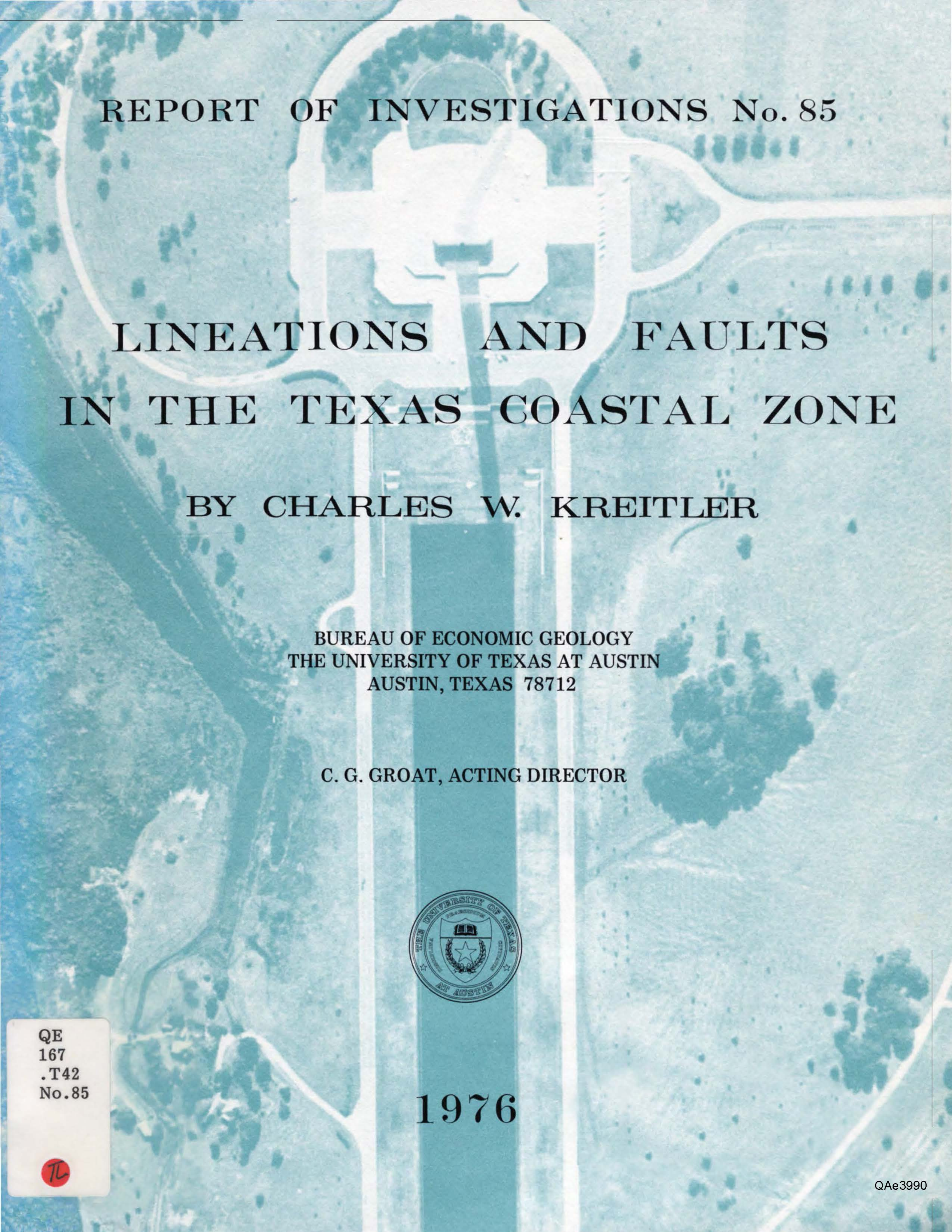

REPORT OF INVESTIGATIONS No. 85

LINEATIONS AND FAULTS IN THE TEXAS COASTAL ZONE

BY CHARLES W. KREITLER

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Cover photograph: Active fault through the reflection pool of the San Jacinto Monument. Note the absence of the gravel walkway at the monument end of the pool. See page 23 for detailed discussion.

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LINEATIONS AND FAULTS IN THE TEXAS COASTAL ZONE

Charles W. Kreitler

ABSTRACT

Over 7,000 miles of lineations have been observed on aerial photographic mosaics of the Texas Coastal Zone. These lineations, in part, represent the surface traces of faults originating in the Tertiary sediments and propagating through the Quaternary sediments. The extrapolation of subsurface faults from specific oil and gas reservoirs are commonly coincident to lineations in those areas. Some extrapolated fault traces weave back and forth across lineations for 10 to 20 miles and then coincide with another lineation and follow it for 20 miles. They also may partially represent fracture-joint systems within the sedimentary deposits of the Gulf basin.

In the Houston-Galveston area of land subsidence, lineations commonly correspond with zones of active faulting. Coincidence of lineations and active faults occurs along the Hockley escarpment and in the complexly faulted Ellington Air Force Base-NASA area. Many lineations coincide with zones of differential subsidence; fifty percent of intersections of subsidence profiles and lineations occur at points of differential subsidence. Differential subsidence may be a precursor to active faulting; the land surface flexes before fault displacement is evident. With increased regional subsidence, active surface faults may be expected to develop within zones of differential subsidence.

Movement on faults in the Houston area is being activated and accelerated by ground-water withdrawal. The rate of fault movement on the Long Point fault and Eureka Heights fault increases and decreases as the piezometric surface rises and declines, respectively.

Land subsidence and fault activation can be expected in areas of the Texas Coastal Zone other than the Houston-Galveston area if in these areas there is extensive ground-water withdrawal from shallow (less than 3,000 ft) fresh-water artesian aquifers. In these areas surface faulting and/or differential subsidence would be expected to occur in part within the zones defined by the lineations.

INTRODUCTION

The Texas coastal plain and the underlying portion of the Gulf Coast basin comprise a structural province characterized by growth faulting with very low levels of seismic activity. These faults actively displace the land surface in the Houston-Galveston area. Some were active before man's presence. Extensive use of ground water, however, has recently accelerated the rates of movement on these faults and has probably activated others.

A complex pattern of over 7,000 miles of surface lineations is observable on aerial photographic mosaics of the Texas coastal plain. The lineations represent, in part, the surface manifestations of an extensive network of growth faults and associated fractures that developed during the Tertiary and that has continued into the Recent (fig. 1). On the upper Texas coastal plain, many lineations coincide with zones where subsurface faults have been extrapolated to the surface. In the areas of heavy ground-water usage and concomitant subsidence, many lineations coincide with active faults and with zones of differential subsidence.

Land surface subsidence and active faulting, both natural processes in the Texas Coastal Zone, are becoming critical hazards that are accelerating under the impact of massive withdrawal of ground water from Pliocene-Pleistocene aquifers. Prudent use of ground-water resources will require a variety of continuing studies that investigate the aquifer system and its interrelationship with the structural and sedimentary framework of the region.

This report evaluates several lines of evidence that indicate a relationship between surface lineations, subsurface faults, active surface faults, and differential subsidence. Before discussing these

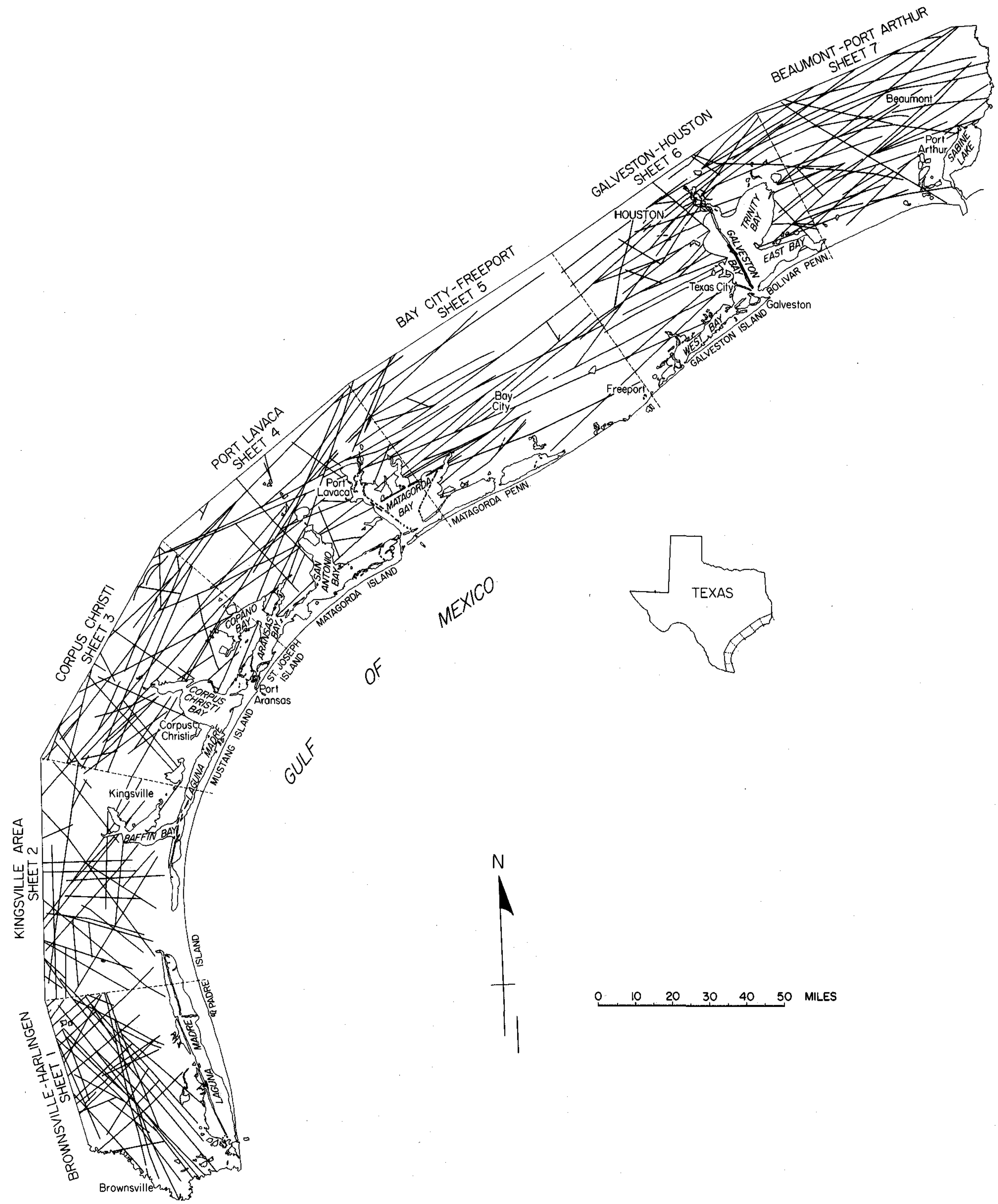

Figure 1. Distribution of lineations in Texas Coastal Zone compiled from Physical Properties Maps, Environmental Geologic Atlas of the Texas Coastal Zone, Bureau of Economic Geology, The University of Texas at Austin.

relationships, it is necessary to establish pertinent points about previous work on lineations in Texas and the Gulf Coast, hydrologic and geologic framework in which the lineations occur, and method of mapping lineations, as well as to define those geologic terms that are critical to understanding the importance of lineations in the Texas Coastal Zone.

ACKNOWLEDGMENTS

Many individuals, State and Federal agencies, and corporations have provided information and data used within this report.

W. L. Fisher provided special support and incentive in the formulation of this study. L. F. Brown, Jr., C. G. Groat, and E. G. Wermund reviewed the manuscript. Conversations with R. O. Kehle and W. R. Muehlberger added insight into the problems of faults and lineations.

Other individuals at the Bureau of Economic Geology aided in the research, preparation, and publication of this report. Russell Lewis, Dawn McKalips, and Ernst Kastning assisted with the research; James W. Macon and members of the cartographic section prepared all figures; Elizabeth T. Moore edited the initial manuscript; Dawn Roberts Weiler composed the manuscript, and K. M. White performed final editing.

Additional thanks go to Geomap Company for permitting the use of their data. U. S. Geological Survey, Geologic Division, is acknowledged for its financial assistance.

DEFINITIONS

The problems involved with evaluation of lineations and their structural meaning have, in part, been clouded by imprecise definitions of critical geologic terms. These terms are defined here to help clarify the writer's use of the terms.

Lineations are any straight, lengthy features of the natural earth's surface and generally of geologic origin.

Photographic lineations are the visual manifestation of linear tonal variations on black-and-white aerial photographs, the linear color variations of color and color-infrared aerial photographs, and the linear coincidence of geomorphic features, such as rectilinear drainage patterns.

Fault is a surface or zone along which displacement has occurred. In the Gulf Coast the major displacement is in the dip direction.

Surface fault is a fault that intersects the land surface. Most faults evident at the surface in the Gulf Coast probably extend deep into the subsurface and are not the product of surficial or shallow subsurface phenomena. Surface faults, though only the extension of subsurface faults, need to be defined separately from the general term because not all faults reach the surface. In the Gulf Coast region where seismic activity from fault movement is not an apparent problem, it is the surface expression of a fault that is the geologic hazard to man.

Five criteria can be used to identify the presence of a surface fault: (1) breaks in man-made structures caused by vertical and horizontal displacement of land surface, (2) presence of topographic scarps, (3) recognition of shallow subsurface faults using electric logs or other geophysical data and subsequent extrapolation of the fault to land surface, (4) recognition of shallow subsurface faults by coring or trenching, and (5) lineations observed on aerial, black-and-white, color, and color-infrared photographs or by other remote sensing techniques that identify the surface trace of the fault.

The absence of a single criterion does not disprove the existence of a fault. Similarly, no single criterion of the five listed positively confirms that a fault does exist because the suggested techniques may identify geologic phenomena other than faulting. Confirmation by several criteria, however, is strong evidence for the existence of a fault.

Electric log correlation and geophysical techniques may not identify faults with small displacements. Faults with measurable displacement in the deeper subsurface which appears to die out in the Plio-Pleistocene sediments may actually continue to land surface. The lack of reliable marker beds in Plio-Pleistocene sediments prevents the identification of the fault in this section. Similarly, faults originating at shallow depths will not be easily recognizable because of the lack of reliable marker beds in the Pleistocene sediments. Coring or trenching across suspected faults may or may not confirm the presence of a fault. Displacement on a fault may be too small to be detected by an offset of marker beds between holes. Conversely, the presence of abrupt changes in sedimentary facies between adjacent core holes may be misinterpreted as evidence of a fault. This is a problem in the coastal plain sediments of Texas because of rapid facies changes within the fluvial and deltaic sediments. Trenching across a suspected fault may confirm fault displacement because of the presence of drag structures, offset of sedimentary or soil units, or slickensides. The lack of these features, however, does not necessarily preclude the presence of a fault. The zone of faulting may be wide with displacement occurring in small increments across the entire zone. Apparent variations in composition along a trench also may be the result of soil phenomena (e.g., gilgaies) or sedimentary facies variations rather than the product of faulting. Lineations from aerial photography are a powerful tool in locating surface faults. Careful mapping will eliminate interference from man-made features such as power lines, fence lines, highways, and mosaic tears.

Active surface fault is a fault in which displacement is presently occurring or has occurred in the recent past at land surface.

Three criteria can be used to identify active faults: (1) breaking of man-made structures because of vertical and horizontal displacement of land surface, (2) topographic scarps that affect young geologic deposits, and (3) differential subsidence from releveling National Geodetic Survey benchmark data.

Faults reaching land surface may not be presently active; therefore, it is important to differentiate those which are moving and those which are not. The damaging of man-made structures along a fault trace is confirmatory, whereas topographic scarps on the Gulf Coast imply recent movement but only confirm displacement since the age of sediment deposition. It is reasonable to assume, however, that faults active in the Pleistocene still may be active today. Differential subsidence accurately documents the amount of displacement along a fault. Benchmarks, however, are commonly located 1 mile apart; this spacing may prevent the exact location of the fault. Zones of differential subsidence may also identify flexing of the land surface before the actual rupture occurs.

