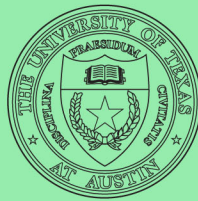


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FAULTING AND LAND SUBSIDENCE FROM GROUND-WATER AND HYDROCARBON PRODUCTION, HOUSTON-GALVESTON, TEXAS

C. W. Kreitler

Reprinted from
Symposium of Anaheim, 1977
Land Subsidence, IAHS Publication No. 121

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BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
W. L. Fisher, *Director*



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FAULTING AND LAND SUBSIDENCE FROM GROUND-WATER AND
HYDROCARBON PRODUCTION, HOUSTON-GALVESTON, TEXAS

by

Charles W. Kreitler

ABSTRACT

Land subsidence in Harris and Galveston Counties, Texas, results from production of both ground water and hydrocarbon. Although ground-water withdrawal (over 2 million m³) is the predominant cause of land subsidence, subsidence and faulting are also associated with at least six oil and gas fields: South Houston, Clinton, Mykawa, Blue Ridge, Goose Creek, and Webster fields.

The two-county area is interlaced by active surface faults with topographic escarpments and surface faults which control drainage patterns and create subtle photographic linear patterns, but which exhibit no topographic escarpments.

Fluid production activates a given fault by differential compaction of the sediments on either side of the fault. The faults appear to be partial fluid barriers which compartmentalize land subsidence. The Texas City area is an example of a subsidence compartment where subsidence has been restricted by growth faults. Correlation of electric log data from boreholes across the faults indicates as much

as 21 m of displacement of sand beds within the Chicot aquifer. This much offset of permeable beds is considered sufficient to create partial hydrologic barriers.

INTRODUCTION

Land subsidence in the Houston-Galveston area, Texas, U. S. A. (fig. 1), 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; Jorgenson, 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. These workers imply that major ground-water withdrawals from industrial complexes along the Ship Channel are causing much of the

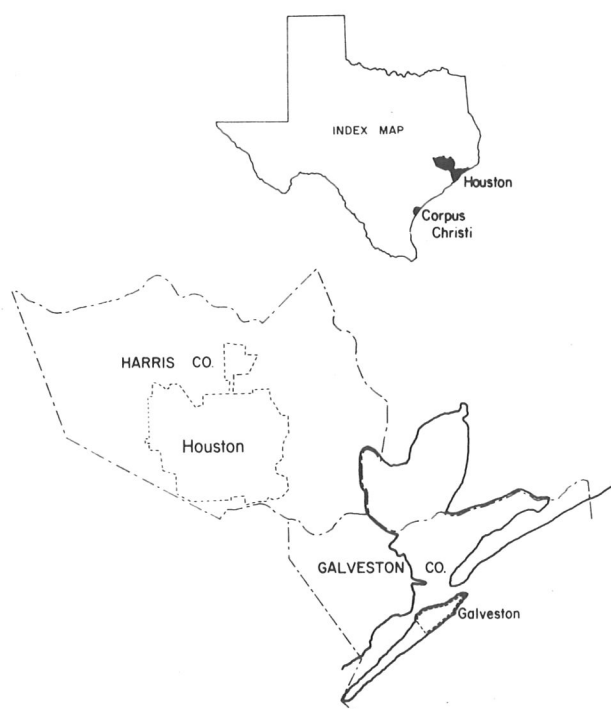


Figure 1. Map of Houston-Galveston area, Texas, USA.

land subsidence in Harris County. Extensive hydrocarbon production from approximately 75 fields has also occurred in the two-county area. As early as 1918 land subsidence and fault activation from hydrocarbon production were observed in the Goose Creek field, Baytown, Texas (Pratt and Johnson, 1926).

The Houston-Galveston area is interlaced with over 240 km of active faults exhibiting topographic escarpments, as well as with several hundred km of faults, not marked by escarpments, but which do control drainage networks and which do coincide with photographic lineations. This paper describes the interrelationship of fault activation and ground-water and hydrocarbon production on land subsidence.

STRUCTURAL FRAMEWORK

Tertiary sediments of the Texas Gulf coast have been cut by many growth faults and by 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) (fig. 2). Most 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 streams commonly coincide with the surface traces of faults extrapolated from the subsurface (Kreitler, 1976).



Figure 2. Shallow trench across Battleground Fault, Pasadena, Texas, showing complete offset of their sands. Fault offset approximately 1.5 ft (0.5 m). View looking southeast. Photograph courtesy of Wilbur Evans.

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. 3). Van Siclen (1967) described the continuity of the Addicks surface fault in western Houston with the subsurface fault which controls the location of the Addicks oil field.

