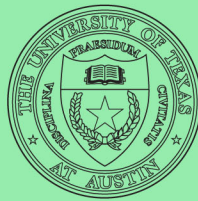


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FAULT CONTROL OF SUBSIDENCE, HOUSTON-GALVESTON AREA, TEXAS

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BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
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FAULT CONTROL OF SUBSIDENCE, HOUSTON-GALVESTON AREA, TEXAS

Charles W. Kreitler

ABSTRACT

Land subsidence increases the area in the Texas Coastal Zone which will be inundated by marine waters from hurricane flooding. Storm surge from a Carla-sized hurricane in 1976 would flood at least 25 square miles more land than Hurricane Carla did in 1961.

Land subsidence in Harris and Galveston Counties results primarily from ground-water production. The two-county area is interlaced with active surface faults with topographic escarpments and surface faults with no topographic escarpments that control drainage patterns and create subtle photographic linear patterns. Ground-water production activates these faults by differential compaction of the aquifer. The faults appear to be partial hydrologic barriers that compartmentalize land subsidence into several individual basins.

INTRODUCTION

In the Texas Coastal Zone, subsidence of the land surface is most common in the Greater Houston area (fig. 1). In this heavily populated coastal region, each 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. In the Brownwood subdivision, Baytown, Texas, several houses are continually submerged (fig. 2). The U. S. Army Corps of Engineers (1975) estimated the minimal cost to relocate the residents of this community to be \$16,980,000.

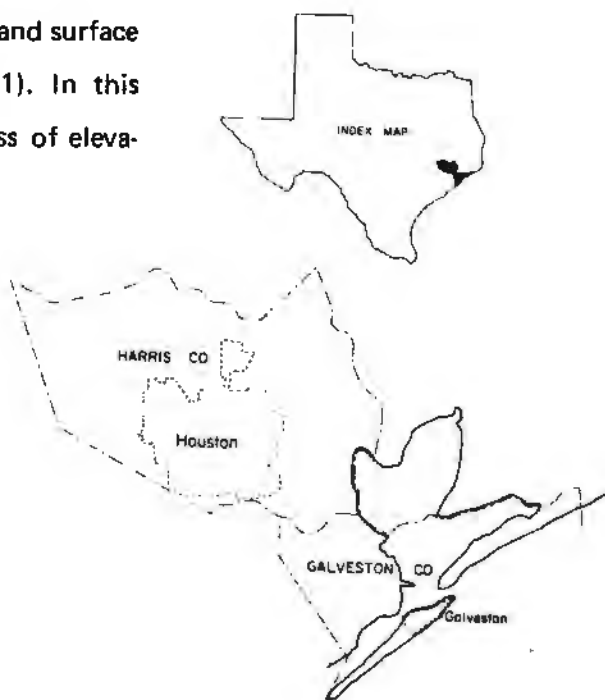


Figure 1 (right). Location map of Harris and Galveston Counties, Texas.

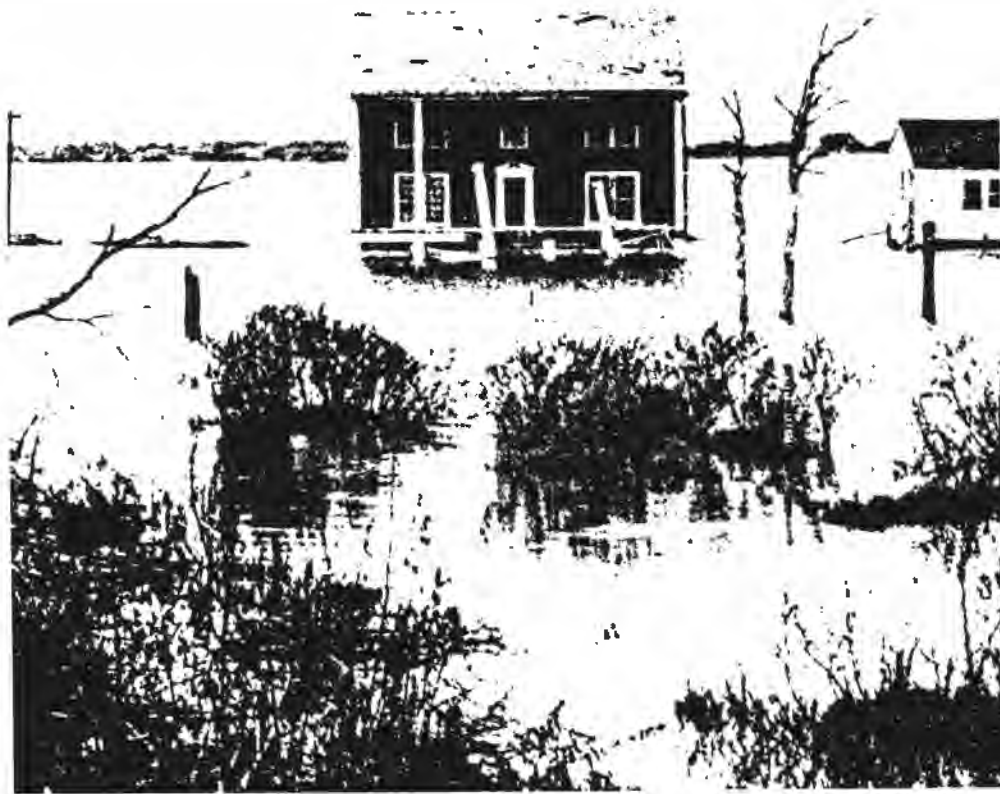


Figure 2. Submerged house in Brownwood subdivision, Baytown, Texas.

From 1943 to 1973, total property damage and loss from marine inundation caused by subsidence of 300 square miles of the Houston-Baytown area surrounding Galveston Bay is estimated to be \$113 million (Warren and others, 1974). A 6-foot tide associated with tropical storm Delia in 1973 resulted in subsidence-related damages estimated at over \$53 million.