Land subsidence is a loss of elevation of the land surface. Subsidence can be the result of the consolidation of subsurface sediments by natural or man-made causes. Land subsidence also occurs on the downthrown side of an active surface fault as a result of the differential vertical motion of the fault blocks.

Differential subsidence of the land surface is the uneven loss of land elevation. The term refers to the process of uneven subsidence which may be measured by the loss of elevation between two benchmarks. Zones of differential subsidence can delineate an active surface fault or indicate warping of the land surface as a precursor to surface faulting.

LINEATIONS IN THE GULF COASTAL ZONE

Lineations in the Gulf Coastal Zone were recognized as early as 1933. Barton (1933) studied lineations in South Texas and considered that the features were undoubtedly of structural origin. He noted that drainage patterns in the calichified surface of South Texas were structurally controlled and had three major trends: north-south, northeast-southwest, and northwest-southeast. Most of the lineations recognized by Barton could be traced on aerial photographs for less than 10 miles; however, some extended for more than 20 miles. He believed the lineations to be post-Pliocene fractures since they cut the calichified post-Pliocene surface. Origin of the lineations was attributed to either basement control or to gulfward creep of unconsolidated sediment and/or differential consolidation of argillaceous sediments. He found very little subsurface evidence for these obvious surficial structural features.

Fisk (1944) similarly recognized a complex pattern of lineations in the unconsolidated Gulf

Coast sediments of the Mississippi River valley region. Active faults in this area have the same trends as the lineations. Evidence from soil borings indicated that subsurface displacement occurred within the well-defined linear zones. At the surface, the lineations were expressed as ill-defined topographic depressions, up to 2,000 feet wide, but not of sufficient relief to show on 5-foot-contour topographic maps. Fisk attributed their origin to crustal adjustment from deltaic sediment loading.

Wermund (1955) studied in detail the relationship of faults and lineations in parts of two parishes (Sabine and De Soto) in western Louisiana. Lineations observed on aerial photographs were checked by coring and by using lignite beds as datum surfaces to see if they were faults. Most of the lineations correlated with faults in which maximum throw was 65 feet. Movement on the faults probably occurred in the Recent, because the lineations continue to propagate through modern floodplain deposits of the Sabine River.

Anderson (1960) similarly correlated aerial photographic lineations with faults in the Fisher area of Sabine Parish and then tried to map all the faults in Sabine Parish by detailed lineation mapping. His mapping defined a shatter pattern which has little correlation to accepted regional structures.

Reid (1973) found that surface breaks in the Mykawa oil field area were coincident with lineations mapped from NASA color-infrared photography. He concluded that (1) lineations are related to faults, and (2) "all linears must be considered to represent active faults capable of moving at damaging rates" (Reid, 1973, p. 33).

Frierson and Amsbury (1974) observed lineations in the Texas coastal plain that did not correspond to previously mapped subsurface structures.

Geologists with Woodward-Lundgren and Associates (1974), in a detailed analysis of an active surface fault in the Pasadena, Texas, area, found that several remote sensing techniques could be used to identify a surface fault: stereo-aerial photography, color-infrared photography, and thermal-infrared imagery. Low sun-angle photography was found unacceptable.

Lineations evaluated elsewhere in Texas also have been considered to be of structural origin. Brown (1961) compared aerial photographic lineations, joints, and faults in North-Central Texas and found that all faults were accurately identified as lineations, and joint systems were also accurately defined. Wermund and others (1974) analyzed lineations in the Edwards Plateau area and found a correlation of lineations with Balcones faulting as well as with fractures from older tectonisms.

HYDROLOGIC FRAMEWORK OF THE TEXAS COASTAL ZONE

The Coastal Zone is underlain by thousands of feet of mostly unconsolidated deposits of sand and clay. Shallow (less than 3,000 ft deep) subsurface sands, charged with fresh water, constitute the important aquifers in the Coastal Zone. The sand and interbedded clays are saturated with water almost to the land surface, but the gently dipping impermeable clays retard the vertical movement of water, creating artesian conditions in the aquifers. Withdrawals of water from the artesian aquifers result in a decrease in hydraulic pressure within the system. Hydraulic pressure supports part of the weight of the overlying sediments (buoyant effect). When the pressure is reduced, the hydraulic gradient between the sands and clays causes water to move from the clays to the sands. This depressuring of the interbedded clays results in an increase in overburden load and subsequent compaction. A reduction in the volume of clays in turn results in subsidence of the overlying land surface.

The results of repeated land-leveling surveys indicate three areas of subsidence in the Texas coastal plain: (1) an extensive area centered near Houston and extending north from the latitude of Bay City to Beaumont, (2) a local area in Jackson County, and (3) an area in the vicinity of Corpus Christi. The most acute area of subsidence includes a 230-square-mile area centering on Pasadena and Baytown; throughout this area recorded subsidence exceeds 5 feet, and locally has been as much as 8 feet. Surrounding this area of maximum subsidence and extending from approximately the Brazos to the Trinity Rivers, over 2,000 square miles of the Coastal Plain had subsided from 1 to 5 feet by 1973 (Brown and others, 1974). The most severely impacted areas are restricted to Pasadena-La Porte, Baytown, Highlands, southeastern sections of Houston, Clear Lake City, Kemah-Seabrook, and Texas City-La Marque, all within Harris and Galveston Counties.

The amount of land impacted by subsidence has increased rapidly since the 1940's and will continue to expand unless ground-water management is exercised throughout the area. In 1943 a little more than 140 square miles had subsided 1 foot; by 1954, the area having 1-foot subsidence increased to 1,000 square miles; by 1964, to 1,800 square miles; and by 1973, to more than 3,000 square miles. These data indicate that the 1-foot subsidence contour line has been moving away from the metropolitan Houston area at a rate of approximately 1 mile per year.

Within this zone of increased land subsidence in Harris and Galveston Counties, active faulting has caused serious problems. Over 150 miles of active surface faults have now been mapped (St. Clair and others, 1975). Fault displacements have accelerated because of the extensive ground-water withdrawal. Direct correlation of fault displacement on the Eureka Heights faults and Long Point fault (from tiltmeters located across these faults) with the decline of the piezometric surface substantiates that fault movement is accelerated by ground-water withdrawal (fig. 2). The annual fluctuation of the height of the piezometric surface is inversely related to movement on the Eureka Heights fault with a regression coefficient of -1.0.

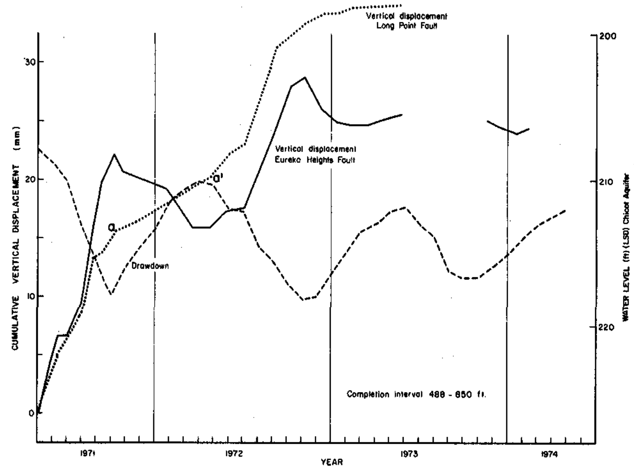

Figure 2. Cumulative vertical displacement on Long Point and Eureka Heights faults in western part of Houston compared to drawdown of piezometric surface of Chicot aquifer. Displacement data for April 1971 to April 1972 from Reid (1973); displacement data for May 1972 to January 1974 and drawdown data for federal observation well L-J-65-13-408 from R. Gabrysch (personal communication, 1974).

GEOLOGIC FRAMEWORK OF THE TEXAS COASTAL ZONE

Though fault movement is presently accelerating because of ground-water withdrawal, the presence of the faults is the result of natural geologic processes in the Gulf Coast sedimentary basin. The Texas coastal plain and the shallow Pleistocene aquifers overlie a thick wedge of Cenozoic terrigenous sediments within the Gulf Coast basin. In some areas, over 50,000 feet of sediment has accumulated. These Tertiary clastic rocks are principally of fluvial-deltaic origin and include lower Wilcox and upper Wilcox strata and Yegua Formation of Eocene age, Vicksburg Formation of Oligocene age, and Frio Formation of Miocene age (Fisher and McGowen, 1967).

The deltas in which the lower Wilcox and Yegua Formations were deposited were lobate or elongate river-dominated systems covering several thousand square miles. They were associated with large fluvial systems that extended 1,000 to 2,000 miles inland and contributed large volumes of relatively high mud sediments. The deltas buried deep beneath the coastal plain are composed of thick mud facies and thinner elongate and lobate sand bodies. The deltas of upper Wilcox, Frio, and Vicksburg Formations, on the other hand, were marine-dominated systems associated with smaller fluvial support systems and have a lower mud content than the river-dominated systems.

Growth faults are commonly associated with deltaic deposits, especially the large river-dominated high-mud delta systems. The principal zones of growth faults are approximately at the boundary between the delta-front sands and the thick, rapidly deposited prodelta mud facies. Increased consolidation of the thick, highly compressible mud facies causes this fault development. Sections often double in thickness across the growth faults with the greater sediment thickness in the prodelta muds (Carver, 1968). Growth faults may be reactivated with each new period of deposition where delta facies may be superimposed.

Growth fault development in the Gulf Coast basin is concomitantly enhanced by gulfward creep (landslide type of activation) of the entire sediment mass (Bornhauser, 1956; Bruce, 1972). Cloos (1968) showed experimentally that the growth faults of Tertiary section could develop by basinward, mass movement of sediments. When the Gulf Coast sedimentary mass is modeled as a large landslide, it has a factor of safety less than one and should theoretically be moving basinward (Reid, 1973). Faulting in the Gulf Coast basin may also be affected by regional basement tectonics (Bornhauser, 1956; Murray, 1961; Shelton, 1968).

Growth faults in the Gulf basin are characterized by seven common features (Carver, 1968).

(1) Fault traces on datum surfaces are arcuate and normally concave toward the coast.

(2) The average dip of the fault is approximately 45 degrees. The faults dip steeply near the surface and diminish to become bedding plane faults at depth (Hardin and Hardin, 1961; Murray, 1961; Ocamb, 1961; and Bruce, 1972).

(3) Faults are normal and are generally downthrown toward the coast (down to the coast). Cloos (1968) showed experimentally and Bruce (1972) documented with seismic profiles that the major growth faults should have associated antithetic faults (up-to-the-coast faults). The growth fault-antithetic fault pair will tend to form graben structures (Murray, 1961).

(4) Fault displacement tends to increase with depth to a maximum and may then decrease at greater depths.

(5) Growth faulting produces rollover or reverse drag on the downthrown side.

(6) Progressively younger faults occur nearer the coast. As the major deltaic depocenters moved coastward, the growth faulting also moved in that direction.

(7) Growth faults are commonly associated with rapid increases in overall sediment thickness and a change from predominantly sand to mud facies on the downthrown side (Carver, 1968).

Faults are also associated with salt tectonism in the Gulf Coast sedimentary basin. Murray (1961) records seven distinctly different types of faults controlled by salt structures: normal faulting with single offset; normal faulting with multiple offset, grabens, horsts, radial faulting, and peripheral or tangential faulting; and reverse or thrust faulting. Quarles (1953) attributes the regional down-to-the-coast faults as well as salt-dome faulting to salt tectonism, rather than to depositional loading or landslide-type mass movements.

The combination of faults caused by salt tectonism and faults generated by deltaic sedimentation and landslide mass movement dominates the structural framework of the Tertiary section of the Gulf Coast basin. Subsurface mapping by Cambe[1] and Geomap[1] shows that extensive Tertiary fault movement continued at least until the end of the Oligocene. Some faulting beneath the coastal plain, however, has continued through the late Tertiary (Miocene and Pliocene) and Quaternary. Geologists working for Woodward-Lundgren and Associates (1974) traced a fault from the subsurface to the surface in the Pasadena area (southeast of Houston). Using electric logs, Van Siclen (1967) correlated the Addicks scarp with a fault controlling oil production in the Fairbanks oil field (northwest of Houston). Poole (1940) similarly correlated a fault in the Saxet oil and gas field to a surface scarp south of Corpus Christi.

Some geologists, nevertheless, believe that only a few faults penetrate Pleistocene and Recent sediments of the Texas coastal plain and that the majority of faults disappear upward within the Tertiary section (Sheets, 1947). The hypothesis that faults disappear upward is based on the fact that well-defined fault scarps in the young coastal plain sediments are limited in number. Likewise, conventional electric log and seismic data may not necessarily resolve minor fault displacement in the complex and discontinuous facies of the Pleistocene. The absence of reliable continuous marker beds in Pleistocene fluvial and deltaic deposits and the inability to identify small fault displacements with geophysical methods may have precluded positive identification of faults in the shallow subsurface.

Similarly, the recognition of the small number of surface-expressed faults is further restricted (1) by man's inability to see extremely small

[1] Commercial map services.

surface displacements in the unconsolidated sediments of the Gulf Coast, and (2) by his own conception of what a fault should look like at land surface. Breaks in highways and steep, narrow topographic escarpments are obviously more easily recognized than surface fault zones which may be broad, subtle topographic scarps. The upward extension of the fault through unconsolidated sediments may result in a broad fault scarp.

The surface lineations observed on aerial photographs (fig. 1) are inferred to represent, in part, the surface expression of faults passing upward through the Tertiary, Pleistocene, and Recent sedimentary deposits. These faults, therefore, do not die out in the deeper deposits but extend to the land surface as faults of small displacement or fractures with no displacement. Surface displacement within the poorly consolidated Pleistocene sediments, if present, may be too subtle for recognition; if the linear feature is a fracture, no topographic expression will exist. Lacking topographic expression, lineations may be detected only by color or tonal contrasts on aerial photographs.

MAPPING OF LINEATIONS

Using aerial photographs of the Texas coastal plain, geologists of the Bureau of Economic Geology mapped over 7,000 miles of lineations from Brownsville to Beaumont. The mapped area includes upper Tertiary and Quaternary outcrops; thus, the lineations are not exclusively restricted to Pleistocene deposits. The lineations were observed and mapped on Edgar Tobin aerial photographic mosaics at a scale of 1 inch equals 2,000 feet (7½-minute quadrangles); the entire Texas Gulf Coast was reviewed by making a mosaic of over 700 7½-minute-scale aerial photographic mosaics. The lineations were mapped from this regional perspective. In most cases, the lineations extended across several mosaics and were not easily identifiable on individual mosaics. Before a lineation was considered valid at least three geologists approved the observation. Tape was applied to the photograph to mark the feature; it was later transferred to the back of the photograph for a permanent record. Cartographers then transferred these data to a map at a scale of 1:125,000 based on U. S. Geological Survey topographic maps.

Lineations within the area covered by the Environmental Geologic Atlas of the Texas Coastal Zone were published on the Physical Properties Maps of that atlas series. Figure 1 is a composite of the lineations from these maps. Unpublished maps showing lineations are available for review at the Bureau of Economic Geology.

Only lineations of regional extent were mapped. They are long, straight features that, to a trained observer, do not resemble pipelines, electric power lines, fence lines, man-made features, or photomosaic tears. Before each lineation was mapped, a check was made to verify that the feature was not man-made.

Lineations represent a zone of variable width expanding to several thousand feet. The width of lineations is difficult to determine, but understanding that they have width is important in understanding their origin.

The aerial photographic mosaics of the coastal plain were reviewed two additional times to verify the accuracies of the mapping. Lineations mapped by geologists of the Bureau of Economic Geology have been viewed by geologists with the U. S. Geological Survey, the Nuclear Regulatory Commission, and private consulting firms. With few exceptions, these observers have verified the presence and natural character of the lineations.

EVALUATION OF LINEATIONS

The structural significance of lineations has been evaluated by studying (1) the relationship of lineations to subsurface faults, (2) the relationship of lineations to active surface faults, and (3) the relationship of lineations to differential subsidence.