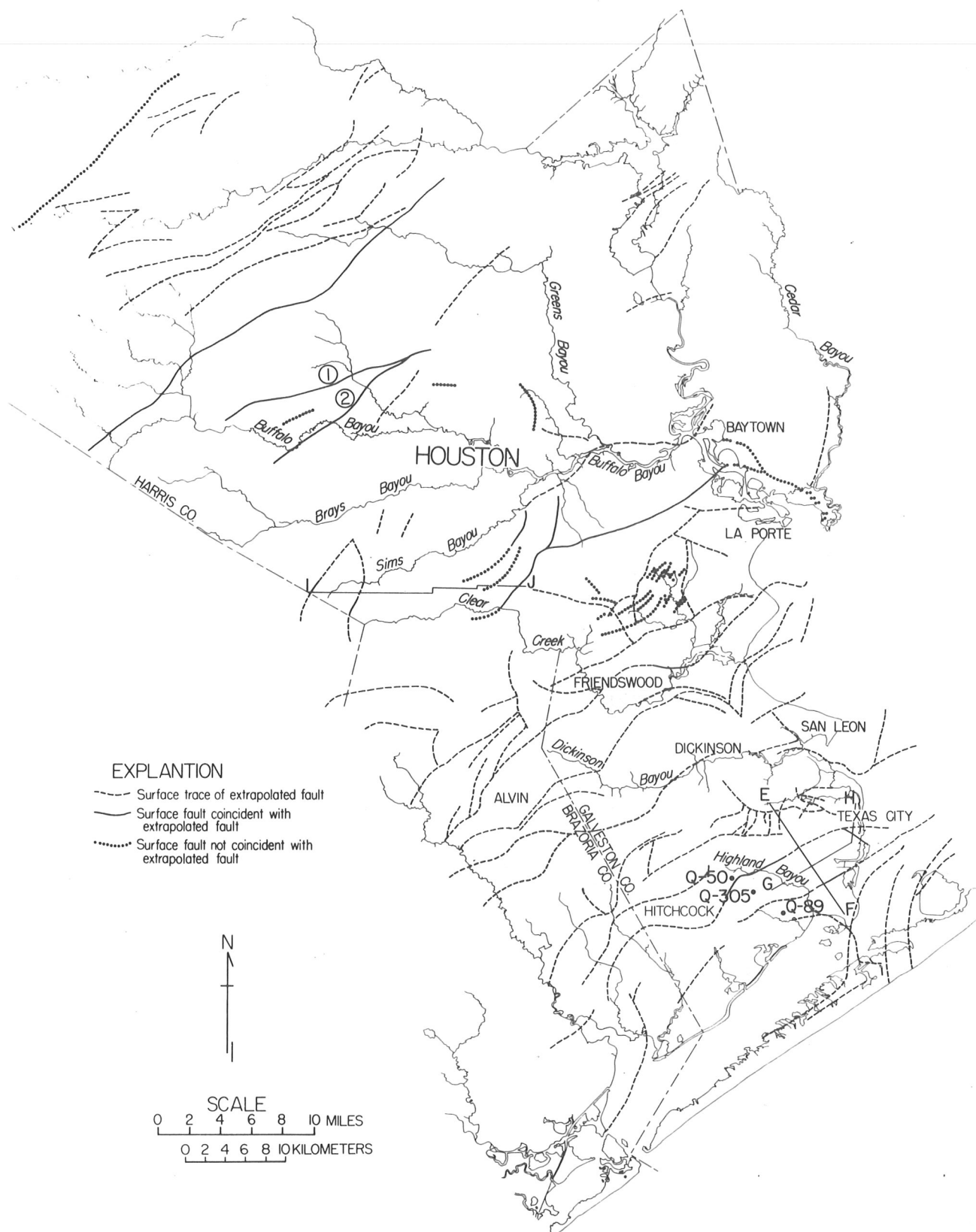


Figure 3. Active surface faults and surface traces of extrapolated subsurface faults, Harris and Galveston Counties, Texas. Surface traces were determined by extrapolating subsurface faults based on subsurface maps of Geomap Co. A fault plane of 45° or the dip calculated between two datum surfaces was used for the extrapolations.

The location of several streams and bayous in the Houston-Galveston area, such as Buffalo Bayou, Clear Creek, Highland Bayou, Dickinson Bayou, Brays Bayou, Cedar Bayou, Sims Bayou, and Greens Bayou, appears to be structurally controlled. These streams either are parallel to active faults and fault extrapolations or exhibit rectilinear drainage patterns indicating fault control (fig. 3).