Salt-water flooding in the Houston-Galveston area from hurricane storm surges is far more devastating than flooding from a 6-foot tide as discussed by Warren and others (1974). In 1961, Hurricane Carla, with a peak flood surge of 16.4 feet, flooded 123 square miles of Harris and Galveston Counties surrounding Galveston Bay (fig. 3). The land flooded was calculated by measuring the area below the maximum surge line based on several tidal gauges. A hurricane the size of Hurricane Carla, striking Galveston Bay in 1976, would flood at least an additional 25 square miles (total 146 square miles) because of the subsidence that has occurred since 1961 (fig. 3). This additional flood-prone area is calculated by adding the amount of subsidence that occurred between 1963 and 1973 to height of the hurricane surge at

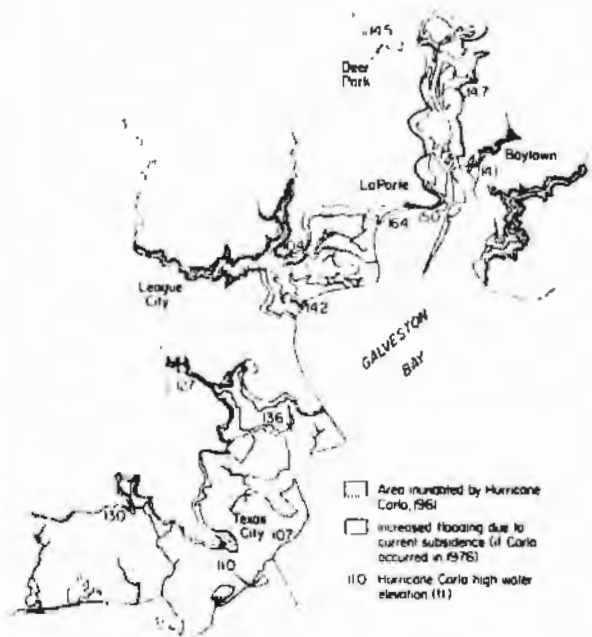


Figure 3. Land inundated by Hurricane Carla in 1961 and land that would be inundated by a Carla-sized hurricane in 1976.

that same locality. With continued subsidence, the area of potential salt-water inundation increases. In order to predict future hurricane flooding, a third calculation is presented to determine how much land would be flooded by a Carla-sized storm if an additional 10 feet of subsidence occurs (compared to pre-Carla 1961 elevation) (fig. 4). A 10-foot subsidence value was assigned to the area that exhibited the maximum subsidence from 1963 to 1973. Proportionately smaller amounts of subsidence were assigned to other areas based on the 1963-1973 data. For example, subsidence (1963-1973) at benchmark 21146 (Pasadena, Texas) was 3.8 feet. This area had the maximum subsidence between 1963 and 1973 and, therefore, was assigned a hypothetical subsidence value of 10 feet. Benchmark P1187 (Clear Lake, Texas) subsided 2.2 feet; a hypothetical subsi-

dence value of 6.2 feet since 1961 was assigned. The potential area inundated by marine-water flooding after a hurricane was calculated by adding the estimated subsidence to the previously determined flood-surge height from Hurricane Carla. This calculated area is 184 square miles, an increase of 61 square miles since Carla struck in 1961 (fig. 4).

The communities surrounding Galveston Bay have been and will be most adversely affected by the coupling of land subsidence and hurricane flooding. Though these communities will receive the brunt of the damage, they are not the areas where the heaviest pumpage is occurring.

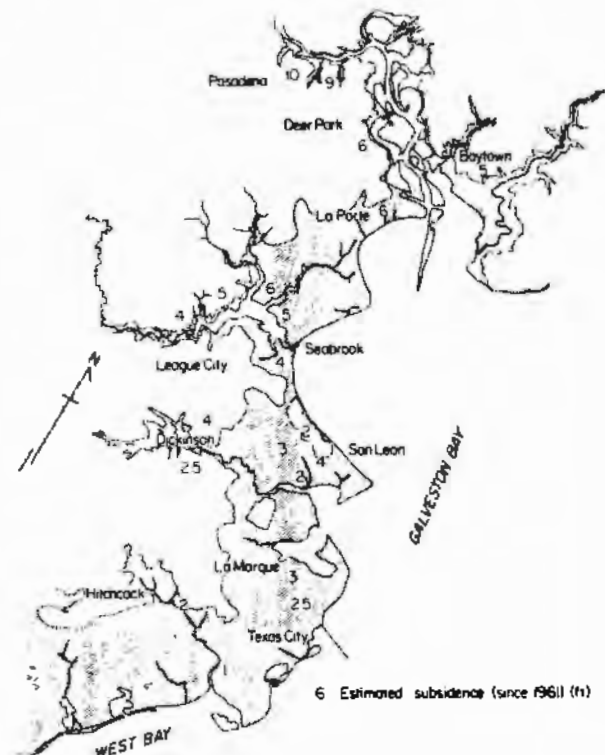


Figure 4. Land that would be inundated by a Carla-sized hurricane if an additional 10 feet of subsidence occurred since 1961.

Land-surface subsidence in the Houston-Galveston area has been attributed primarily to ground-water withdrawal (Gabrysch and Bonnet, 1975). Previous investigators (Weaver and Sheets, 1962; Winslow and Doyel, 1954; Winslow and Wood, 1959; Wood and Gabrysch, 1965; Jorgensen, 1975; Gabrysch and Bonnet, 1975) have mapped the subsidence surface and the piezometric surface as gently dipping, bowl-shaped depressions centering on the Houston Ship Channel. Simply stated, these workers imply that the major ground-water withdrawals from the industrial complexes along the channel are causing much of the land subsidence in Harris County. The object of this paper is to show that subsidence does not conform to a simple model. The Houston-Galveston area is interlaced with over 150 miles of active faults exhibiting topographic escarpments and several hundred miles of faults that have no associated escarpments but that control drainage networks and coincide with photographic lineations. These faults appear to be hydrologic barriers that divide Harris and Galveston Counties into several individually subsiding basins. Because of these fault barriers, pumpage from individual fault-bound compartments may not contribute significant land subsidence beyond the bounding fault. Land subsidence needs to be considered within this structural framework.

STRUCTURAL FRAMEWORK

Tertiary sediments of the Texas Gulf coast have been extensively faulted by growth faults and faults associated with shallow-piercement and deep-seated salt domes. Many of the subsurface faults extend to land surface (either a Recent or Pleistocene surface) and do not die out in the upper Tertiary sediments. The majority of these faults are either presently inactive, or the rate of movement is so slow that no obvious topographic fault escarpment has developed. The surficial evidence that these faults do extend to land surface is subtle. Rectilinear drainage patterns indicate structural control. Aerial photographic lineations and bayous commonly coincide with the surface traces of faults extrapolated from the subsurface (Kreitler, 1976).

Similarly the active surface faults in the Houston area are not just surficial features, but are integrally related to subsurface structures. Many of the surface faults are coincident with the surface traces of faults extrapolated from the subsurface (fig. 5). These surface traces were determined by extrapolating subsurface faults based on Geomap data. A fault plane dip of 45° or the dip calculated between two datum surfaces was used for the extrapolations. Van Sicien (1967) described the continuity of the Addicks surface fault in western Houston with the subsurface fault controlling the location of the Addicks oil field. Woodward-Lundgren and Associates (1974) showed a similar relationship between a surface fault and its subsurface counterpart in Pasadena (eastern Houston), Texas.