LINEATIONS AND SUBSURFACE STRUCTURES

The general trend of the lineations approximately coincides with the general trend of the faults in the Gulf Coast basin (figs. 3, 4). Com-

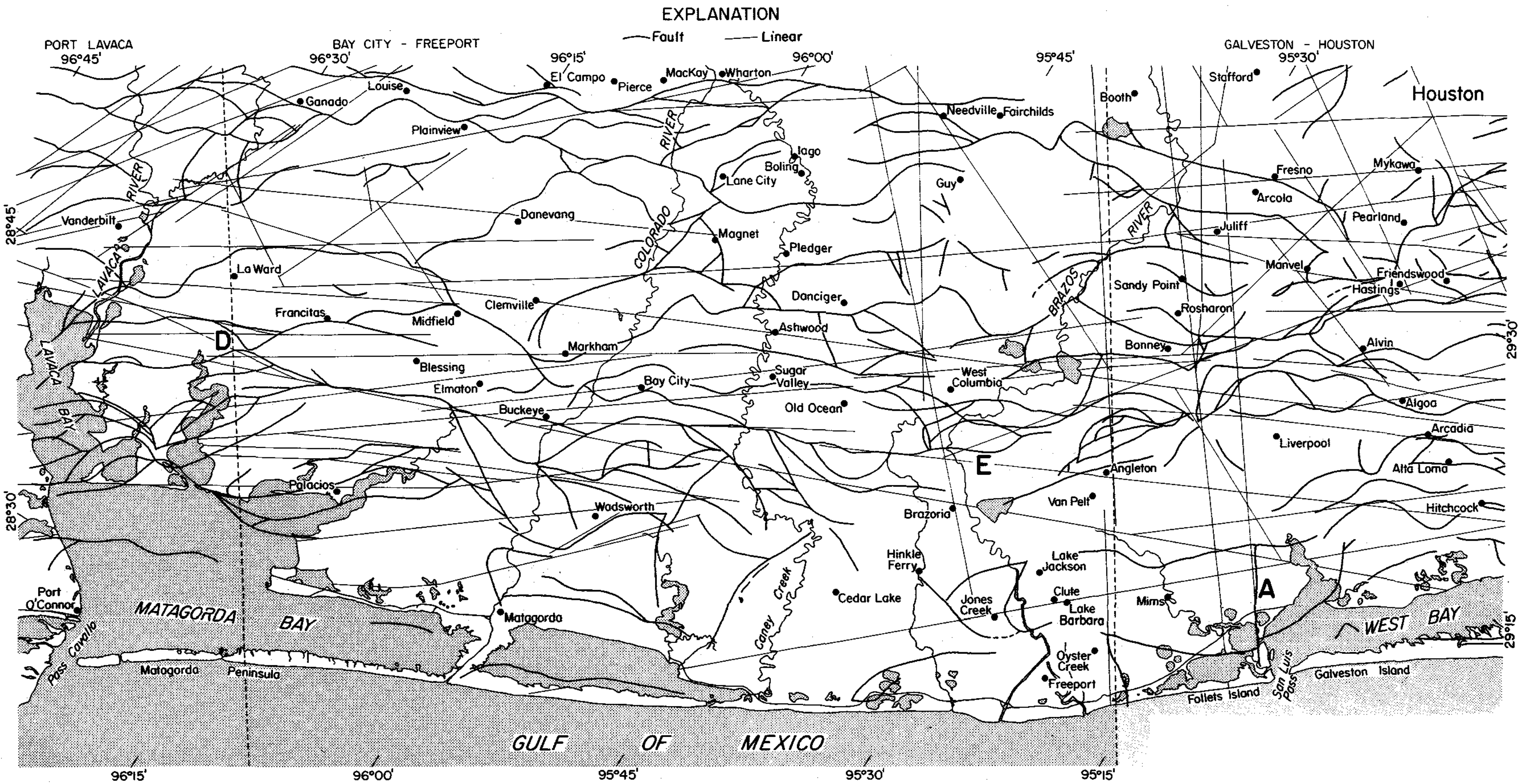

Figure 3. Lineations and surface traces of faults extrapolated from the Frio Formation (Oligocene), Matagorda Bay to Galveston Bay. Lineations from Physical Properties Maps, Environmental Geologic Atlas Series, Bureau of Economic Geology. Original fault data released with permission of Geomap Company.

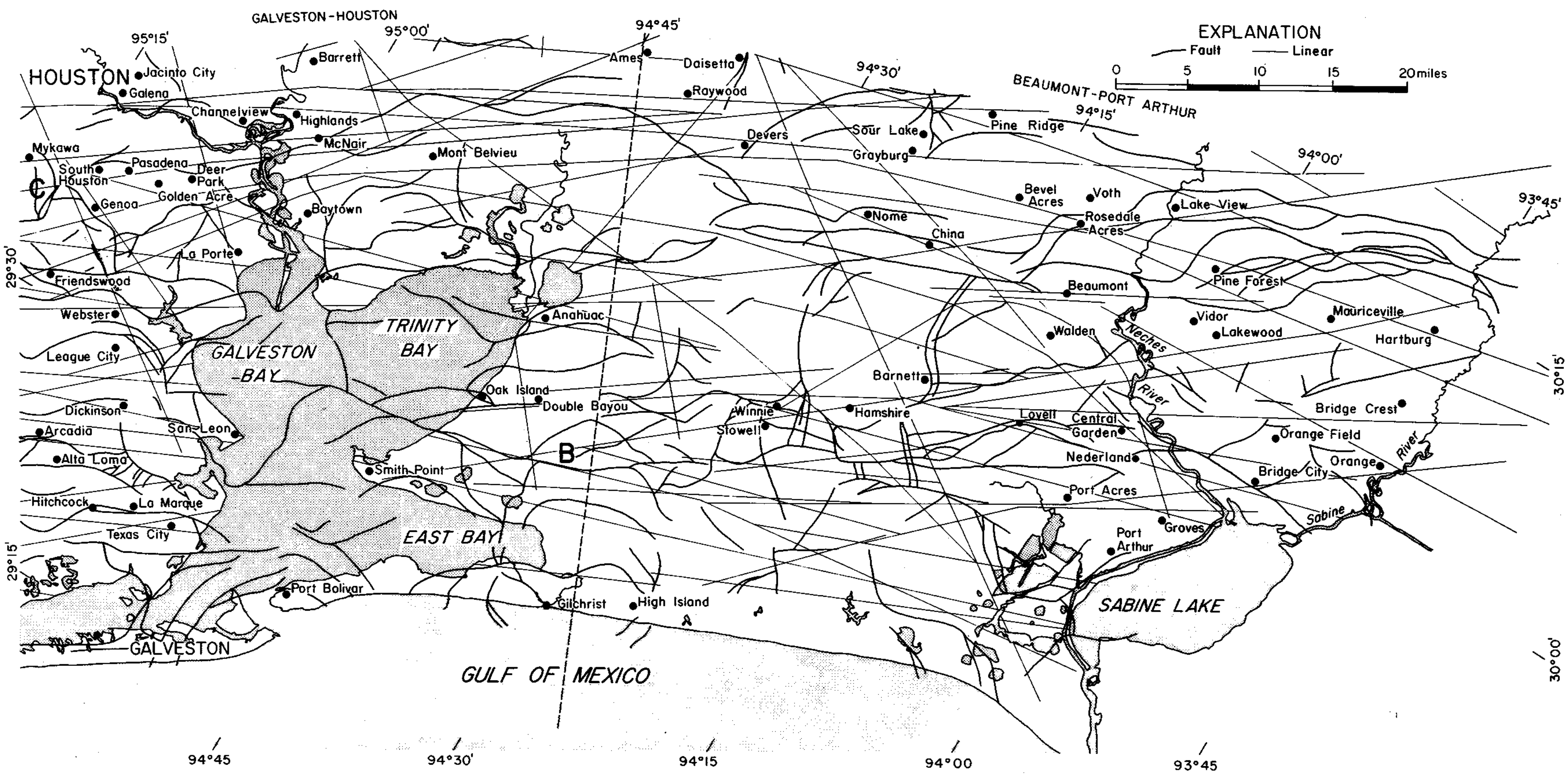

Figure 4. Lineations and surface traces of faults extrapolated from the Frio Formation (Oligocene), Galveston Bay to the Neches River. Lineations from Physical Properties Maps, Environmental Geologic Atlas Series, Bureau of Economic Geology, The University of Texas at Austin. Original fault data released with permission of Geomap Company.

parisons of lineations and expected surface traces of subsurface faults were made by extrapolating to land surface subsurface faults that had been mapped on at least one datum surface in the Frio Formation.[2]

Most of the faults were extrapolated from the 6,000- to 12,000-foot depth range. The dip of the fault extrapolated to land surface was assumed to be either 45 degrees or the same as the dip on the fault between two subsurface datum surfaces. Because of the depths from which the faults were extrapolated and the fact that growth faults have curvilinear rather than linear surfaces, the location of the surface traces of the extrapolated faults can only be considered as approximate.

Through the study area (Bay City-Beaumont), several excellent correlations between lineations and fault extrapolations exist. Lineations in some locations are exactly coincident with expected surface traces of the extrapolated faults (fig. 3, loc. A; fig. 4, loc. B). In other areas, the surface traces weave back and forth across lineations. At location C on figure 4, the trace follows a lineation in this fashion for approximately 28 miles from South Houston to Mont Belvieu. Numerous other examples of this type are shown in figures 3 and 4. In some areas an extrapolated fault follows one lineation and then another lineation at a different strike. Between D and E on figure 3, the trace of an extrapolated fault follows sections of five different lineations for over 60 miles.

The weaving of the traces of extrapolated faults across the lineations indicates that either (1) the lineations are zones that are normally several thousand feet wide, or (2) the lineations are segmented and identify different portions of the curvilinear fault trace as it intersects land surface. The fact that the traces of extrapolated faults follow several lineations as the strike of the fault changes suggests that only part of each lineation may be related to Tertiary faults.

Detailed comparisons of specific subsurface structural features controlling the location of oil and gas fields and lineations also show significant coincidences. The location of most Gulf Coast oil and gas fields is controlled by growth faults or faults associated with piercement salt domes and deep-seated salt domes or by a variety of anticlinal structures.

Piercement salt domes which generally occur at relatively shallow depths break the continuity of the overlying sedimentary strata. Faults associated with piercement domes are generally steep and extend either radially or tangentially from the dome and commonly form tensional grabens over the domes (Murray, 1961). Where domes are shallow, the extension of steeply dipping faults intersects the land surface relatively close to the dome. Based on available geologic data, 71.4 percent of the 28 piercement salt domes in the region between Bay City and Beaumont are closely associated with the lineations. Lineations are tangential to the projected surface outline of ten domes, and lineations radiate from directly over ten other domes. Only eight domes (28.6 percent) do not have lineations associated with them.

Aerial photographic lineations correlate closely with the faults located over the West Columbia salt dome (fig. 5); salt is within 1,000

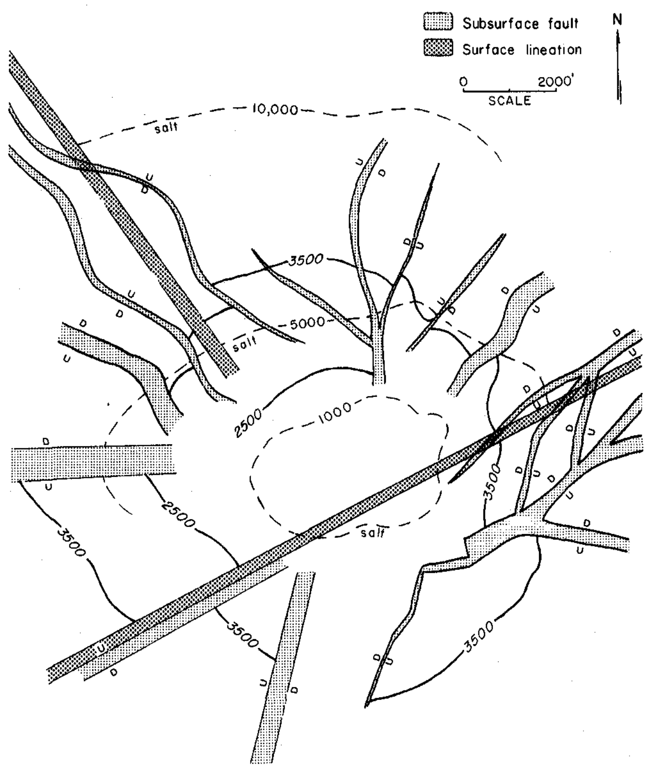

Figure 5. Coincidence of lineations with extrapolated subsurface faults, West Columbia salt dome, Brazoria County, Texas. Modified from Hackbarth, 1953.

[2]Fault data and release provided by Geomap Service.

feet of the surface. A number of faults radiate from the dome and two lineations intersect over the dome. Each lineation trends approximately parallel to major radial faults that have been mapped within 2,500 feet of the surface.

Deep-seated salt domes (domes identified by gravity anomalies or domes in which salt is deeper than 8,000 ft) provide the most important oil and gas traps in southeast Texas (Sheets and Cockrell, 1962). Forty-four fields have been classified as deep-seated domes (Gardner, 1952), Lineations coincide with the surface extension of subsurface faults associated with 13 of these domes; lineations either originate or pass directly over 16 of the domes. Over four of the oil and gas fields that are associated with deep-seated salt domes, the lineations either are on the opposite side of the field from where the extrapolated fault intersects land surface or are perpendicular to the strike of the major faults. Correlation between faults and lineations associated with these four fields is obviously very poor. Eleven fields cannot be evaluated because of insufficient data. In summary, 88 percent of the fields associated with deep-seated domes for which adequate data exist exhibits good fault-lineation correlations.

Many oil and gas fields formerly thought to be associated with anticlinal or domal structures are now known to be fault controlled—either grabens or down-to-the-coast faults with "rollover" structural closure (Murray, 1961). Forty oil and gas fields of the domal or anticlinal type were evaluated to determine the degree of correlation between the trends of fault traces and lineations. Lineations associated with 18 oil and gas fields have the same approximate location and strike as the expected surface trace of the faults extrapolated from the subsurface; there were five fields where a poor lineation-fault coincidence occurred. For 18 fields, there were insufficient data for evaluation. Good correlation between lineations and fault extrapolations occurs in 78 percent of those fields where sufficient data are available for evaluation. Two examples of good correlations between the expected traces of fault extrapolations and lineations are the Blessing field, Matagorda County (fig. 6), and the Angleton field, Brazoria County (fig. 7).

The regional correspondence is good between lineations and the traces of the extrapolation of faults associated with piercement salt domes, deep-

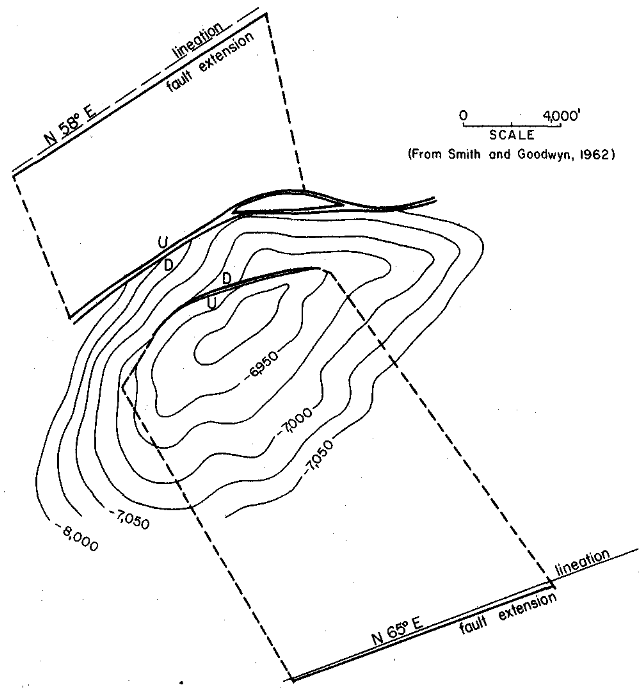

Figure 6. Coincidence of lineations with extrapolated subsurface faults, Blessing oil field, Matagorda County, Texas. Modified from Smith and Goodwyn (1962).