FAULTING AND SUBSIDENCE FROM GROUND-WATER WITHDRAWAL

Even though many Tertiary faults in the Texas Coastal Zone extend upward to land surface, few show evidence of recent movement. However, in the areas of extensive fluid withdrawal (water, oil, or gas) these passive structural features become active faults. At least 240 km of active faults with topographic escarpments occur in Harris and Galveston Counties, where over 2 million m³ of water per day are pumped.

Data from tilt meters across two active faults in western Houston show annual cyclic vertical movement which coincides with change of the piezometric surface of the Chicot aquifer (fig. 4). On the Long Point fault, vertical movement increased as the piezometric surface declined (May 1971 to October 1971). When the piezometric surface rose from October 1971 to March 1972, fault movement decreased. This cycle was repeated for the next year. Data from a tilt meter on the Eureka Heights fault show a more definite correlation of cumulative fault movement related to changes of the piezometric surface. A linear regression analysis between cumulative fault displacement and

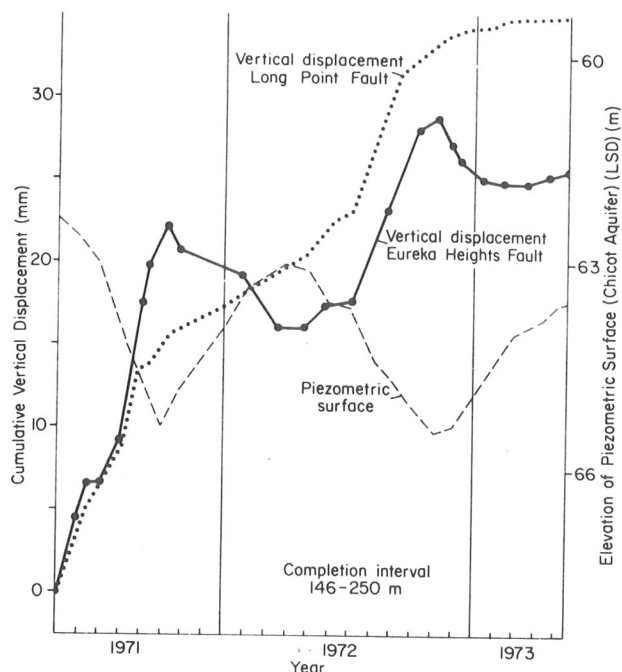


Figure 4. Cumulative vertical displacement on Long Point (1) and Eureka Heights (2) faults in the western part of Houston compared to elevation of piezometric surface of Chicot aquifer. Displacement data for April 1971 to April 1972 from Reid (1973); displacement data for May 1972 to May 1973 and draw-down data for Federal observation well L-J-65-13-408 from R. Gabrysch (personal communication, 1974). See figure 1 for meter locations.

decline of the piezometric surface has a correlation coefficient of .98 and .99 from April 1971 to October 1971, and from March 1972 to October 1972, respectively, indicating a very close statistical relationship. As the piezometric surface rose between October 1971 to March 1972, and between October 1972 to March 1973, the downthrown side of the fault rebounded relative to the upthrown side.

Faults in the Houston-Galveston area appear to act as fluid barriers. Fluid production on one side of a fault causes pressure declines and aquifer or reservoir compaction on that side of the

fault, but not on the other side. This differential sediment compaction is translated to the surface as differential land subsidence or fault movement.

Ground-water production is activating the Eureka Heights fault (fig. 4). The occurrence of rebound or reverse movement on the fault suggests that differential compaction is the principal mechanism of activation. This rebound of the downthrown side 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 reverse movement on the fault, 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 differential rise of the piezometric surface on either side of the fault, suggesting that the fault acts as a partial hydrologic barrier. Fault movement, as recorded by the tilt meters, is not affected by precipitation. A linear regression analysis of fault movement and rainfall (International Airport, Houston, National Weather Service) for the same time periods has a correlation coefficient of 0.27, which indicates that shrinking and swelling of soils during dry and wet periods is not the cause of tilt-beam movement. The repetition of the fault movement cycle for the second year indicates that the meter boxes are not "settling in" to the soil, but are measuring real fault displacement.