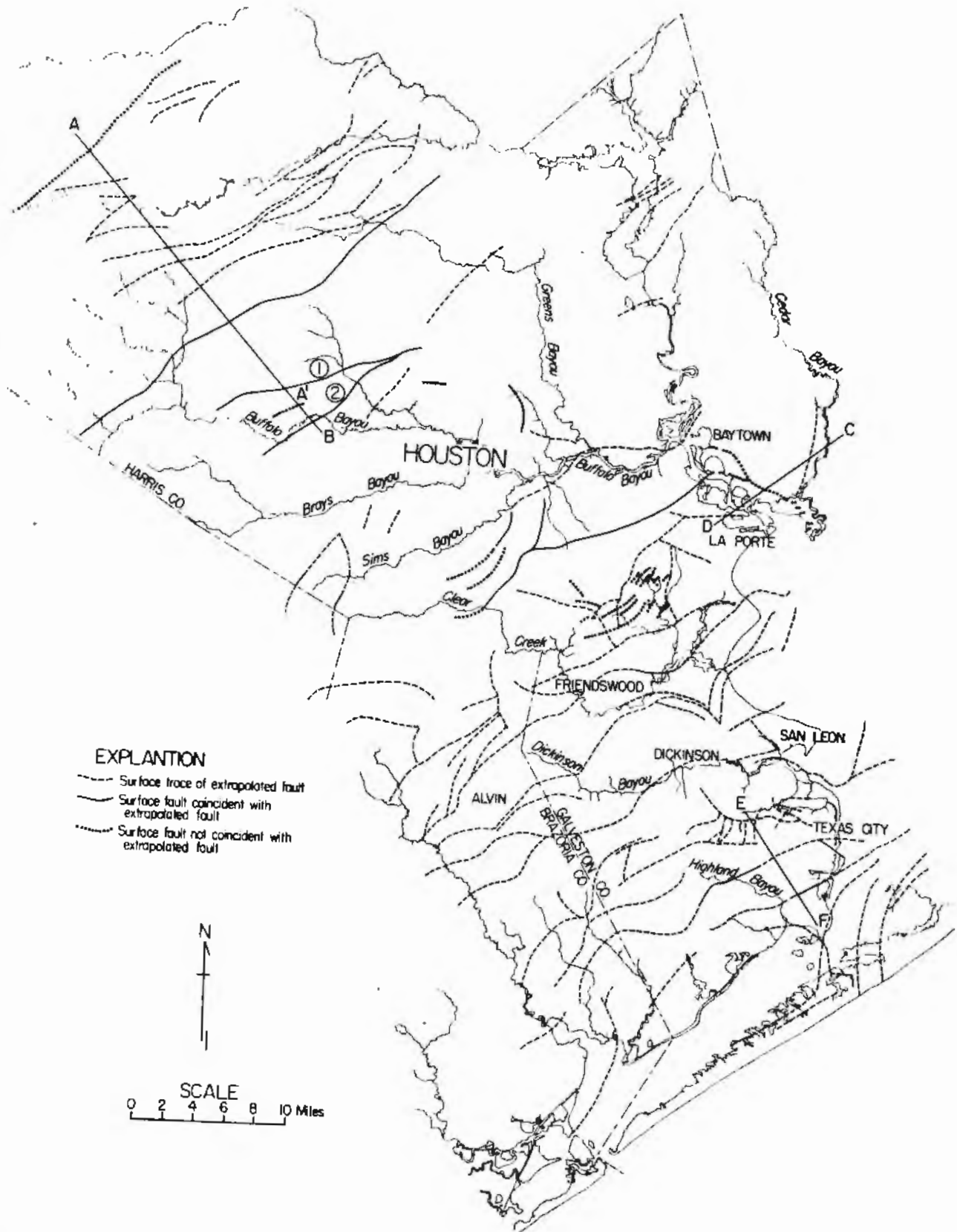


Figure 5. Active surface faults and surface traces of extrapolated subsurface faults, Harris and Galveston Counties, Texas.

Several streams and bayous in the Houston-Galveston area (Clear Creek, Highland Bayou, Dickinson Bayou, Brays Bayou, Cedar Bayou, Sims Bayou, and Greens Bayou) appear to be structurally controlled. These streams are parallel to active faults and fault extrapolations or have rectilinear drainage patterns indicating fault control (fig. 5). A model of the structural framework for subsidence must include the extrapolated faults and the structurally controlled streams as well as the active surface faults.

MECHANISM OF FAULT ACTIVATION

Even though many of the Tertiary faults in the Texas Coastal Zone extend upward to land surface, few show evidence of recent movement. It is in the areas of extensive fluid withdrawal (water, oil, or gas) that these passive structural features become active faults. At least 150 miles of active faults with topographic escarpments occur in Harris and Galveston Counties where over 500 million gallons of water per day are pumped. Active faults in Baytown, Texas, were recognized as early as 1926 by Pratt and Johnson (1926).

McClelland Engineers (1966) and Reid (1973) measured surface displacement of active faults from topographic profiles along highways. McClelland Engineers (1966) and Van Siclen (1967) suggested that faulting and subsidence were unrelated because the faults crossed the subsidence contours and the strikes of the faults were not tangential to the regional subsidence bowl. Castle and Youd (1972) challenged Van Siclen's conclusions and suggested that radial-oriented strain from aquifer compaction was the mechanism for fault activation. Reid (1973) correlated horizontal fault displacement from two active faults in western Houston with decline of the piezometric surface. None of these investigators, however, suggested a regional fault control of subsidence.

Faults in the Houston-Galveston area may act as hydrologic barriers. Fluid production on one side of a fault causes piezometric surface declines and aquifer compaction on that side of the fault and not on the other. This differential sediment compaction is translated to the surface as differential land subsidence or fault movement.

Data from tilt meters across two active faults in western Houston show annual cyclic vertical movement that coincides with change of the piezometric surface of the Chicot aquifer (fig. 6). On the Long Point fault, vertical movement increased as the piezometric surface declined (May 1971 to October 1971). When the piezometric surface rose between October 1971 and March 1972, fault movement decreased. This

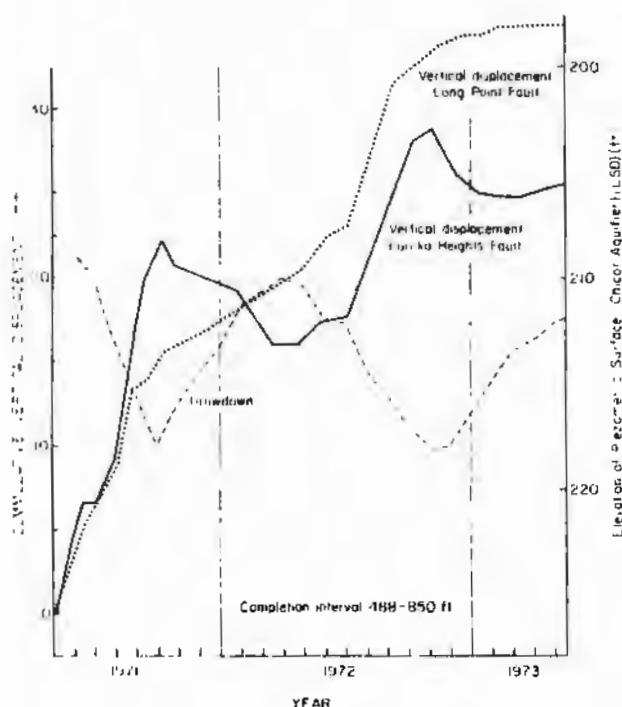


Figure 6. Cumulative vertical displacement on Long Point and Eureka Heights faults in the western part of Houston compared to drawdown of piezometric surface of Chicot aquifer. Displacement data for April 1971 to April 1972 from Reid (1973); displacement data for May 1972 to May 1973 and drawdown data for Federal observation well L-J-65-13-408 from R. Gabrysch (personal communication, 1974).