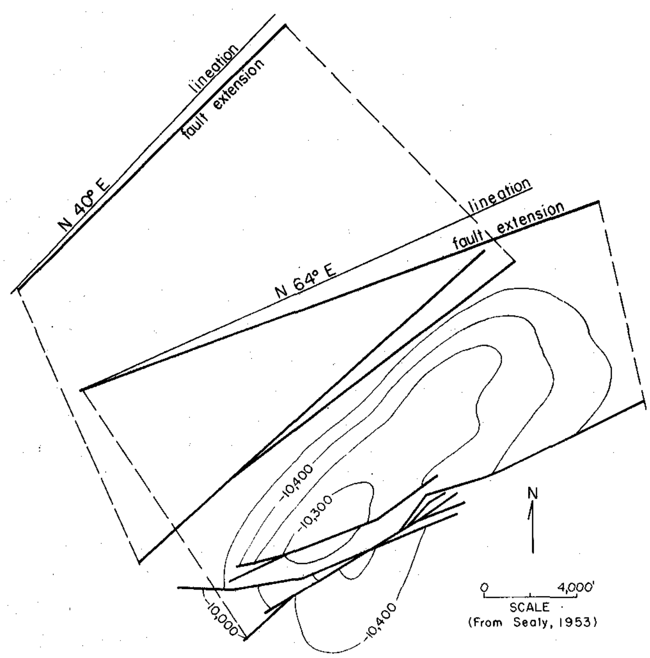

Figure 7. Coincidence of lineations with extrapolated subsurface faults, Angleton oil field, Brazoria County, Texas. Modified from Sealy (1953).

seated salt domes, and anticlinal structures. These correlations, however, have been made by extending faults through several thousand feet of Pleistocene and Tertiary sediments. Similarly the dips of the faults (where cross sections were available) were assumed to remain constant. Because of these broad assumptions, the relationship between surface lineations and subsurface faults cannot be completely confirmed, but a correspondence between these two phenomena appears very probable.

LINEATIONS AND SURFACE FAULTS

The coincidence of many active faults with aerial photographic lineations in the Houston-Galveston area further demonstrates the structural genesis of lineations. The coincidence of lineations with faults along the Hockley scarp, the Ellington Air Force Base-NASA area, and San Jacinto Monument Park best demonstrates these relationships. (The San Jacinto Monument example will be described in the subsidence profile section.)

HOCKLEY ESCARPMENT

A lineation is coincident with the Hockley escarpment, which is the surface expression of an active fault. The Hockley escarpment (fig. 8) in northwest Harris County exhibits approximately 45 feet of relief in approximately 1 mile. The escarpment can be traced from northwest of Katy to Tomball (both in northwest Harris County), a distance of approximately 30 miles. Barton (1930, p. 1302) believed that the escarpment "can be traced from south Texas, north of Eagle Lake, south of Sealy, past the Hockley salt dome and Tomball, south of Conroe, past Cleveland, Warren and Kirbyville and eastward into Louisiana." Rogers and Longshore (1965, p. 161) stated, "A fault zone with a width of not more than one mile has clearly been active across the Colorado River near Eagle Lake." This fault is approximately coincident with the escarpment described by Barton (1930). The Hockley escarpment is one of the most prominent geomorphic and structural features on the Pleistocene coastal plain of Texas.

Various authors have considered the escarpment to be a possible fault escarpment, an erosional phenomenon, or a depositional feature. Barton (1930) offered three alternatives for the

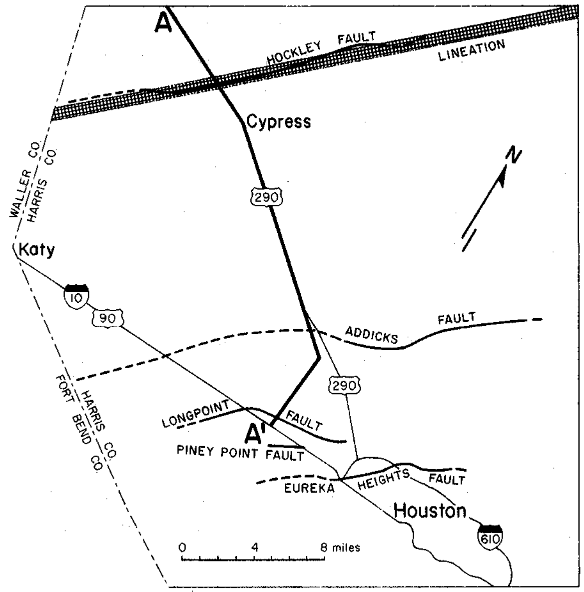

Figure 8. Coincidence of lineation with Hockley fault, northwest of Houston, Texas.

escarpment's origin—(1) an ancient Pleistocene shoreline, (2) a flexure escarpment marking a deep-seated fault, and (3) an uplifted flexure-shoreline escarpment—but he favored the fault escarpment hypothesis. Barton (1933) reaffirmed the fault concept by stating that the Hockley escarpment lies along the great thickening of the Pleistocene-Miocene-Oligocene section.

Van Siclen (1961) suggested that the escarpment was similar to steep slopes (shoreface) off barrier islands in the Gulf of Mexico. Bernard and others (1962) stated that the Hockley escarpment was an erosional escarpment between the Willis and Lissie plains. Proctor (1974), however, showed that these surfaces were not different terrace deposits of different ages because abandoned meander loops can be traced from the supposedly older surface to a younger surface.

The writer believes that this escarpment is the direct result of an active fault and is neither depositional nor erosional in origin. Fault evidence includes (1) the breakup of U. S. Highway 290 where it crosses the escarpment, and (2) the differential subsidence exhibited along a subsidence profile which crosses the escarpment. U. S. Highway 290, a four-lane divided highway where it crosses the Hockley escarpment, is breaking up at the same elevation on both the northbound and southbound lanes. The railroad tracks and gravel bed which parallel Highway 290 have a distinct break in grade at the same elevation as the breaks in the adjacent highway.

Two subsidence profiles that cross the Hockley escarpment quantify the amount of recent vertical displacement along the fault. A profile parallel to U. S. Highway 290 indicates an abrupt increase in the amount of subsidence on the downthrown side of the fault (fig. 9). Between 1953 and 1973, the downthrown side of the fault had subsided twice as much as the upthrown side. A subsidence profile along the Katy-Hockley road (5 miles west of U. S. Highway 290) also shows that almost twice as much subsidence has occurred on the downthrown side as on the upthrown side.

A lineation coincides with the Hockley escarpment (fig. 8) as observed on the Warren Lake and Rose Hill U. S. Geological Survey topographic maps; it coincides with the locations of the breaks in the subsidence profiles and with the breaks in concrete on U. S. Highway 290. This lineation extends southwestward through the Allen's Creek nuclear power plant site to the Gulf of Mexico.

FAULTS IN ELLINGTON AIR FORCE BASE-NASA AREA

In the Ellington Air Force Base-NASA area, Clanton and Amsbury (1976) have mapped an extensive fault network (fig. 10). Surface faults south of Ellington Air Force Base probably are related to the subsurface faults controlling oil production in the Friendswood-Webster oil field and the Clear Lake City oil field. These subsurface faults (Turner, Collie, and Braden, Inc., 1966) exhibit the same trend as the surface faults. At the surface, the faults form a complex graben. North of the graben, Ellington Air Force Base is laced with faults which have caused extensive damage to runways and buildings. In the NASA-Webster area, surficial evidence of faulting is less apparent, but breaks in asphalt pavement and cracks in swimming pools and apartments are the evidence of active faults, even though no topographic scarps have been identified.

Six lineations cross the Ellington Air Force Base-NASA area. Two lineations (lineations 1 and 2, fig. 10) that intersect east of Webster are coincident with active faults in that area. Lineation 3 (fig. 10) extends down the middle of the major graben. Where the graben system trends more northerly and passes over Clear Lake oil field, lineation 4 intersects lineation 3 and continues down the center of the graben along its more northerly strike. For approximately 2 miles, lineation 5 parallels a fault passing through the air base;

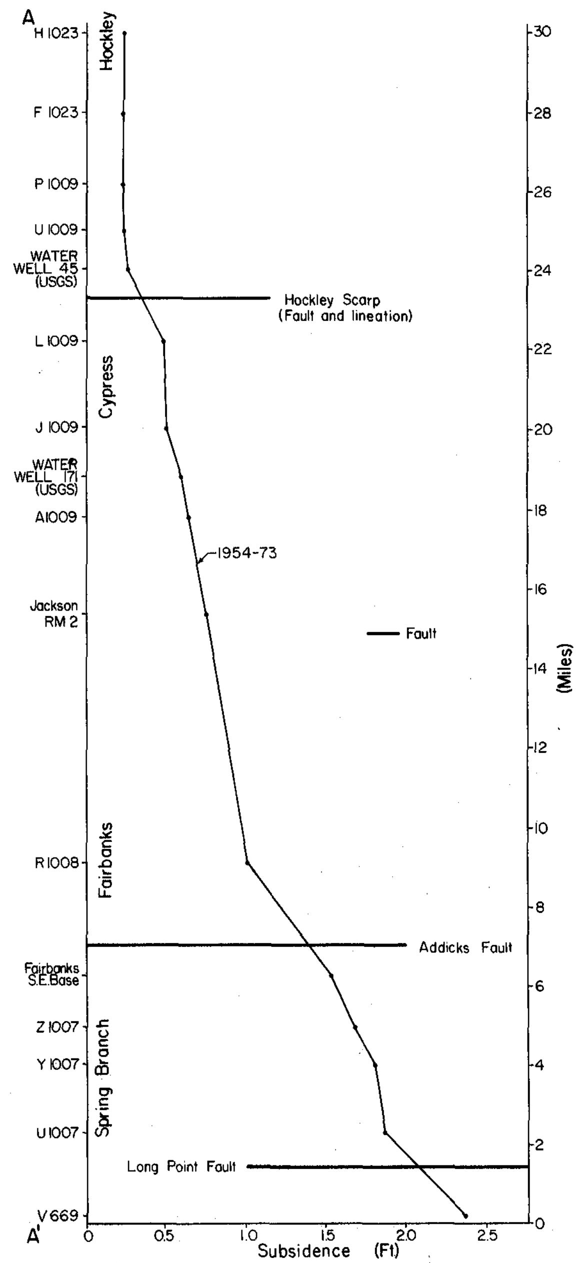

Figure 9. Differential subsidence for time period 1954–1973 across Hockley fault, Addicks fault, and Long Point fault. Location of profile line A-A′ on figure 8. Benchmark leveling and releveling data from National Geodetic Survey.

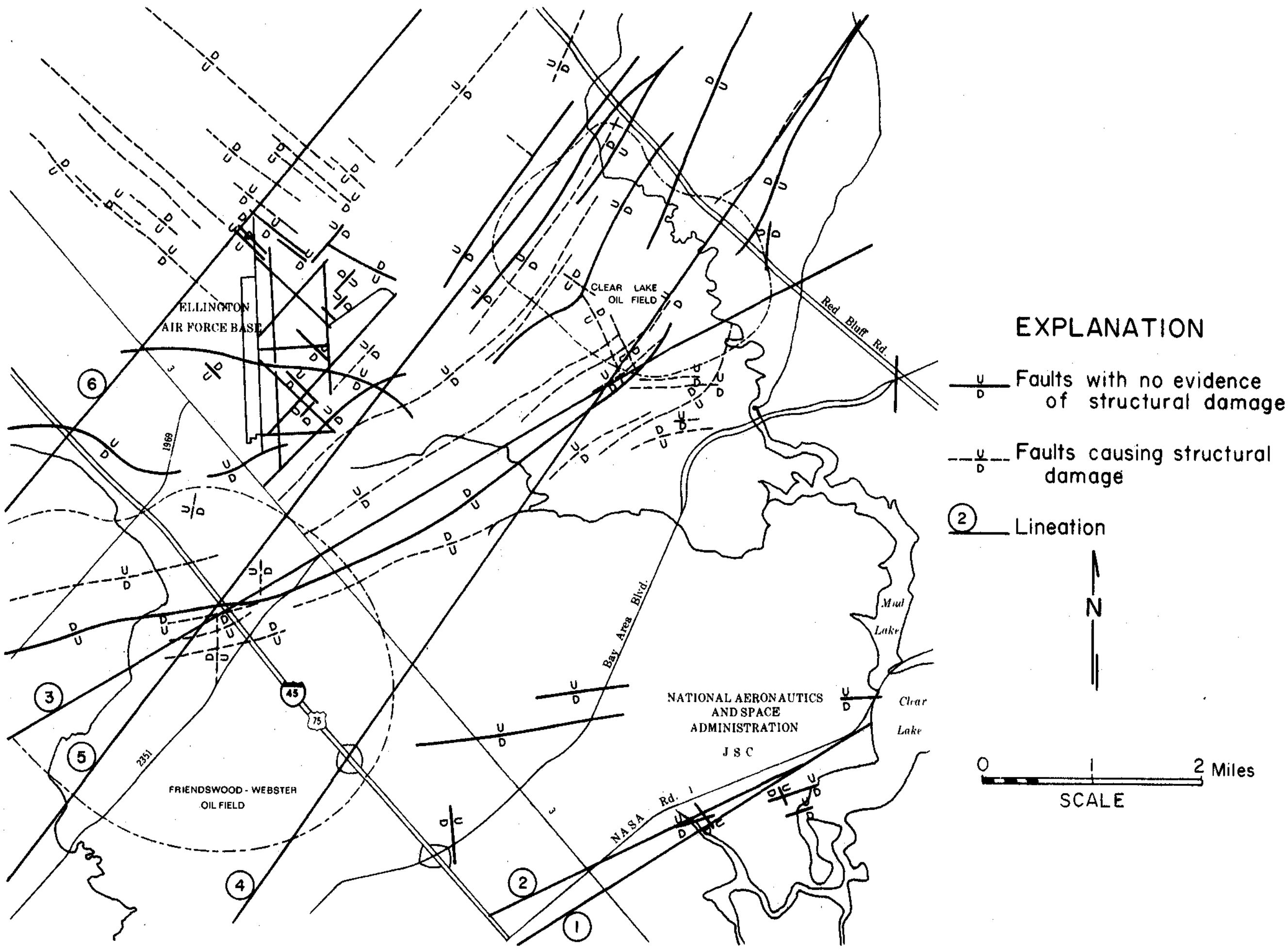

Figure 10. Comparison of lineations and surface faults, Ellington Air Force Base-NASA area, Harris County, Texas. Modified from Clanton and Amsbury (1976).

1 mile further to the northeast, it parallels another pair of faults. This parallelism continues northeastward where the lineation is coincident with an active surface fault that crosses the Spencer Highway. Lineation 6 is not coincident with any known surface faults.

These lineations in the Ellington area closely follow the trend of the surface faults and generally are located on the downthrown side of the faults, which normally are wetter areas supporting different types of vegetation. The upthrown sides are characterized by prairie grasses and the downthrown sides are characterized by spike rushes, bulrushes, and bogrushes (Clanton and Amsbury, 1976). Because the fault trends change strike while the lineations are straight, lineations are not entirely coincident with the surface faults. In the map area (fig. 10), lineations 3, 4, and 5 total 31 net linear miles whereas only 14 miles are coincident with known active faults. Active surface faults occur along 45 percent of the linear extent of the lineations. The other 55 percent, where no active faulting is recognized along the lineations, could contain zones of inactive faults or passive structural features (joints, potential faults, or fracture systems) or areas with no structural affinities.

OTHER EXAMPLES

Other localities in the Houston-Galveston area where lineations coincide with active surface faults are (1) the reflection pool at San Jacinto Monument, (2) the intersection of Farm-to-Market Road 519 and State Highway 3 in La Marque, (3) State Highway 3 at locations 2 miles and 3 miles north of Farm-to-Market Road 1744 at La Marque, (4) 1 mile south of the Almeda-Genoa Road on Mykawa Road, and (5) 0.5 mile east of State Highway 35 on Almeda-Genoa Road.