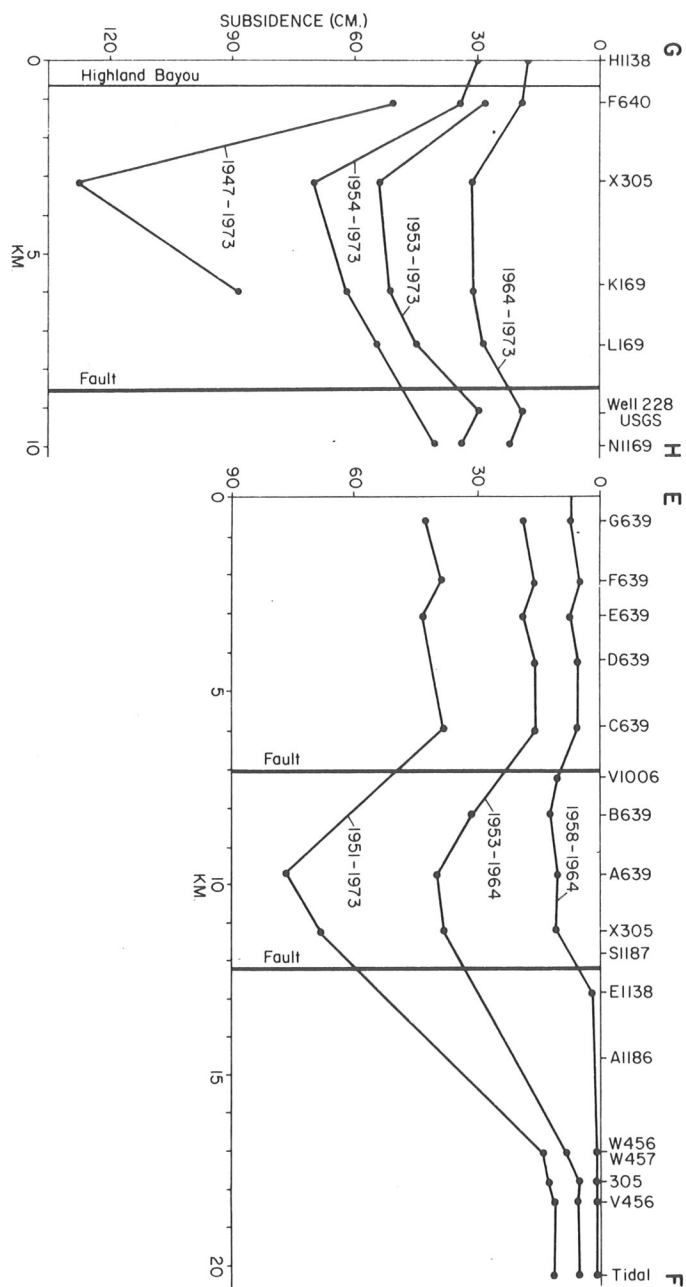


Figure 5. Fault control of subsidence, Texas City area, Galveston County. All subsidence data for all figures from adjusted NGS level lines. See figure 1 for profile locations.

In the Texas City area, Galveston County, where heavy ground-water production has caused approximately 1.5 m of subsidence, subsidence has been restricted to a limited area between faults on the northern and southern sides, and another structural feature (reflected by Highland Bayou) on the western side. Ground-water production between the two faults and Highland Bayou is $12 \times 10^6 \text{ m}^3/\text{year}$; south of the fault there is no production (Harris-Galveston Coastal Subsidence District, 1976 permit applications). Sharp increases in subsidence coincide with the faults and the bayou (fig. 5). Electric log correlations across the two faults show significant displacements in the producing freshwater section of the Pleistocene sediments. Across the northern fault there are 21 m of throw at 150 m, and across the southern fault there are 15 m of displacement at 200 m (fig. 6). On the southern fault, the downthrown side in the shallow subsurface is toward the coast. At the land surface, however, the fault scarp is facing inland, indicating a reversal in the direction of fault movement.

Growth faults in the Texas City area are being activated by ground-water withdrawal, as shown by the reversal in the direction of fault movement on the southern fault. Conversely, these faults are probably limiting the geographic extent of piezometric decline, aquifer compaction, and subsequently land subsidence. The fault displacements, exhibited in the shallow subsurface, are considered sufficient to cause hydrologic boundaries.