cycle was repeated for the next year. Data from a tilt meter on the Eureka Heights fault show a better correlation of cumulative fault movement related to changes of the piezometric surface. A linear regression analysis between cumulative fault displacement and decline in the piezometric surface has coefficients of .98 and .99 from April 1971 to October 1971 and March 1972 to October 1972, respectively; this indicates a very close statistical relationship. Movement on the Eureka Heights fault suggests that differential compaction of the aquifer is the principal mechanism causing this man-induced fault activation. As the piezometric surface rose between October 1971 and March 1972 and between October 1972 and March 1973, the downthrown side of the fault rebounded. This rebound can be explained as differential elastic expansion of the aquifer. As the piezometric surface rose, a decrease in the vertical effective stress permitted a relaxation of the elastic component of aquifer compression. For the tilt meter to measure fault rebound, differential

elastic rebound of the aquifer must occur since no surficial differential displacement will occur if an aquifer rebounds equally. This differential elastic rebound can be caused by a variable rise of the piezometric surface on either side of the fault, suggesting that the fault acts as a partial hydrologic barrier. A profile of the elevation of the piezometric surface across five faults in northwestern Harris County further indicates that the elevation of the piezometric surface is fault controlled (fig. 7). The piezometric surface drops across the Addicks fault and is at its highest and declines on either side of the Long Point fault, the Piney Point fault, and the Eureka Heights fault.

INTERRELATIONSHIP OF FAULTING AND SUBSIDENCE

Releveling profiles (all subsidence data based on National Geodetic Survey releveling programs) across active faults quantify the increased subsidence on the downthrown side. A subsidence profile across

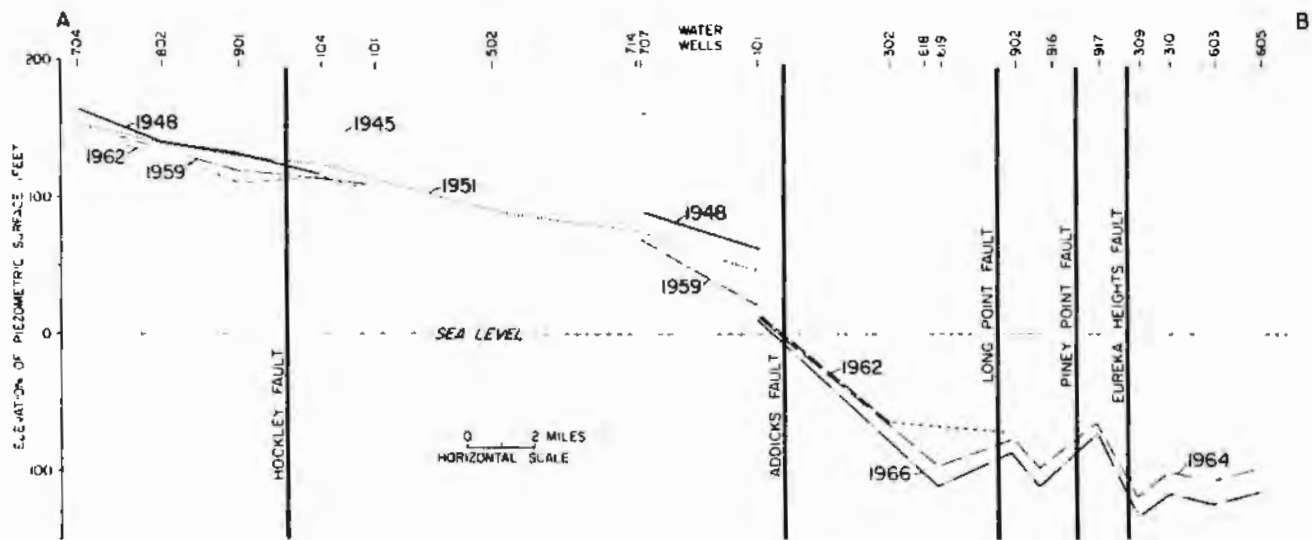


Figure 7. Fault control of the elevation of the piezometric surface, northwestern Harris County, Texas.
See figure 5 for profile location.

three active faults—the Hockley, Addicks, and Long Point faults—in northwestern Harris County shows a definite increase in subsidence on downthrown sides of each fault (fig. 8). The increase in subsidence along this profile, however, cannot automatically be attributed to ground-water withdrawal and differential aquifer compaction because these faults were active before major ground-water production occurred. Topographic maps (1-foot contour intervals) surveyed in 1917 before extensive ground-water production show that topographic escarpments were coincident with these faults. The increased subsidence on the downthrown sides of the respective faults (fig. 8) may be the result of natural tectonic activity as well as fluid production.

More conclusive evidence that ground-water withdrawal causes differential land subsidence (uneven loss of land elevation over a relatively short distance) and recent fault activation is a reversal in the normal direction of fault movement coupled with increased subsidence on the normal upthrown side of the fault. Fault movement opposite to the normal movement during its Tertiary history indicates that fluid withdrawal and not natural tectonic forces are currently the important mechanisms.

The Mykawa-Battleground fault, which extends from Mykawa, southwest Harris County, to Baytown, eastern Harris County, exhibits recent reversals of fault movement. There are also increases in subsidence on the upthrown side and increases in subsidence on both the upthrown and downthrown sides with the fault remaining in a zone of minimal subsidence. Based on subsurface mapping by Geomap Co., the natural direction of fault movement on the Mykawa-Battleground fault is down to the coast. Seven