LINEATIONS AND SUBSIDENCE PROFILES

Construction of land subsidence profiles using the benchmark releveling data provided by the National Geodetic Survey is one approach to the problem of locating active faults that are forming subtle escarpments and land flexures where future surface faulting may occur. Anomalies in the level lines (differential subsidence) commonly correspond with recognized active faults and the lineations mapped by the Bureau of Economic Geology. These anomalies result from differential rates of land subsidence. Level lines show abrupt increases in subsidence on the downthrown side of active faults such as the Hockley fault, the Addicks fault, and the Long Point fault (fig. 9). Similar abrupt changes in subsidence occur across lineations indicating either the warping of the land surface before the surface ruptures or an actual activation of a surface fault coincident with the photographic lineation.

The National Geodetic Survey has measured an extensive net of first-order and second-order horizontal control benchmarks in the Houston-Galveston area. The earliest benchmarks were established in 1908. New benchmarks have been added and previously established benchmarks have been continually releveled in 1916, 1932, 1939, 1942, 1950, 1954, 1959, 1964, and 1973. These data permit a comprehensive evaluation of land subsidence.

Total measured subsidence from benchmark data for the Houston-Galveston area defines a subcircular pattern with maximum zones of subsidence in the Pasadena-Deer Park area and in the Texas City area (Brown and others, 1974; Gabrysch and Bonnet, 1975). Subsidence maps are approximate, because of the required extrapolation of data from benchmarks and because elevations are not measured at all benchmarks for each survey.

Distinct from the regional analysis, detailed analyses of the change in benchmark elevations do not show a smooth subsidence bowl but indicate that subsidence can occur at radically different rates at adjacent benchmarks. Subsidence profiles (see figs. 12, 13, 14a, 14b, 17, 18, and 19) represent the amount of subsidence which has occurred between various surveys. The location of each profile is shown on figure 11.

The lineations from the Physical Properties Map of the "Environmental Geologic Atlas of the Texas Coastal Zone—Galveston-Houston Area" (Fisher and others, 1972) are also located on the profiles and index map. Fifty percent of the lineations intersect the profiles at points of differential subsidence. Lineations intersect the level profiles at points of subsidence highs (areas of minimal land subsidence), subsidence lows (areas of maximum subsidence), and major breaks in slope between adjacent benchmarks. These abrupt variations in subsidence have occurred during several different time periods, indicating that the variations are real and not the result of swelling soils or erroneous measurements by National Geodetic Survey. Examination of six specific profiles demonstrates the hypothesis that the lineations have structural significance.

PROFILE 1. HIGHLANDS, TEXAS, AREA

Subsidence profiles in the Highlands-Barrett area based on ten benchmarks show two areas exhibiting subsidence lows (fig. 12). Lineation A coincides with a subsidence low in the town of Barrett. A few water wells exist in Barrett, but the density of wells in the low is no greater than the rest of the area, nor is there centralized pumping from a water district.

Lineation B (fig. 12) coincides with a sudden change in rate of subsidence in Highlands. The 1953–59 and 1953–64 profiles (most complete data) show that the principal subsidence is restricted to the south side of lineation B; substantial subsidence has not occurred north of the lineation. The land south of lineation B has subsided two times faster than the land on the north side of the lineation. Two water districts in Highlands pump a total of approximately 1 million gallons per day (mgd). This relatively small pumpage has caused 5 feet of subsidence between 1953 and 1973.

DIFFERENTIAL SUBSIDENCE AND LINEATIONS

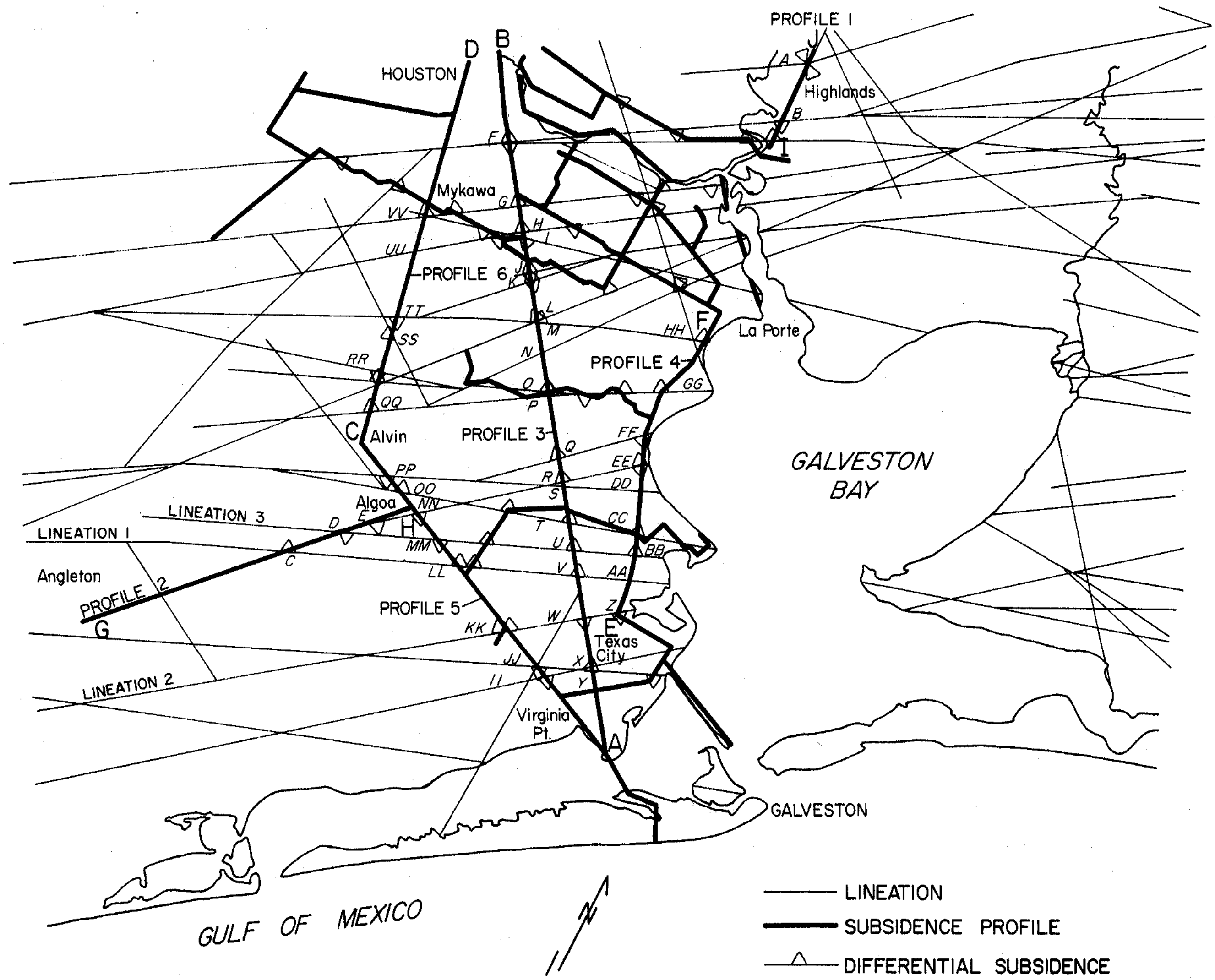

Figure 11. Index map of subsidence profiles and lineations (figs. 11-14, 16-19). △ **indicates points of differential subsidence. Subsidence data calculated from leveling and releveling data of National Geodetic Survey. Lineations mapped by Bureau of Economic Geology.**

Pumpage of approximately 14 mgd in the Alta Loma water field (Alta Loma, Texas) has caused only 1.75 feet of subsidence over approximately the same time period (1950–73).

The coincidence of lineations A and B with areas of substantial differential subsidence is evidence that these lineations reflect the presence of hydrologic boundaries which are probably faults.

PROFILE 2. ANGLETON TO ALGOA

Profile 2, based on 19 benchmarks which were originally leveled in 1942 and releveled in 1950, 1963, and 1973, demonstrates the differential subsidence in this area (fig. 13). Sharp increases in subsidence occur east of Liverpool and west of Algoa. The 1942–50 profile is a relatively smooth curve with a slight break at benchmark F691; the 1942–63 and 1942–73 curves indicate

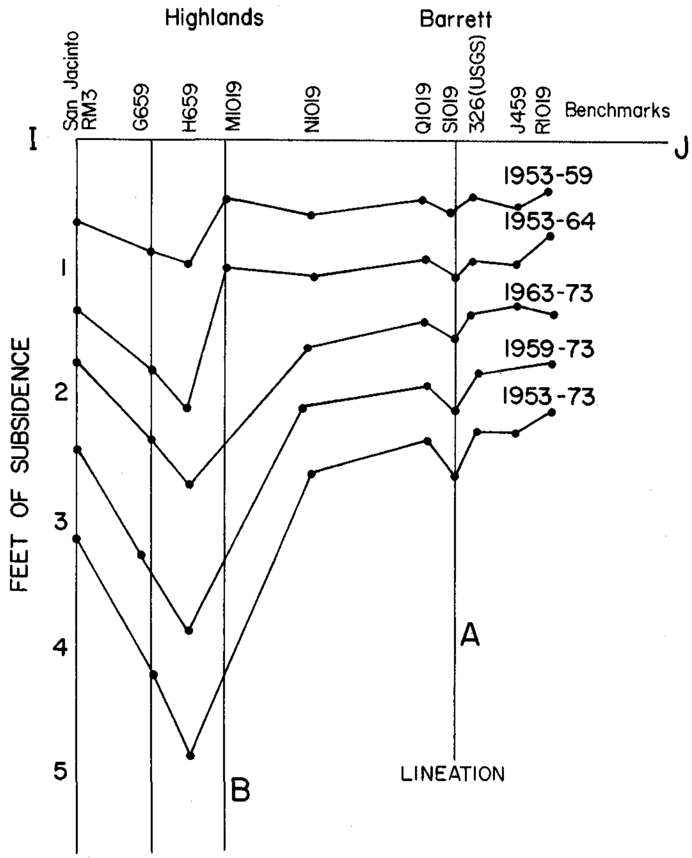

Figure 12. Profile 1. Differential subsidence and lineations, Highlands, Texas, area. See figure 11 for location of profile 1.

significant change in subsidence between RM2 and P53, K691 and L691, and M691 and N691. Lineations C, D, and E are coincident with these points of differential subsidence.

Fluid production from Chocolate Bayou oil and gas field located between benchmarks P53 and N691 is the probable cause of the land subsidence; faults enclosing the oil field probably limit the lateral extent of land subsidence. Lineations C, D, and E (fig. 13) are considered to be the surface expression of these faults which were mapped in the subsurface. Lineation E is coincident both in location and strike with the surface trace of an extrapolated subsurface fault.

PROFILE 3. HOUSTON TO GALVESTON

Profile 3 based on 61 benchmarks shows subsidence along a line from Buffalo Bayou (Houston) to Virginia Point (figs. 14a, 14b, 15). The land is subsiding neither uniformly nor gradually. Zones of differential subsidence along the profile are coincident with the intersection of at least one of three geologic phenomena: (1) straight sections or extensions of straight sections of rivers and bayous, (2) active surface faults, and (3) surface lineations. Seven subsidence depressions occur between Buffalo Bayou and Galveston. Each is bounded on both the northern and southern sides by one of these three natural features.

A sharply defined subsidence high occurs where the profile crosses Buffalo Bayou; subsidence rapidly increases on both sides of the bayou (figs. 14a, 15). The amount of subsidence decreases where the profile crosses Country Club

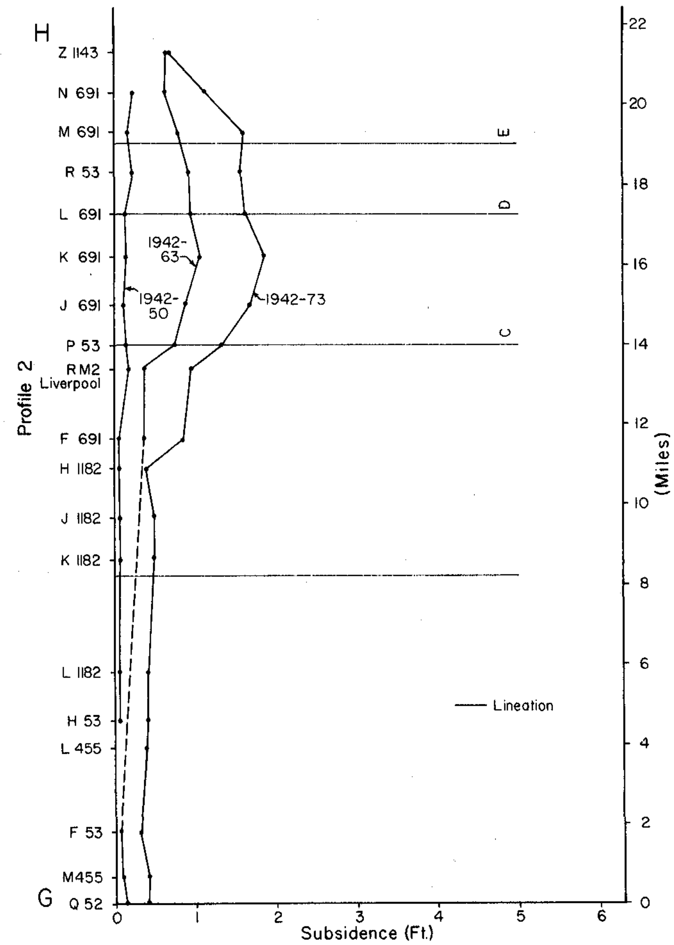

Figure 13. Profile 2. Differential subsidence and lineations, Angleton (G) to Algoa (H), Texas. See figure 11 for location of profile 2.

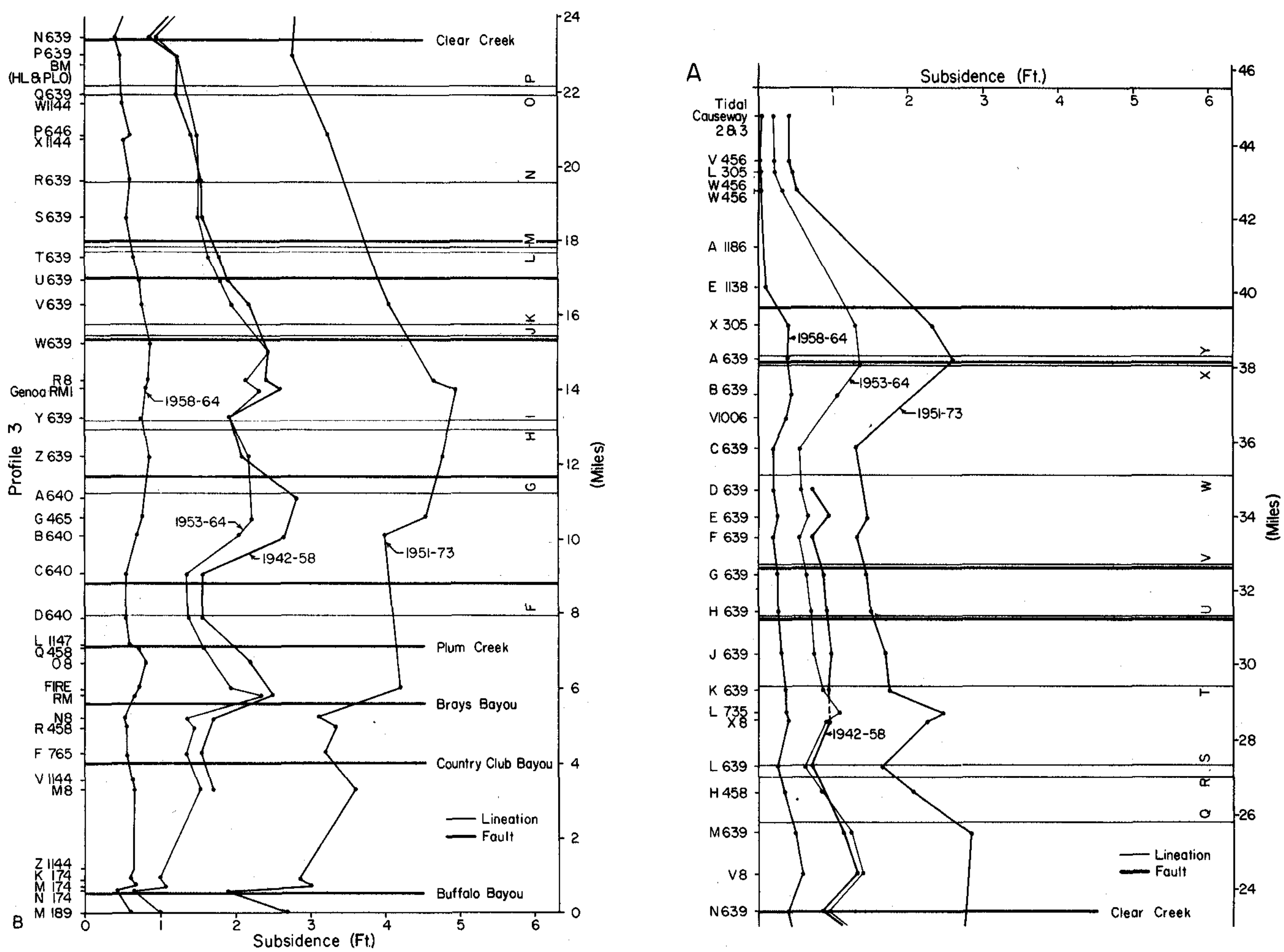

Figure 14. Profile 3. Differential subsidence, lineations, faults, and streams, [a.] Buffalo Bayou (B) to Clear Creek and [b.] Clear Creek to Virginia Point (A), Texas. See figures 11 and 16 for location of profile 3.