Sections of Buffalo Bayou, which flows through the Pasadena-

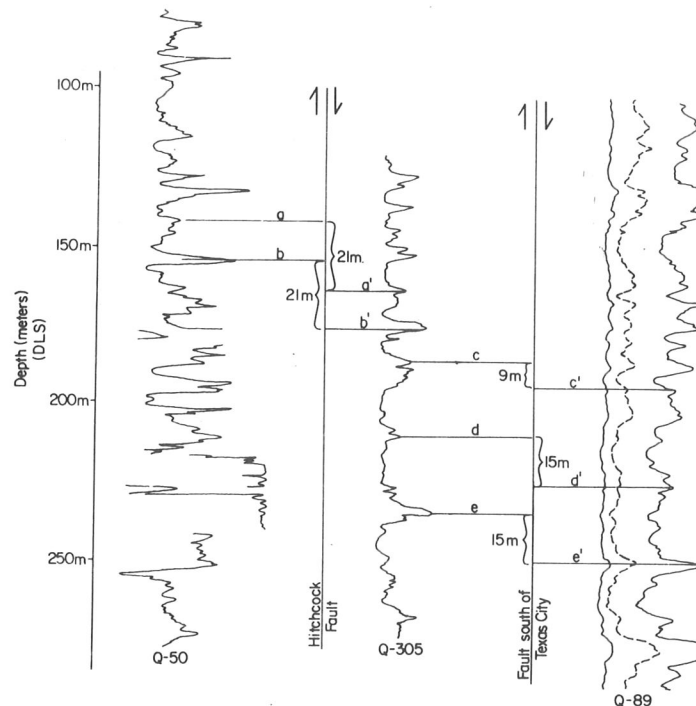


Figure 6. Fault displacement in shallow subsurface across the Hitchcock fault (21 m) and the fault south of Texas City (15 m). Well locations on figure 1.

Channelview area (the area of maximum ground-water pumpage and maximum subsidence), coincides with traces of extrapolated faults and active surface faults. Other sections of the Bayou exhibit rectilinear drainage patterns. Releveling data indicate that subsidence is much less at the bayou than at a distance of 0.4 km (fig. 7). A subsidence map for 1959-1964 demonstrates the relatively low rates of subsidence along Buffalo Bayou compared to the high rates of subsidence in the industrialized areas of Pasadena and Channel view (fig. 7). Buffalo Bayou and the extrapolated fault bisect the large subsidence bowl contoured by Gabrysch and Bonnet (1975), Marshal (1973),