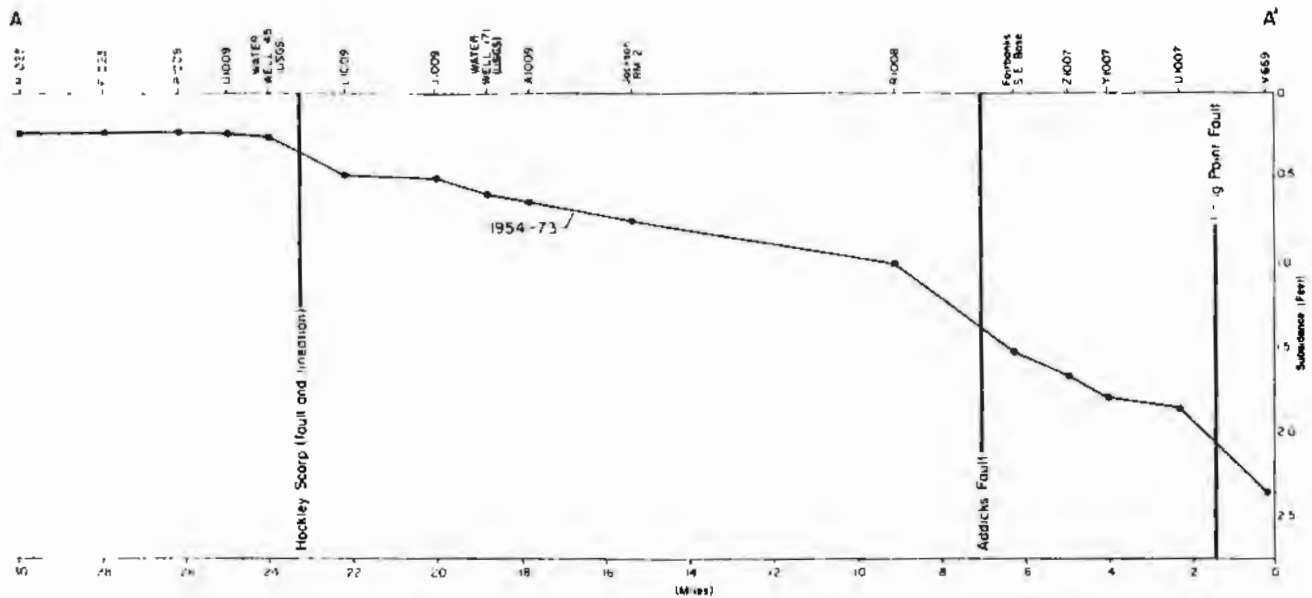


Figure 8. Increased subsidence across Hockley fault, Addicks fault, and Long Point fault, northwestern Harris County, Texas. See figure 5 for profile location.

subsidence profiles cross the fault at different locations (fig. 9). At profiles 102 and 105, increased subsidence occurs on the upthrown side of the fault, and the fault scarp faces inland. At profile 135, the fault scarp faces inland, but subsidence increases on both sides of the fault with the fault remaining in a zone of minimal subsidence. Profile 129 shows rapid increase of subsidence on both sides of the fault with minimal subsidence at the fault; no fault scarp is evident. At Profile 132, there is no rapid increase in subsidence or evidence of a topographic escarpment. At profiles 123 and 126, increased subsidence occurs on the upthrown side. A fault scarp at profile 126 faces in the opposite direction towards the coast; this fault scarp predates ground-water production and represents the natural direction of fault movement. The increased subsidence on the upthrown side of the Tertiary fault can be explained if differential compaction resulting from ground-water withdrawal is the mechanism for fault activation. The increase in subsidence on both sides of the fault suggests that the fault is acting as a hydrologic barrier with ground-water production on both sides of the fault.

OTHER EXAMPLES OF FAULT CONTROL OF SUBSIDENCE

In the Texas City area, heavy ground-water production has caused over 5 feet of land subsidence. Subsidence has been restricted to a limited area because of fault control on both the northern and southern sides (fig. 10). The rapid increases in subsidence on the northern side (C639 to V1006) and the southern side (E1138 to X305) are coincident with an extrapolated subsurface fault (on the northern side) and an

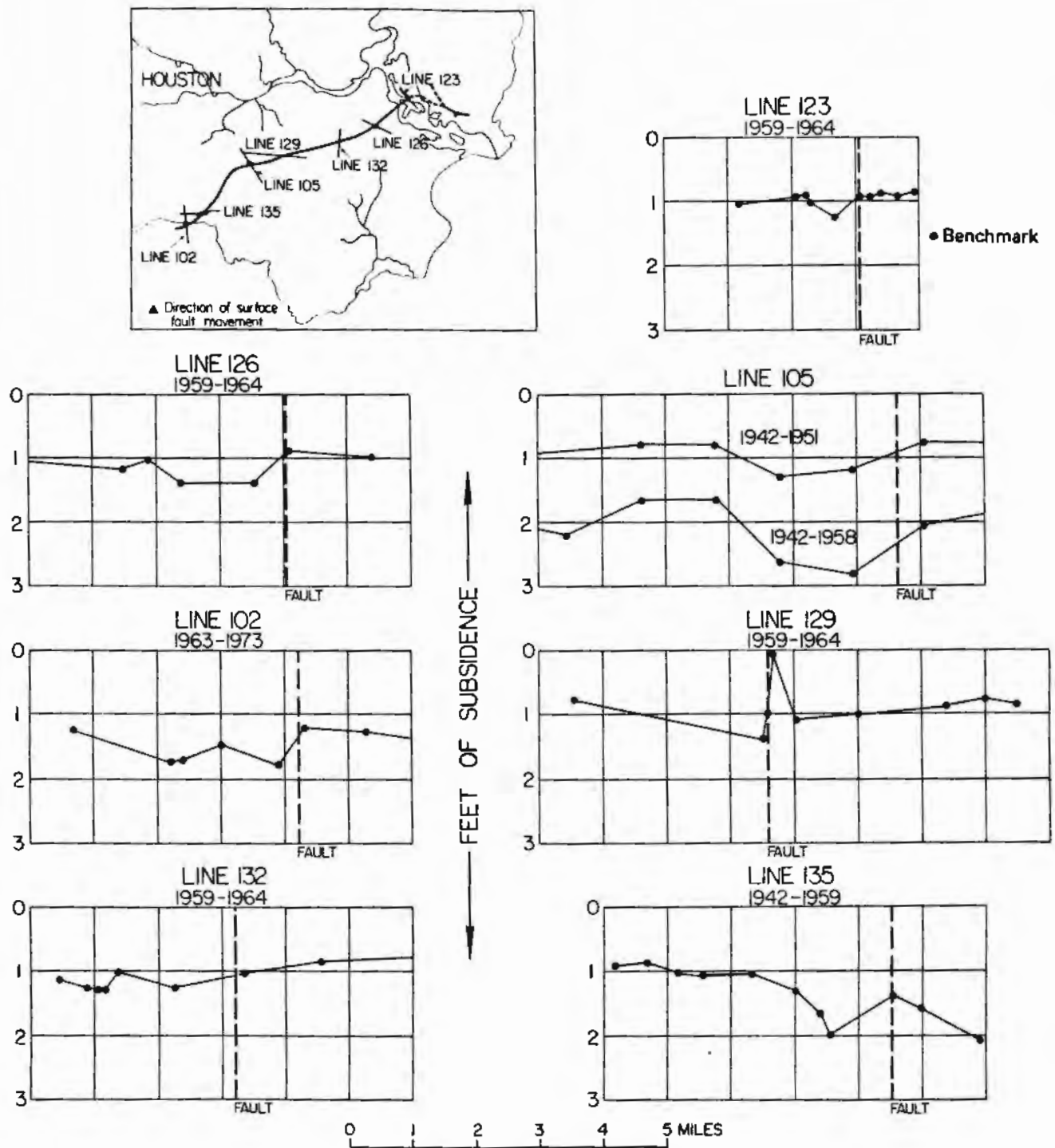


Figure 9. Subsidence profiles and direction of surface faulting along Mykawa-Battleground fault, Harris County, Texas.