Bayou, which has a rectilinear drainage, indicating structural control. A subsidence low, therefore, occurs between Buffalo Bayou and Country Club Bayou.

Southward along the profile a subsidence low extends from benchmark N8 to L1147. Subsidence sharply increases between benchmark N8 and benchmark RM. Brays Bayou, an extension of one straight section of the rectilinear drainage pattern of Buffalo Bayou, intersects the profile at this point. Subsidence decreases sharply between benchmark O8 and benchmark L1147 where the profile crosses Plum Creek and lineation F which is another extension of a straight section of Buffalo Bayou (figs. 14a, 15).

A third subsidence low is located between benchmark C640 and benchmark Z639 and is bounded on the north side by an active fault dipping to the south and on the south side by both a fault dipping to the north and a lineation. These faults bound a graben in the South Houston area (figs. 14a, 15).

The fourth subsidence low along profile 3 extends from benchmarks Y639 to S639, where the profile crosses Ellington Air Force Base area (figs. 14a, 15). This subsidence depression is bounded on the north by lineations H and I and on the south by a fault and lineations L and M (relationship between lineation and fault shown on figure 10).

Lineation N intersects the profile near the location of benchmark R639, where there is no indication of significant differential subsidence. A slight increase in subsidence occurs at benchmark

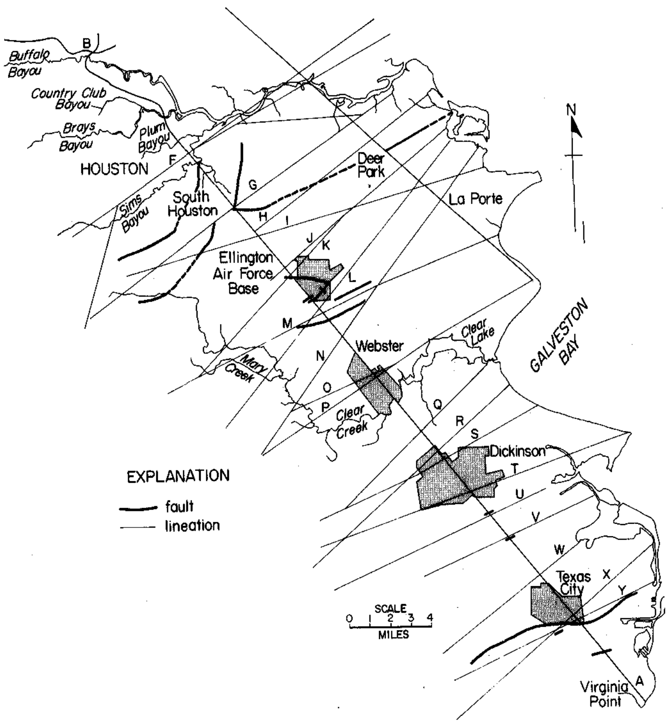

Figure 15. Index map for profile 3 showing location of lineations, faults, and streams intersecting the profile.

Q639 where the profile is intersected by lineations O and P. These lineations pass through sections of the community of Nassau Bay where they coincide with a surface fault. Where the profile crosses Clear Creek (figs. 14a, 14b, 15), which is probably structurally controlled, the creek coincides with a high.

A fifth subsidence low exists between benchmark N639 and benchmark L639. The northern side of this low is bounded by Clear Creek, and the southern side is bounded by lineations R and S. This subsidence low is centered in the town of League City.

A sixth subsidence low is located along the profile at the town of Dickinson and between benchmark L639 and benchmark K639. The zone of increased subsidence between these points is bounded on the north and south sides by lineations S and T (figs. 14b, 15). Differential subsidence of 0.7 foot occurs in a distance of 2 miles. A second subsidence profile through Dickinson (3a) but perpendicular to profile 3 shows that the same differential subsidence of 0.7 foot occurs over a distance of 5 miles (fig. 16). A contour map of the

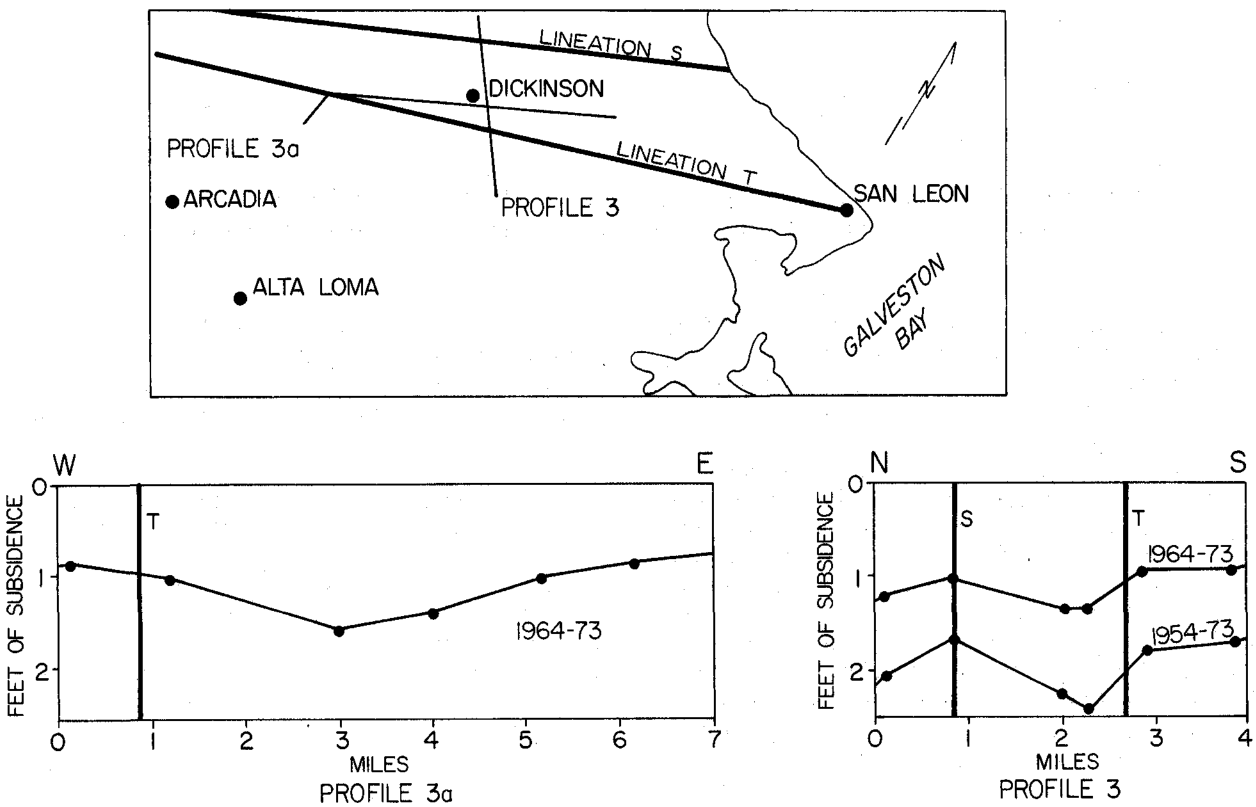

Figure 16. Index map of subsidence profile 3a and section of subsidence profile 3 showing structural control of subsidence.

subsidence in the Dickinson area defines an oval surface. A circular subsidence area would indicate homogeneous, isotropic conditions in the aquifer with no structural control whereas an oval contour surface indicates that the lineations are structural elements that control the shape and extent of the subsiding area.

Between Dickinson and La Marque, lineations U and V (figs. 14b, 15) are coincident with active faults and intersect the subsidence profiles where there is a slight increase in subsidence.

A seventh subsidence depression is located in the Texas City area (figs. 14b, 15). The north side of this low at benchmark C639 is coincident with the intersection of lineation W. A pair of lineations (X and Y) and a coincident active surface fault intersect the lowest part of the Texas City subsidence area at benchmark A639. The southern boundary is an active fault intersecting the profile just to the north of benchmark E1138.

PROFILE 4. TEXAS CITY TO LA PORTE

Subsidence profile 4 from Texas City to La Porte is based on 30 benchmarks. Several sharp discontinuities in subsidence occur where the profile is intersected by lineations (fig. 17). North of Texas City at benchmark T169, lineation Z intersects the profile at a point where the rate of subsidence rapidly increases toward the Texas City area. The intersection of lineation AA with the profile does not coincide with an area of differential subsidence. Lineation BB, however, intersects the profile within a zone of differential subsidence at benchmark Pivot Pier (USE). Lineation CC intersects profile 4 south of a sharp break at benchmark W169. Lineation DD, which crosses the profile between benchmark C1006 and benchmark Y169, is coincident with a section that is subsiding evenly. Lineations EE and FF intersect the profile at sharp subsidence breaks. Lineations GG and HH intersect the profiles at slight subsidence breaks.

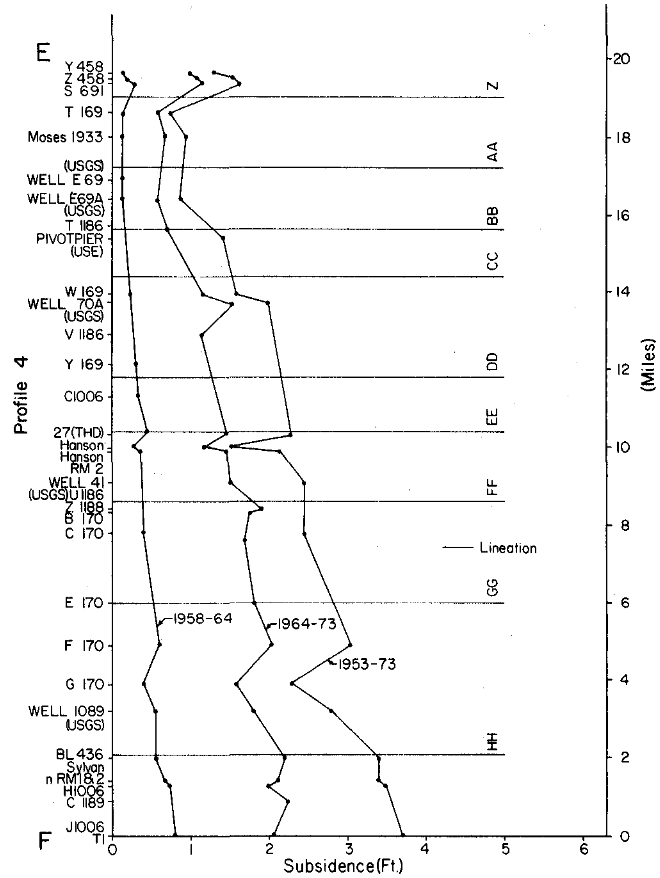

Figure 17. Profile 4. Differential subsidence and lineations, Texas City (E) to La Porte (F), Texas. See figure 11 for location of profile 4.

PROFILE 5. VIRGINIA POINT TO ALVIN

A subsidence profile from Virginia Point to Alvin is based on the releveling data of 34 benchmarks. Along this profile there is a high coincidence between the intersection of lineations and breaks in the subsidence profile (fig. 18). South of Hitchcock between benchmarks N456 and Z456, two lineations (II and JJ) intersect the profile within a subsidence low. An active surface fault in the town of Hitchcock, which passes beneath the high school, is not evident in the subsidence profile. The Hitchcock fault passes between benchmarks R305 and N456, but the benchmark data show no evidence of differential subsidence.

Northward along profile 5, lineation KK bounds the south side of a small subsidence depression. In the town of Arcadia between benchmarks V305 and K1144, lineations LL and MM bound both the northern and southern margins of

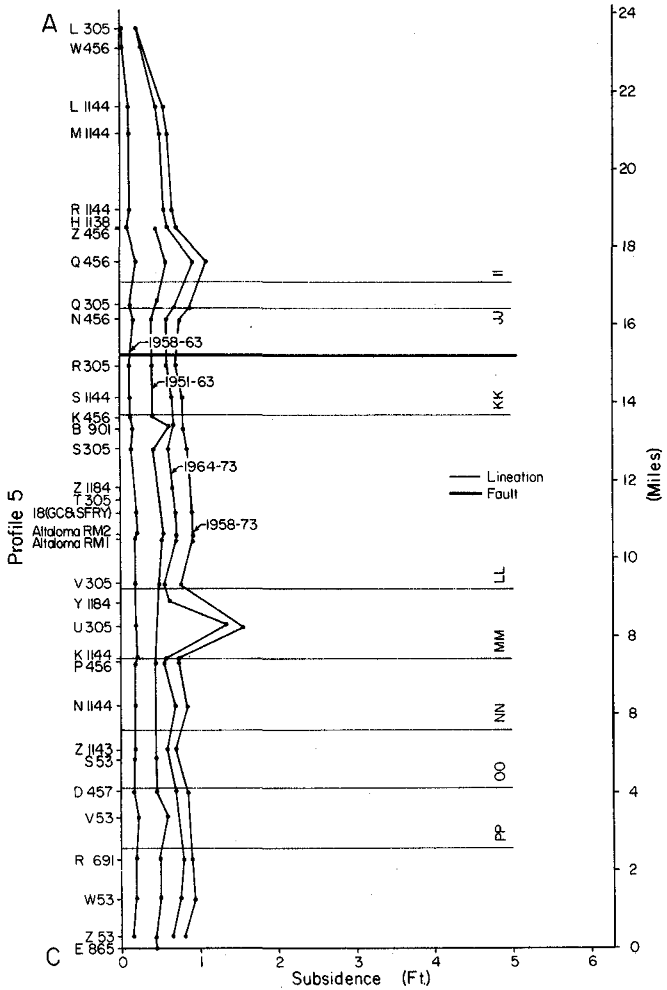

Figure 18. Profile 5. Differential subsidence, lineations, and surface fault, Virginia Point (A) to Alvin (C), Texas. See figure 11 for location of profile 5.

the subsidence low. Ground-water production in Arcadia is limited to domestic and livestock wells; no large industrial or water district wells are present. By contrast, at benchmark Alta Loma RM2 where the profile crosses the southwest end of the Alta Loma well field 2 miles south of Arcadia, no differential subsidence has occurred despite the production of approximately 14 mgd of ground water.