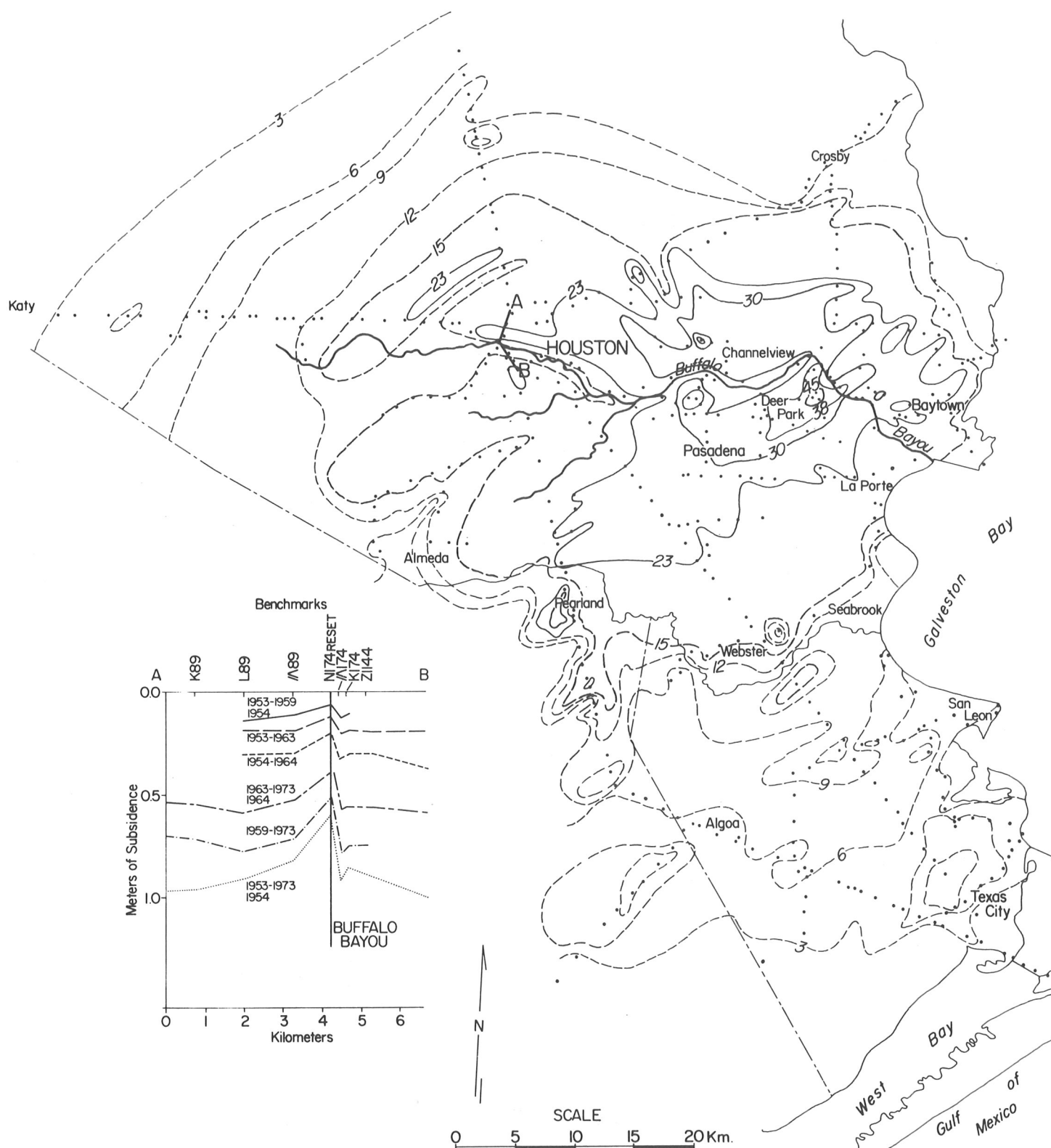


Figure 7. Subsidence map (1959 to 1964) for Harris and Galveston Counties. Note that Buffalo Bayou divides severe subsidence into two separately subsiding bowls. Subsidence profile across Bayou shows rapid increase of subsidence on both sides of Bayou. Subsidence contours in cm. Dots indicate data point.

and others, into two separately subsiding basins. This demonstrates that there may be more subsidence on both sides of a fault than along the trace of the fault.

FAULTING AND SUBSIDENCE FROM OIL AND GAS PRODUCTION

Land subsidence and fault activation are also attributable to oil and gas production. The Saxet oil and gas field, although not in the Greater Houston area, but west of Corpus Christi, Texas, best demonstrates the interrelationship between oil and gas production and faulting and land subsidence in the Texas Coastal Zone.

In the Saxet field, a 2 m scarp has appeared along a segment of the surface extrapolation of a regional growth fault. The active segment of this fault lies almost exclusively within the Saxet oil and gas field. The topographic escarpment dies out along strike away from the field; natural, geologic activation, therefore, is not considered significant. Because there is no ground-water production in the area, ground-water withdrawals cannot be responsible for the movement. Fault movement has occurred since the onset of oil and gas production (W. A. Price, personal communication, 1975). Leveling profiles across the Saxet field show sharp increases in subsidence at the fault (fig. 8). Subsidence rates from 1950 to 1959, 7 cm per year (0.22 ft per year), are approximately twice the rates from 1942-1950, 4 cm per year (0.14 ft per year). A rapid increase in gas production from shallow sands occurred from 1950 to 1959. Oil production, however, decreased during this period (Kreitler and Gustavson,

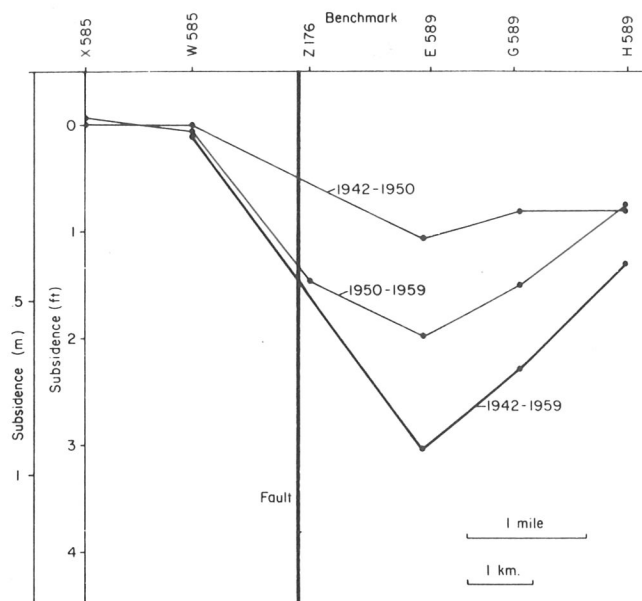


Figure 8. Land subsidence over Saxet oil and gas field, Corpus Christi, Texas. Note fault control of subsidence between benchmarks W585 and Z176.

1976). Production of high-pressured gas may have led to the compaction of the shallow gas sands on the downthrown side of the Saxet fault and subsequent differential land subsidence and fault activation.

If oil and gas production in the Corpus Christi area causes subsidence and fault activation, then these phenomena must also be considered for the Houston-Galveston area, where there is extensive hydrocarbon production. In 1976, at least 6 producing fields have associated subsidence and faulting (table 1). Detailed mapping of waterwell locations and approximate pumpage shows minimal shallow

Table 1. Land subsidence and surface faulting associated with oil and gas fields, Harris Co., Texas.