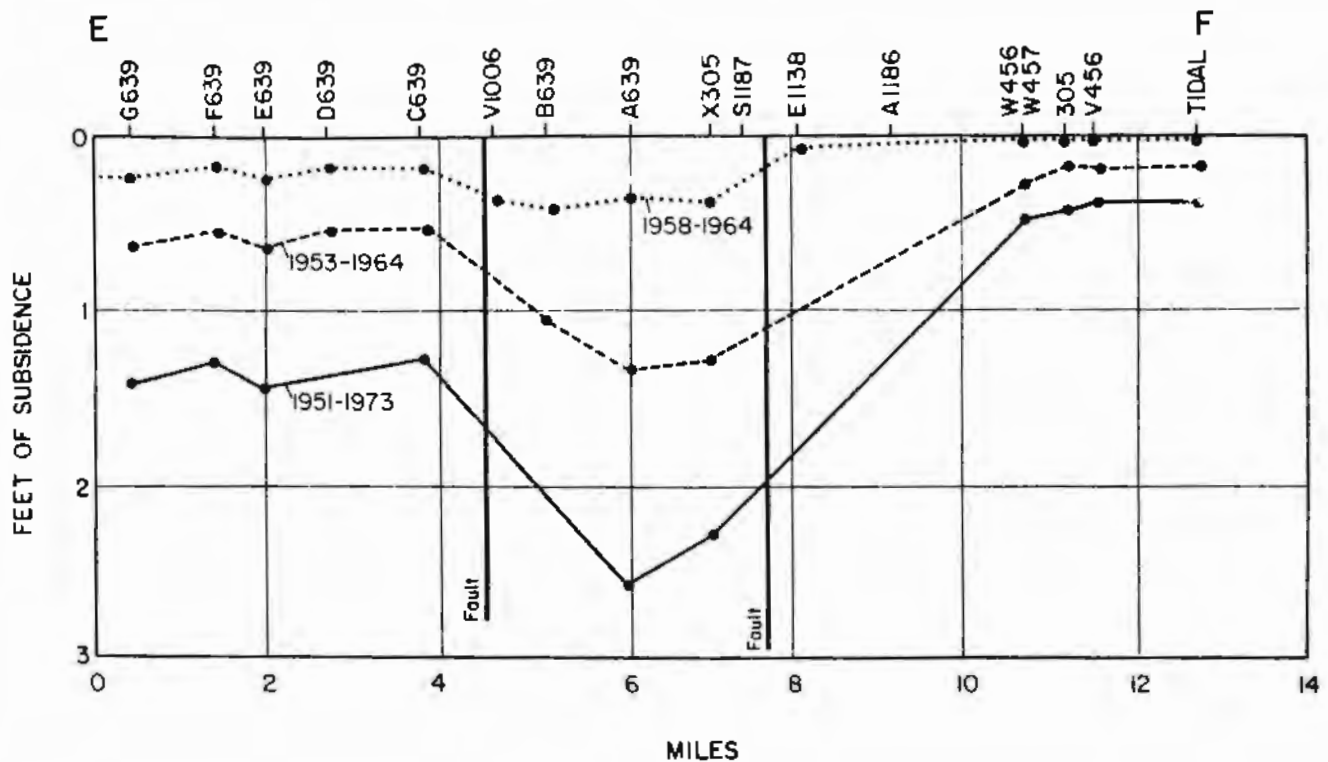


Figure 10. Fault control of subsidence, Texas City area, Galveston County. See figure 5 for profile location.

active surface fault (on the southern side). No topographic escarpment is evident along the trace of the extrapolated fault. The fault on the southern side of the Texas City area exhibits a reversal in direction of fault movement; in the subsurface, the fault is dipping down to the coast, whereas the surface topographic escarpment is dipping up to the coast. Severe subsidence has been restricted to the Texas City area and has not adversely affected the city of Galveston. The fault acting as a hydrologic barrier has probably prevented significant subsidence in Galveston.

The surface trace of an extrapolated subsurface fault parallels Cedar Bayou, suggesting that the location of this bayou is structurally controlled (fig. 5). This extrapolated fault is also coincident with a rapid increase in subsidence (fig. 11). Severe subsidence appears to have been restricted to the Baytown area and has not yet affected Chambers County because of an inferred hydrologic barrier created by the fault.

Sections of Buffalo Bayou which flow through the Pasadena-Channelview area, an area of maximum ground-water pumpage and maximum subsidence, are coincident with extrapolated faults and active surface faults. Other sections of the bayou exhibit structurally controlled, rectilinear drainage patterns. Releveling data indicate that subsidence is far less on or next to the bayou than it is .25 mile away (Kreitler, 1976). A subsidence map for 1959 to 1964 demonstrates the relatively low rates of subsidence along Buffalo Bayou

