2 μm and <0.2 μm fractions are 26 cmol_c (+) kg^{-1} and 66 cmol_c (+) kg^{-1}, respectively (Tuck, 1991).

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Tuck, L. K. (1991) Adsorption of cadmium and lead by clay liner material amended with the zeolite clinoptilolite. *M.S. Thesis*, University of Houston-Clear Lake, Houston.

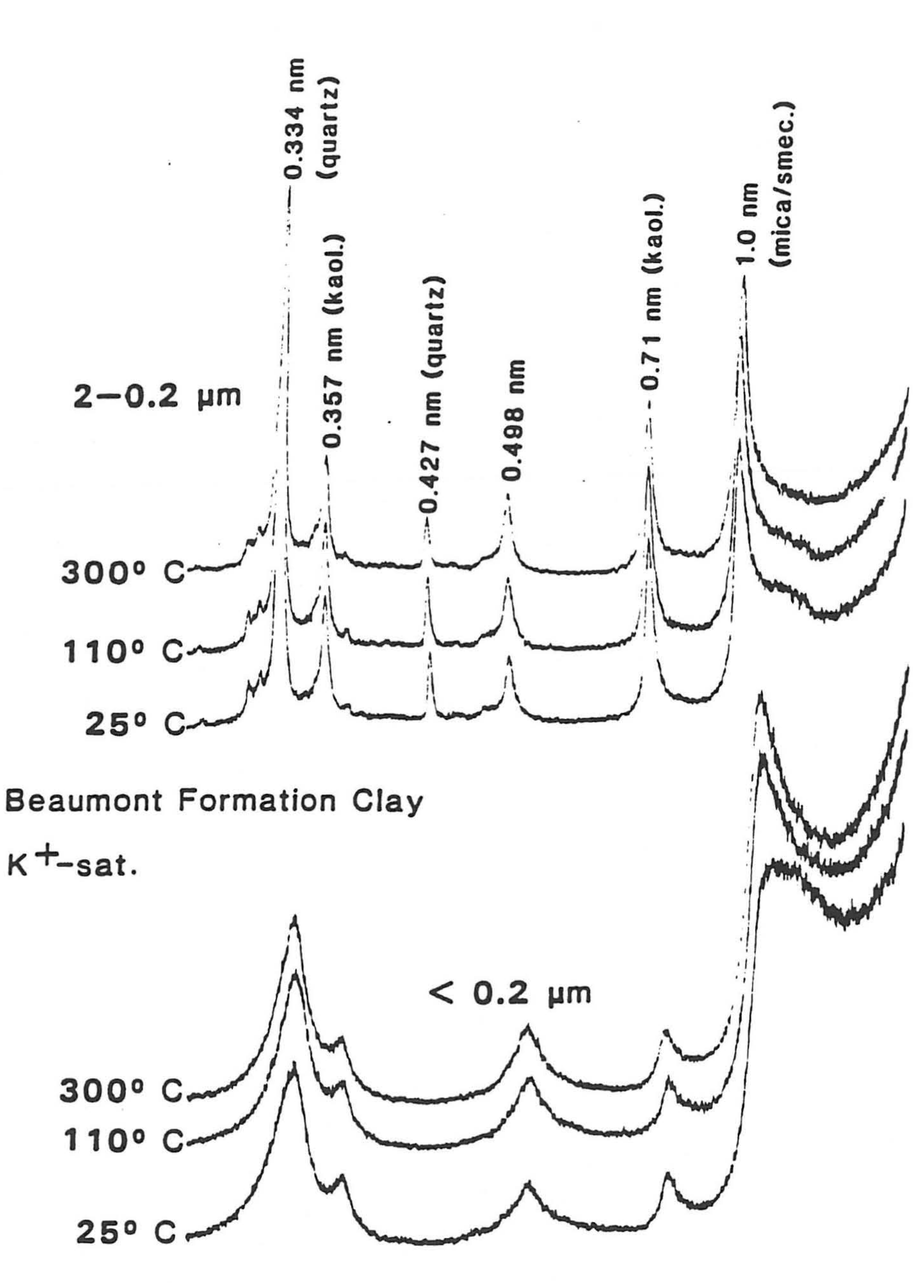

FIGURE 4-7. X-ray diffractograms of K-saturated clay-sized fractions of the Beaumont Formation clay from GCA's Campbell Bayou Facility. Heat treatments of K-saturated clays indicated the presence of smectite, kaolinite, mica, and quartz (Tuck, 1991).

NOTES