Between Arcadia and Alvin, three lineations (NN, OO, PP) coincide with small breaks in the subsidence profiles. The differential subsidence between Arcadia and Alvin is not as great as exhibited on other profiles, but neither has the total subsidence been as great. Generally the greater the total subsidence, the greater will be the differential subsidence shown by the profiles. If subsidence increases in this area, the differential subsidence would be expected to increase.

PROFILE 6. ALVIN TO HOUSTON

A subsidence profile between Alvin and Houston (fig. 19) does not exhibit as close a relationship between the lineations and differential subsidence as those that were displayed on profiles 1 through 5; the sharpest breaks on profile 6 are not coincident with the intersection of lineations, but rather coincide with active faults and streams.

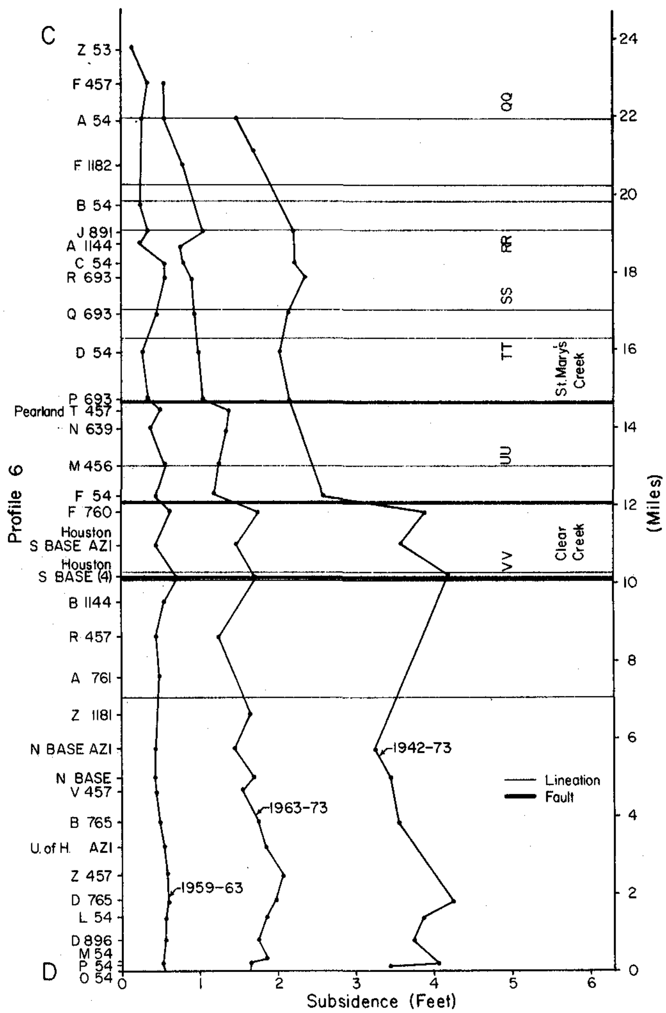

Figure 19. Profile 6. Differential subsidence, lineations, creeks, and faults, Alvin (C) to Houston (D), Texas. See figure 11 for location of profile 6.

Lineation QQ coincides with an increase in the amount of subsidence in the profile. Lineation RR south of benchmark J891 and lineation SS at benchmark Q693 intersect profile 6 in areas of increased subsidence. Both lineations RR and SS and zones of differential subsidence are coincident with the extrapolated trend of faults mapped within the Hastings oil field. Lineation TT south of benchmark D54 is also coincident with an increase in subsidence.

The sharp increases in the subsidence on the profiles that occur from benchmarks P693 to T457 and F54 to F760 are not coincident with lineations but are coincident with straight sections of the rectilinear drainage pattern of local creeks and with active surface faults. This increased subsidence occurs where St. Mary's Creek crosses the profile; the intersection is coincident with the extension of the straight section of Clear Creek (fig. 15). These straight sections of St. Mary's Creek and Clear Creek appear to be structurally controlled by an extension of a fault from the Ellington Air Force Base area. The sharp increase in subsidence that occurs at F54 is coincident with the intersection of an active surface fault with the profile. This fault probably connects with the southern fault of the South Houston graben system; the location of Clear Creek also is controlled by this fault.

Three other lineations intersect profile 6 between F760 and Z1181; these intersections coincide with variations in subsidence. The sharpest break occurs at benchmark Houston South Base which is directly above the Mykawa oil field. An active fault that breaks pavement in Mykawa Road coincides with lineation VV and this subsidence break on profile 6. Some lineations that cross profile 6 do not correlate with rapid increases in subsidence and conversely not all abrupt subsidence variations are coincident with lineations. Most changes in the rates of subsidence along the profile, nevertheless, are coincident with either active faults or lineations. Subsidence in this region has been geographically limited and intensified because of surface faults and lineations.

CORRELATION OF LINEATIONS WITH DIFFERENTIAL SUBSIDENCE ALONG TWO OR MORE PROFILES

The consistent intersection of lineations with points of differential subsidence on several profiles is further confirmation that many lineations mark hydrologic boundaries which are coincident with known faults in some places and most likely reflect the presence of faults in the subsurface at others. Three lineations are identified (fig. 11) as examples to demonstrate this relationship.

Lineation 1 extends from Angleton oil field to Galveston Bay (fig. 11). In the Angleton field area, the lineation coincides with the surface trace of an extrapolated fault. The lineation crosses profile 2 at a point of sharp subsidence increase over the Chocolate Bayou oil field, where the lineation coincides with the surface trace of a fault extrapolated from the subsurface. Lineation 1 intersects profile 5 (Alvin to Virginia Point) where the profile exhibits a subsidence increase in the Arcola area. The same lineation intersects profile 3 at a point of differential subsidence and is coincident with an active surface fault. Lineation 1 intersects profile 4 just south of a subsidence break. At six locations, lineation 1 appears to be structural in nature.

Lineation 2 (fig. 11) intersects profiles 3, 4, and 5 at points of significant differential subsidence. Similarly, lineation 3 intersects profiles 2, 3, 4, and 5 at points of differential subsidence.

The increased subsidence does not consistently remain on the same side of the lineations (fig. 11), nor do the lineations consistently intersect highs or lows on the subsidence profiles. The faults that the lineations, in part, represent may act as complete or partial hydrologic barriers or facies boundaries. The side of the lineation exhibiting increased subsidence, therefore, depends upon the side of the structural element in which maximum ground-water production occurs.

FAULTING IN SAN JACINTO MONUMENT PARK: AN EXAMPLE OF SUBSIDENCE PROFILES AND LINEATIONS AS PREDICTIVE TOOLS

In the San Jacinto Monument area, a clear sequence of structural events can be observed from historical photographs. In areas of poorly consolidated sediments, the land surface apparently flexes across a fault before the surface breaks. Cloos (1968) showed experimentally that flexing of the land surface precedes faulting as grabens or growth faults and that their associated antithetic faults propagate upward through unconsolidated

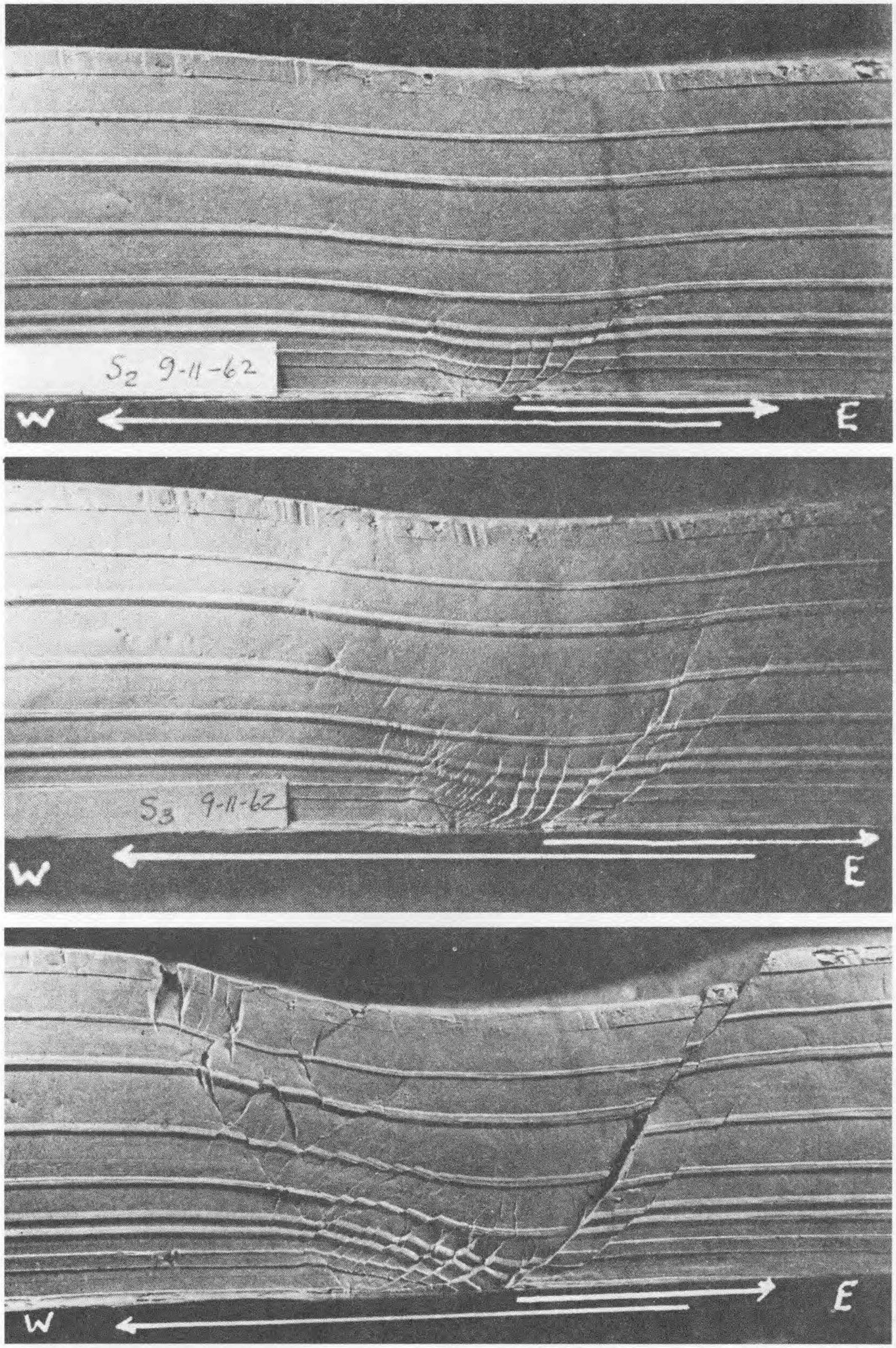

Figure 20. Experimental graben formation developed by applying lateral tension. Note that the faults are transmitted upward and that the top surface warps or flexes before it breaks. Courtesy Cloos (1968) and the American Association of Petroleum Geologists.

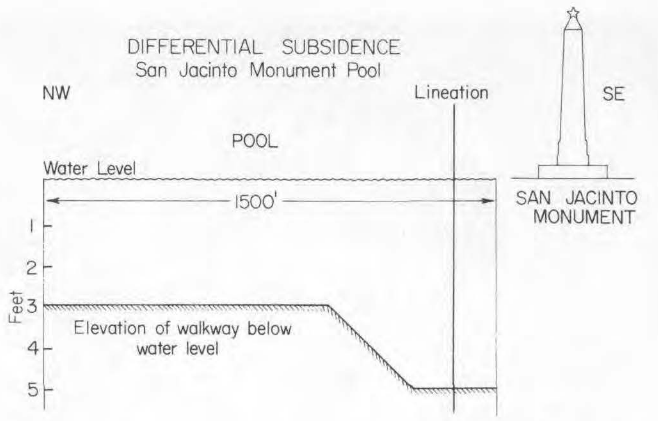

Figure 21. Differential subsidence and lineation in reflection pool of the San Jacinto Monument, Deer Park, Texas. Elevation of water level over walkway measured with stadia rod in March 1974.

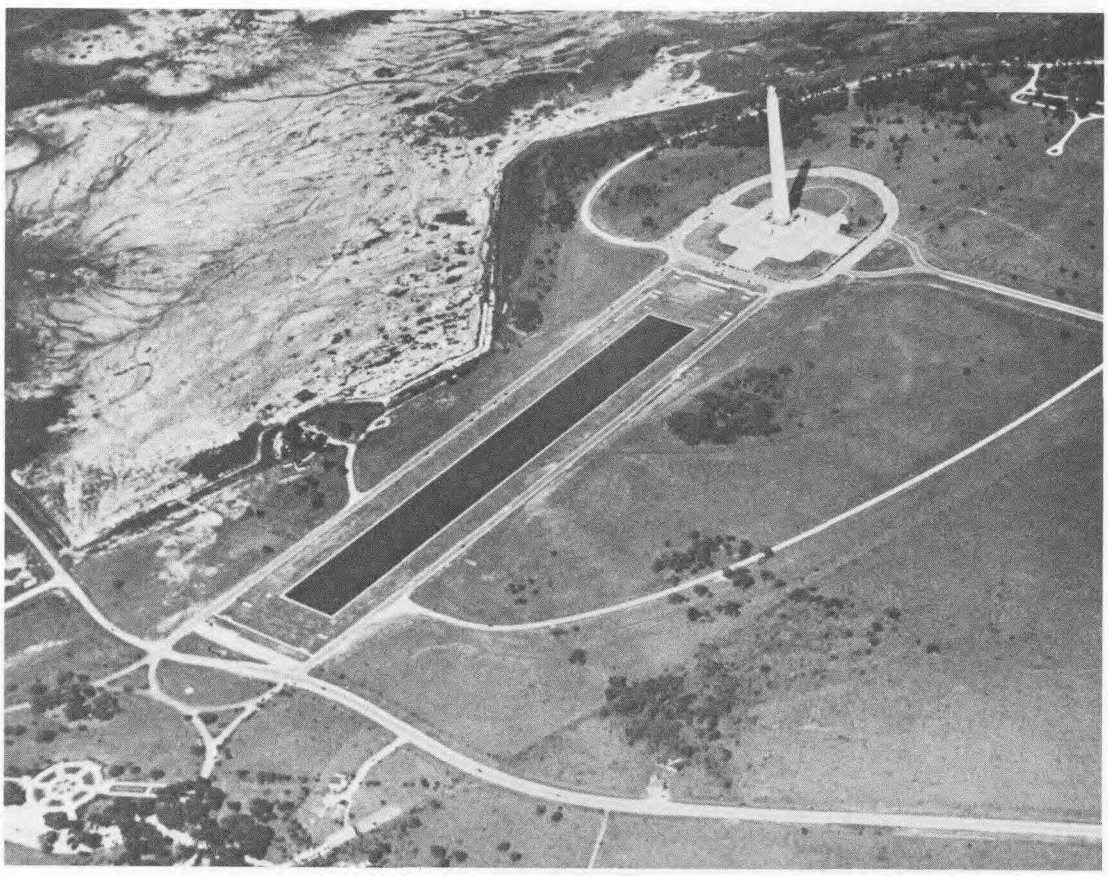

Figure 22. Photograph of San Jacinto Monument and reflection pool (mid-1950's). Note that walkway around reflection pool is completely above water. Photograph courtesy San Jacinto Historical Society.