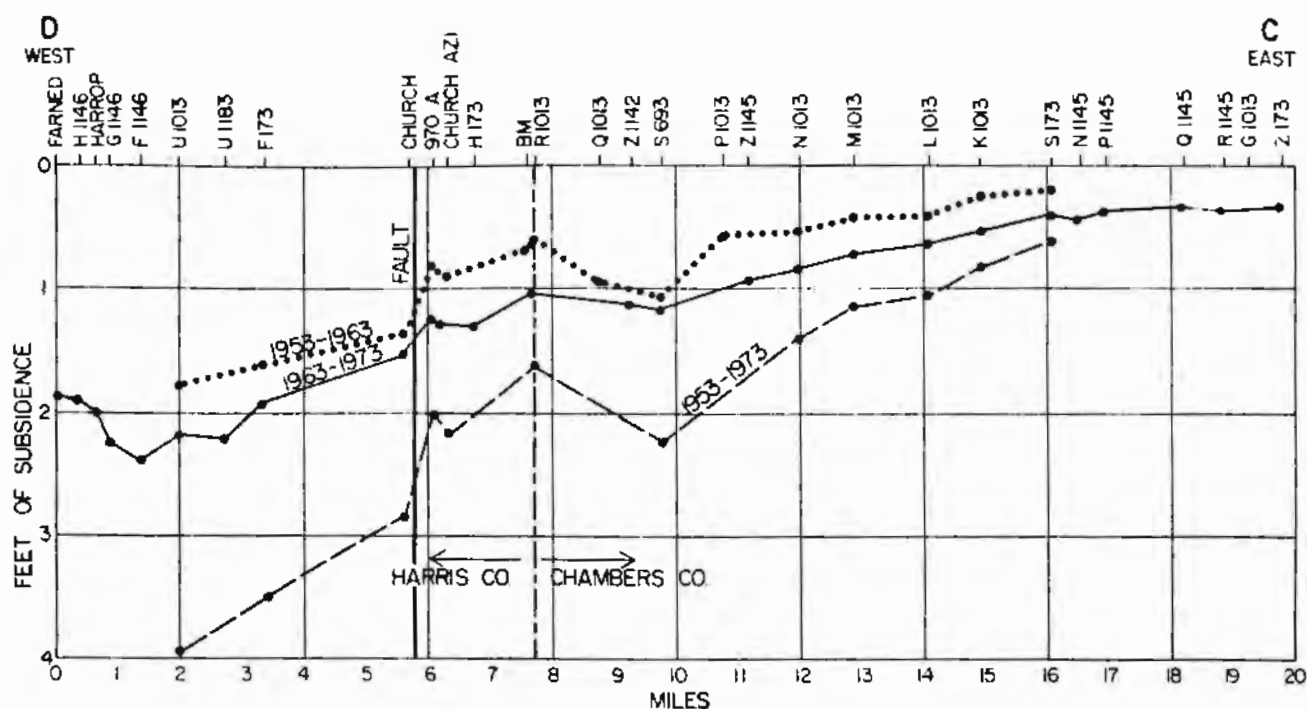


Figure 11. Fault control of subsidence, Baytown, Harris County, Texas. See figure 5 for profile location.

compared to the high rates of subsidence in the industrialized areas of Pasadena and Channelview (fig. 12). Buffalo Bayou and the extrapolated fault bisect the large subsidence bowl that was contoured by Gabrysch and Bonnet (1975), Marshal (1973), and others into two separately subsiding basins. This is another example of increased subsidence on both sides of a fault with the fault remaining in a zone of minimal subsidence.

Similar fault control of subsidence is exhibited on 26 subsidence profiles in Harris, Galveston, and parts of Brazoria, Fort Bend, and Chambers Counties. The location, direction, and magnitude of 87 zones of differential subsidence (from the 26 subsidence profiles) that coincide with active surface faults, fault extrapolations, streams and bayous, and aerial photographic lineations are shown on figure 13. Nearly all points of differential subsidence on the 26 profiles are coincident with some fault-related feature. Fault extrapolations and lineations that exhibit no apparent control of subsidence have not been included. Thirteen examples (fig. 13) show increased subsidence on both sides of a fault with the fault remaining in a zone of minimal subsidence. These faults may act as hydrologic barriers with ground-water production on both sides.

The subsidence patterns exhibited in figure 13 suggest that the producing aquifers and the associated subsidence are compartmentalized. Ground-water production from one compartment causes

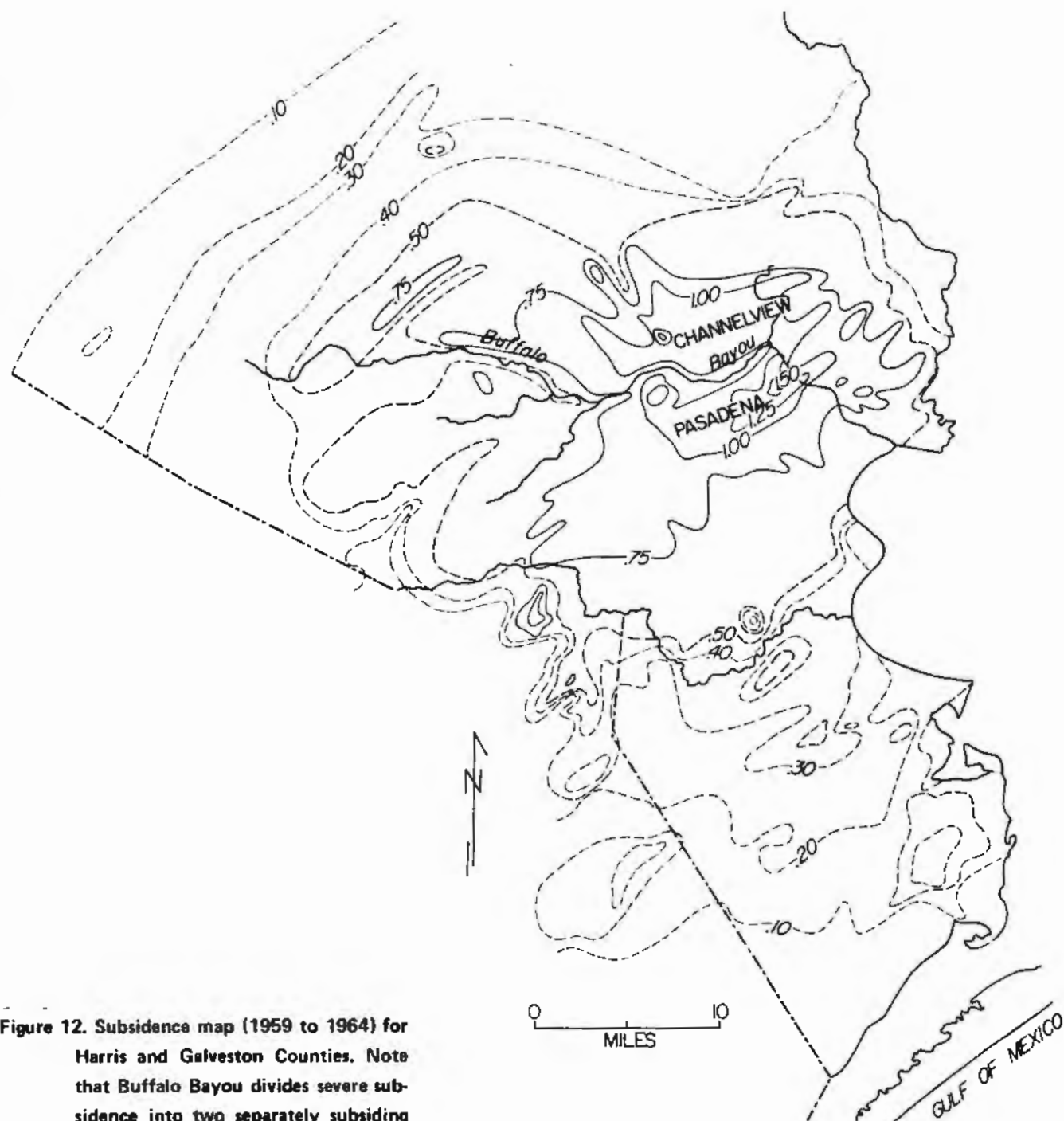


Figure 12. Subsidence map (1959 to 1964) for Harris and Galveston Counties. Note that Buffalo Bayou divides severe subsidence into two separately subsiding bowls.

sediment compaction and associated land subsidence within that compartment but may not adversely affect other areas of the aquifer. The areas with the greatest piezometric decline and land subsidence are the South Houston-Pasadena-Baytown area and the Texas City area. In both areas, faults on the north and south sides appear to restrict the area affected by severe subsidence.