Field No.	Field Name	Producing Horizon (m)	Total Production (10 ⁶ bbl)	Subsidence (m)	Faulting (m)
1	South Houston	1,460 ²	39.3(1974) ²	0.3(1942-1958) ⁴	0.45(1972) ⁵
2	Clinton	915-2,134 ²	2.7(1974) ²	9	0.7 (1972) ⁵
3	MyKawa	1,483-2,645 ²	4.1(1974) ²	0.5(1942-1973) ⁴	0.5 (1942-1973) ⁶
4	Blue Ridge	1,420-2,381 ²	21.0(1974) ²	0.2(1942-1973) ⁴	0.15(1966-1972) ⁵
5	Webster	1,481-2,564 ²	41.3(1974) ²	9	0.45(1942-1975) ⁷
6	Goose Creek	300-1,300 ⁸	60.3(1926) ⁸	1.0(1917-1926) ³	0.43(1917-1926) ³

¹See Figure 9 for field locations

²Texas Railroad Commission

³Pratt and Johnson (1926)

⁴National Geodetic Survey

⁵Reid (1973)

⁶Kreitler (1976)

⁷Clanton and Amsbury (1975)

⁸Minor (1926)

⁹not available

ground-water production within the areas of these fields; piezometric surface declines, resulting from local, shallow, ground-water production, are therefore not considered a primary mechanism for field subsidence. Relevelling profiles across the Blue Ridge and Mykawa fields (fig. 9) show two components of subsidence. Below the dashed

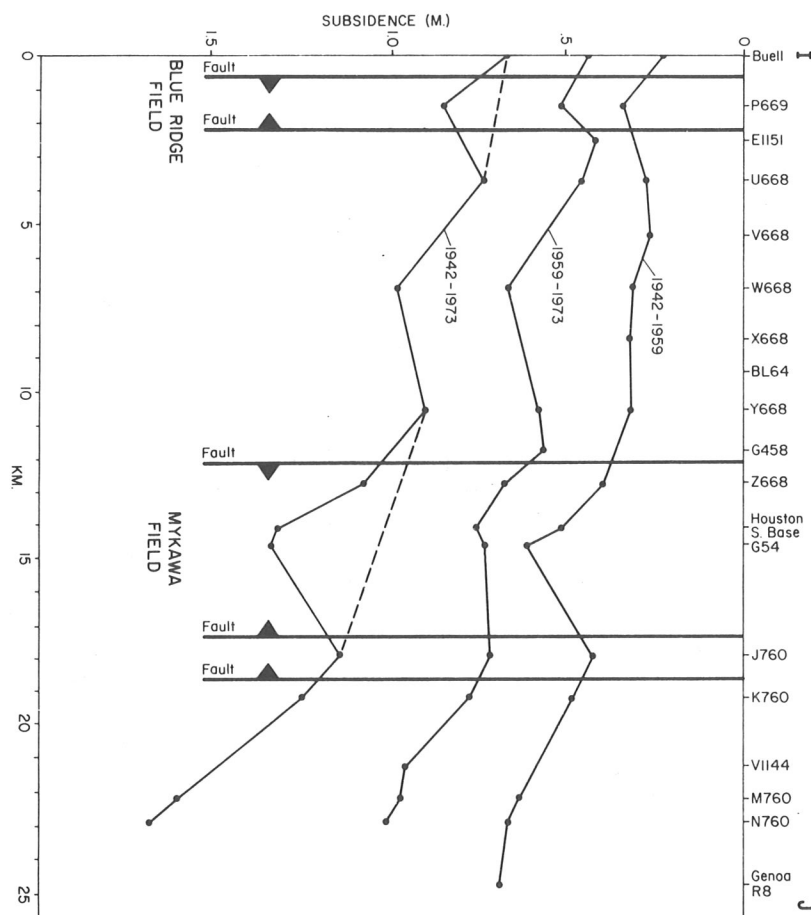


Figure 9. Subsidence over Blue Ridge and Mykawa oil fields. Note increased subsidence on both sides of surface faults east of Mykawa field. See figure 1 for profile location.

line is the localized component caused by hydrocarbon production. Above the dashed line is the regional component caused by ground-water production.

FAULT CONTROL SUBSIDENCE

Fault control of subsidence similar to figures 5, 8 and 9 is exhibited on 26 subsidence profiles in Harris, Galveston, and parts of Brazoria, Fort Bend and Chamber Counties. The location, direction, and magnitude of 87 zones of differential subsidence (from the 26 subsidence profiles) which coincide with active surface faults, fault extrapolations, streams and bayous, and aerial photographic lineations are shown on figure 10. Thirteen examples (fig. 10) 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, or with hydrocarbon production on one side and ground water on the other.

The areas with the greatest ground-water production 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 restrict the area affected by severe subsidence.

The subsidence patterns exhibited in figure 10 suggest that the producing aquifers and the associated subsidence are compartmentalized.