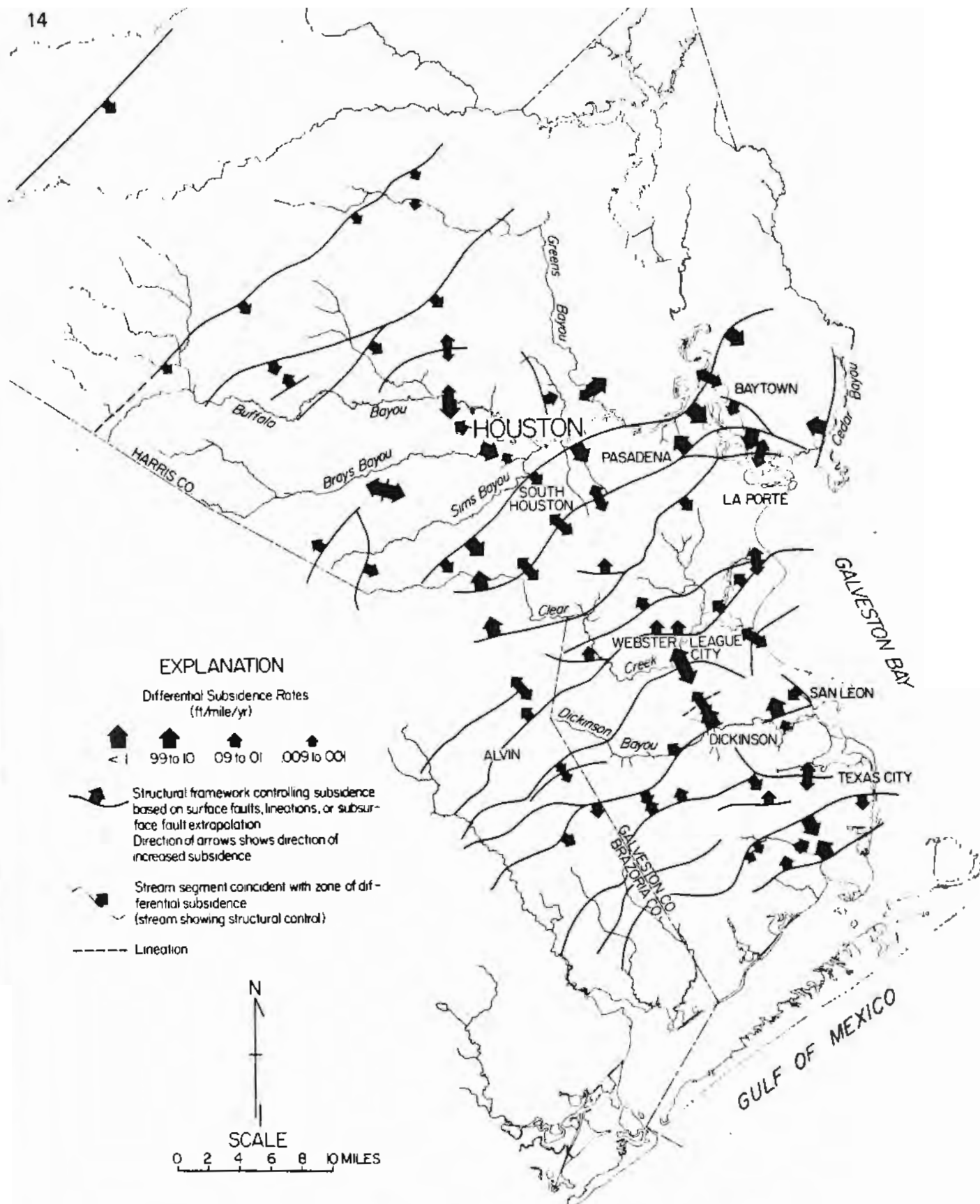


Figure 13. Coincidence of differential subsidence with active faults, surface traces of extrapolated subsurface faults, structurally controlled streams, and aerial photographic lineations. Direction of arrow indicates the magnitude of differential subsidence (ft/mile/year).

DISCUSSION

This paper demonstrates fault control of subsidence. It does not, however, completely resolve whether the faults act as permeability barriers and control the piezometric surface. It only implies this relationship.

Another mechanism for fault activation is needed, however, if differential compaction is not the appropriate model. Natural fault activation has been advocated by several authors (for example, McClelland Engineers, 1966, and Sheets, 1976). The problem with the natural activation model is that all identified active faults with significant displacement occur in areas of extensive fluid production (oil, gas, or water). Surface faults are present in non-fluid-producing areas of the Texas Coastal Zone, but rates of movement are so slow that few topographic escarpments and little evidence of recent movement exist (Kreitler, 1976). Tracing these structures along strike from areas of no fluid production to areas of fluid production shows a change from a passive to an active fault (for example, the Saxet fault; Kreitler and Gustavson, 1976). Fluid production, therefore, is causing fault activation.

Van Siclen (1967) and Castle and Youd (1972) discussed two different mechanisms for ground-water activation of faults. Van Siclen (1967) suggested that an increase in the vertical effective stress caused by a declining piezometric surface activates the faults. Castle and Youd (1972) demonstrated that Van Siclen's mechanism should increase stability and inhibit fault movement rather than activate faults. Castle and Youd's (1972) alternative model suggested that surface faulting was the result of centripetally directed horizontal movements and radially oriented strain. Surface ruptures would be concentrated along planes of weakness, that is, the Tertiary growth faults that extend to land surface. Several factors contradict the model of Castle and Youd (1972) and favor fault control of the piezometric surface and differential compaction: (1) reversals in direction of fault movement, (2) increased subsidence on the upthrown side, and (3) increased subsidence on both the upthrown and downthrown sides with the fault remaining in a zone of minimal subsidence.

If the elevation of the piezometric surface of the Chicot and Evangeline aquifers is fault-controlled, then ground-water management programs need to be reevaluated. For example, Jorgensen's (1975) analog model, designed to simulate piezometric declines in the Chicot and Evangeline aquifers, does not consider the faults as boundary conditions. This ground-water pumpage model develops a single cone of depression that affects a two-county area. With faults acting as hydrologic barriers, the effects of pumpage may be

much more localized. The effects of fault control must be considered in determining who is responsible for the land subsidence in Harris and Galveston Counties.

CONCLUSIONS

1. Additional land subsidence will increase the area that will be inundated from hurricane flood surges.
2. The Houston-Galveston area is interlaced with active surface faults and faults that control drainage patterns and create subtle aerial photographic linear patterns.
3. Ground-water production activates the faults by differential compaction of the aquifer. The faults appear to be hydrologic barriers.
4. The faults compartmentalize land subsidence into several individual basins. Ground-water pumpage from one fault-bound basin may not adversely affect subsidence in another basin.
5. The National Geodetic Survey should consider the location of surface faults in designing future releveling surveys.

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