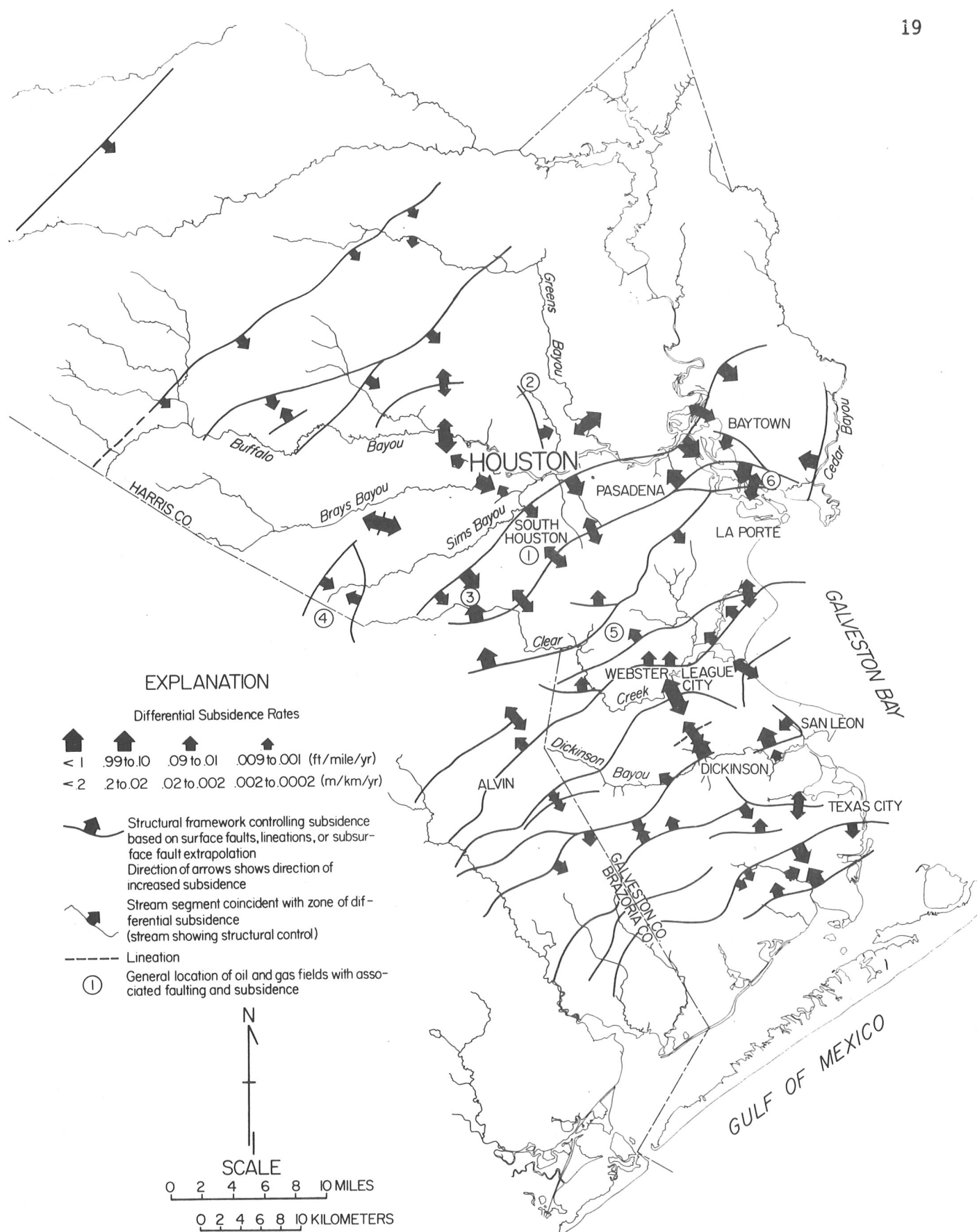


Figure 10. Coincidence of differential subsidence with active faults, surface traces of extrapolated subsurface faults, structurally controlled streams and aerial photographic lineations. Direction of arrow indicates the direction of increased subsidence. Size of arrow indicates the magnitude of differential subsidence.

SUMMARY

Subsidence in Harris and Galveston Counties is the result of both ground-water and hydrocarbon withdrawal. The structural elements (surface faults, extrapolated faults, faults expressed as drainage patterns) are the boundary conditions which limit the geographic extent of subsidence generated from either source of withdrawal. Ground-water production from one compartment causes sediment compaction and associated land subsidence within that compartment, but it may not adversely affect other areas of the aquifer.

Fault activation is the result of differential aquifer or reservoir compaction, as shown by the reversal in direction of fault movement on the fault south of Texas City, and on the tiltmeter data.

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