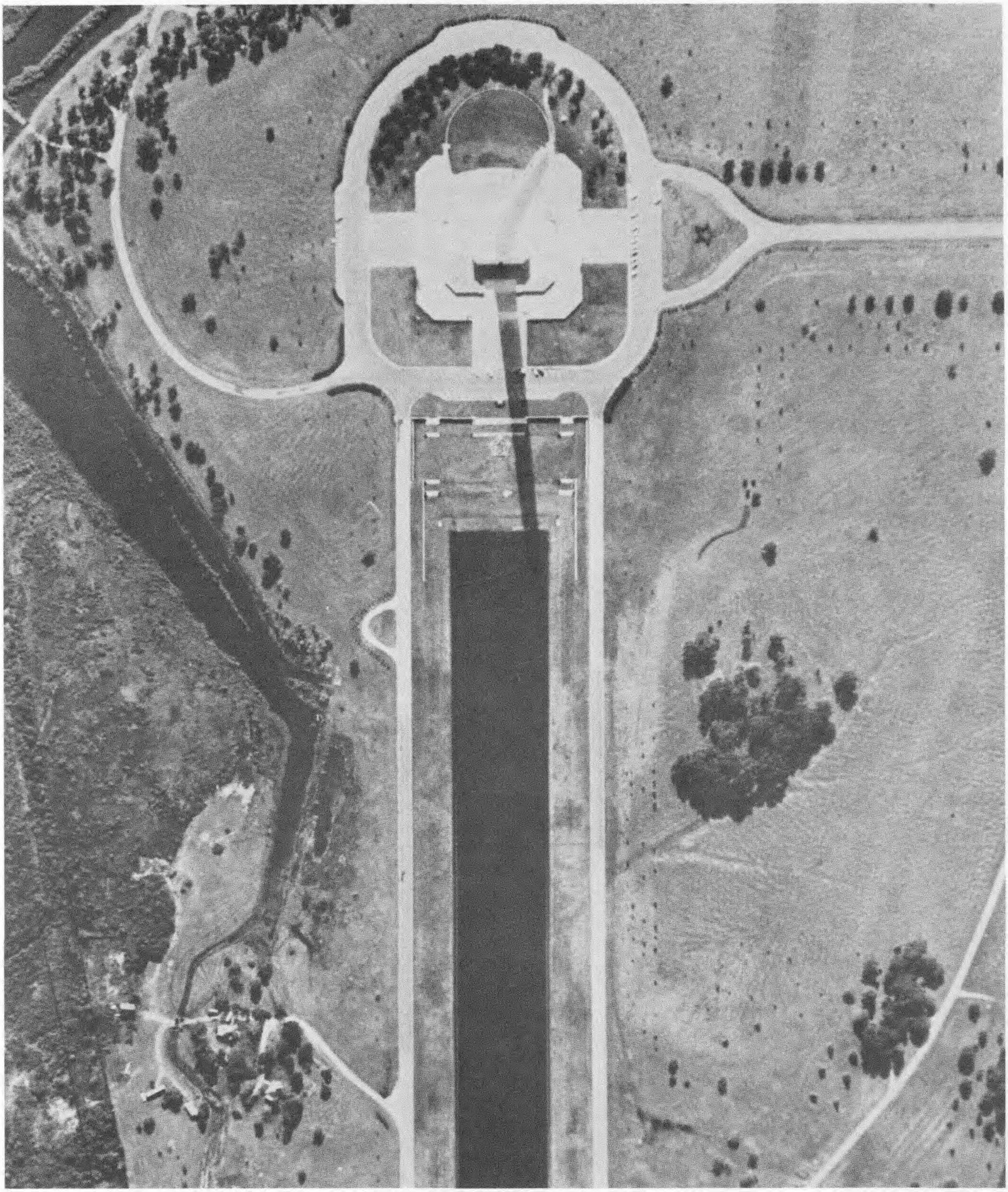

Figure 23. Photograph of San Jacinto Monument and reflection pool (October 9, 1968). Note that walkway around the third of the pool adjacent to the monument is submerged. Photograph courtesy Texas Parks and Wildlife Department.

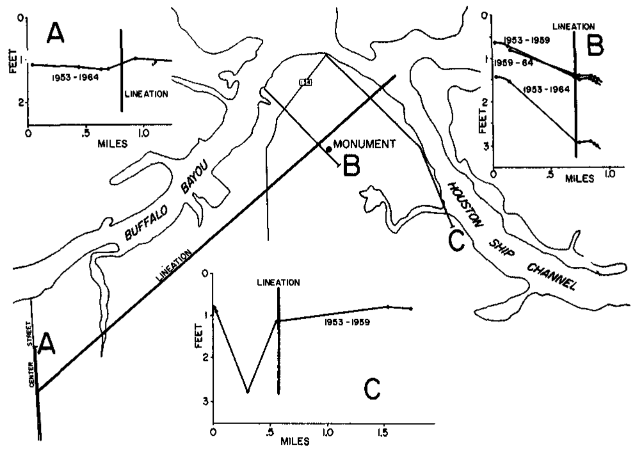

Figure 24. Lineation through reflection pool at San Jacinto Monument and subsidence profiles that cross the lineation.

sediments to the surface (fig. 20). With increased movement these surface flexures become active faults.

Flexing of the land surface in San Jacinto Monument Park was evident in the 1950's. A lineation observed from a 1956 Tobin aerial photograph passes through the southeast end of the reflection pool. Similarly, releveling of benchmarks between 1953 and 1959 indicates that differential subsidence was occurring in the mid-1950's. A surface fault now cuts through the reflection pool. The fault, however, was first detected on aerial photographs taken during the 1960's.

The San Jacinto Monument Park area has had some of the greatest subsidence in the Houston area. Since construction of the monument in 1936, there has been over 6 feet of land subsidence. An estimate of the amount of differential subsidence that has occurred prior to 1974 can be based on the depth of water covering the pea-gravel walkway that surrounds the reflection pool (fig. 21). At the western end the water level is 3 feet over the walkway; this amount of subsidence is relatively constant within the western two-thirds of the pool. The eastern third of the pool has subsided approximately 5 feet; the 2-foot increase in subsidence occurs across a zone approximately 150 feet wide. A road around the pool has had asphalt patches that coincide with the zone of differential subsidence in the reflection pool. To the northeast of the pool, land that was subaerial in 1968 is now continually submerged in the waters of the Houston Ship Channel. This sharp increase in subsidence, the patches on the road, and the submerged land are considered as evidence of an active surface fault.

A historical review of aerial photographs of the area provides further evidence that a fault extends through the reflection pool but did not show up until the 1960's. In the mid-1950's the flagstone edging around the pool was continuous with no breaks; the road around the pool required no asphalt patches (fig. 22). U. S. Air Force aerial photographs from October 1961 show that the flagstone edging in the eastern third of the reflection pool had submerged, but there had been no damage to the park roads encircling the pool. This is the first evidence from aerial photographs of fault movement. By 1968 (September 10, 1968) the road encircling the pool had two breaks and asphalt patches that line up with points where the flagstone edging had become submerged (fig. 23).

An alternate to the fault hypothesis is the possibility that the differential subsidence is caused solely by settlement of the San Jacinto Monument. This is a reasonable hypothesis, but probably incorrect. Measurements of settlement rates from 1937 to 1946 show a total settlement of 4.8 inches with 3 inches occurring in the first 3 years and rates decreasing rapidly for the next 6 years (Dawson, 1947). Theoretically, the rate should keep decreasing. Principal settlement would have occurred early in the monument's history and shown up on early photographs. The breaks in the roads and in the reflection pool do not show up, however, until the 1960's. Consequently, settlement is discounted as the cause of the differential subsidence and faulting.

Coinciding with this inferred active fault is a lineation observed on a 1956 Edgar Tobin aerial photograph. Three subsidence profiles intersect the lineation at points of differential subsidence (fig. 24). The subsidence profile which extends through the park and crosses the fault shows an uneven elevation loss as early as the period from 1953 to 1959, but the photographs made in the 1950's show no apparent faulting. In this case, the lineations and subsidence profiles, therefore, are effective tools in predicting zones of active faulting.

DISCUSSION

The critical problem resulting from active faults in the Coastal Zone is the structural damage to man-made features. In the Houston-Galveston area, two airports (Hobby and Ellington Air Force Base) have active faults through runways; the interstate highway system is cut at 11 different locations by active faults; railroad lines cross active faults at 28 different locations; faults pass through 11 residential neighborhoods; and several industrial buildings are built on active faults.

With hindsight it can be explained why a foundation cracked or why a section of highway needed to be resurfaced. But what is needed even more is the ability to predict where surface faulting will occur so that either the areas of potential faulting can be avoided or the buildings and structures can be designed to accommodate differential movement. The 6,947 miles of lineations mapped on the Physical Properties Maps of the Environmental Geologic Atlas of the Texas Coastal Zone suggests zones where active faulting is presently occurring or where potential active faulting may occur.

An interrelationship of faults, lineations, and differential subsidence occurs where there is presently extensive ground-water withdrawal (as in the Houston area). With the development of ground-water supplies in new areas, there will be subsequent declines in piezometric surfaces in the Gulf Coast aquifers (Pleistocene and Pliocene sands) and concomitant land subsidence and fault activation.

With the possible development of geothermal-geopressured aquifers in the Texas Coastal Zone for geothermal energy, land subsidence may occur with accompanying surface faults. The cause of subsidence over the Chocolate Bayou oil field may be analogous to the effects of future geothermal development. This oil and gas field produces from relatively deep formations (8,000 to 13,000 ft); oil production from 1942 to 1950 was 7.9 million barrels with an average production of almost a million barrels per year. Production from 1950 to 1959 was 19.4 million barrels with average annual production of 2.1 million barrels; from 1959 to 1963, production dropped to an annual average of 880,000 barrels per year and between 1963 and 1970 the annual average dropped further to 680,000 barrels per year (fig. 25). Between 1942 and 1950, the land at the center of the area of subsidence was subsiding at a rate of 0.02 ft/yr. From 1950 to 1959 the rate increased to 0.06 ft/yr and from 1959 to 1963 the rate further increased to 0.12 ft/yr; but between 1963 and 1973 the rate decreased to 0.07 ft/yr. If oil production is the cause of this land subsidence, there is lag period during which this strain is transmitted from producing horizons (8,000 to 13,000 ft) to land surface, because the annual rate of subsidence between 1959 and 1963 is greater than the preceding periods even though production had decreased. Subsidence over the Wilmington oil field (California) occurred concomitantly with oil production with no apparent lag period (Mayuga and Allen, 1969).

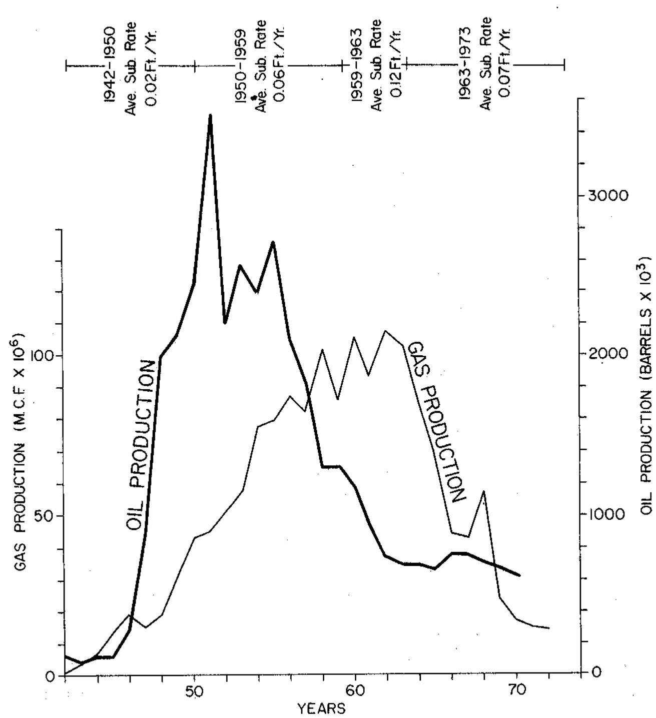

Figure 25. Comparison of rates of subsidence to oil and natural gas production from Chocolate Bayou oil field between the years 1942 and 1973; production rates of oil and gas from Texas Railroad Commission.

The salinity of water from the producing sands of the Chocolate Bayou oil field has generally decreased with time. Fowler (1970) attributes this decrease to the dilution of the original formation waters by lower salinity waters being squeezed from the shales adjacent to the reservoir sands. This decreased porosity of the shales may be a principal contributor to the land subsidence. If this hypothesis is correct, the reservoir most likely causing a majority of the subsidence is the Upper Frio (8,863 to 8,747 ft), which has been the major producing reservoir in the field. Salinity in this sand has decreased 12 percent and reservoir pressures have dropped over 2,000 psi between 1946 and 1968 (W. Fowler, personal communication, June 1975).

A second hypothesis to explain the subsidence as well as the apparent lag time between major production and increased subsidence is the exploitation of natural gas from geopressured reservoirs. The Chocolate Bayou oil field has many producing horizons which are geopressured; pressures rise from approximately 5,000 psi at 10,000 feet to 14,000 psi at 14,000 feet (Myers, 1968; Fowler, 1970). Major development of gas reservoirs did not occur until the mid-1950's.

The increase in the subsidence rate from 0.02 ft/yr (1942–1950) to 0.06 ft/yr (1950–1959) to 0.12 ft/yr (1959–1963) and the decrease to 0.07 ft/yr (1963–1973) coincide with the variations in the rate of natural gas production (fig. 25), In the case of natural gas exploitation, no apparent lag period exists between production and subsidence.

A third hypothesis that needs to be considered but that does not explain the subsidence over the Chocolate Bayou oil field is possible ground-water production for either domestic or industrial use and for secondary recovery operations. There is no record of secondary recovery operation in the Chocolate Bayou oil field (Texas Railroad Commission, 1968). Similarly, there has been insufficient ground-water production for home and industrial usage to cause substantial declines in the piezometric surface. At the sharp break in the subsidence profile between benchmark H691 and P53, the piezometric surface was at about the same elevation in 1967 as it was in 1946. At benchmark R53 the piezometric surface dropped about 40 feet between 1949 and 1967 (data from figs. 12, 13 in Sandeen and Wesselman, 1973). This drop of 40 feet is probably insufficient to generate 1.5 feet of subsidence (0.04 ft subsidence per 1 ft piezometric decline).

Subsidence resulting from oil and gas production from shallower producing horizons has been documented in numerous fields. Subsidence of 28 feet in Wilmington oil field (California) was caused by oil production from less than 4,000 feet. Overall, about two-thirds of this compaction occurred in the oil sands and only one-third in the siltstones (Allen and Mayuga, 1969). Three feet of subsidence at Goose Creek oil field (Baytown, Texas) was caused by oil production at shallow depths; however, large amounts of sand as well as oil were pumped from the reservoir (Pratt and Johnson, 1926). Other areas where oil production has generated land subsidence include the Buena Vista, Huntington Beach, and Inglewood fields in California (Yerkes and others, 1969), and Lake Maracaibo, Venezuela (Van der Knaap and Van der Vlis, 1967).

Subsidence in these fields has resulted from shallow production. Land subsidence caused by deep oil and gas production has not been recorded previously and has not been considered significant since the porosity of the sands and clays should be too low to preclude excessive compaction.

Geertsma (1973) considered that subsidence from deep production (over 4,000 ft) was unlikely but still possible and suggested that four factors control the amount of land subsidence associated with petroleum production: (1) the amount of pressure reduction in the field, (2) the vertical thickness of the producing reservoirs, (3) the degree of cementation, and (4) the depth of burial. Chocolate Bayou oil field which is deep (1) has a thick producing reservoir (350 ft in a 4,000-ft interval) and (2) has experienced appreciable pressure declines.

Land subsidence over the Chocolate Bayou oil field appears to be resulting from oil and gas production and subsequent compaction of sediments at depths greater than 8,000 feet. Lineations which appear to be the surficial extensions of the faults controlling the field have limited the geographic extent of the land subsidence.

This model of land subsidence, which is the result of deep fluid production, suggests that extensive pumpage of ground water from deep geopressured fault blocks in the Gulf Coast for geothermal energy may cause land subsidence. Subsidence over a geothermal field would be relatively uniform; however, differential subsidence and surface fault activation might be expected where the extension of subsurface faults would intersect land surface.

The potential for continued subsidence and additional fault activation should not, however, preclude further development of ground-water resources of the Gulf Coast aquifers or development of geothermal resources. Lineations which are presently passive structural features, and which in the future may become the foci for differential subsidence and active faulting, identify these critical areas of concern. Herein lies the predictive value of lineation analysis and subsidence monitoring.

CONCLUSIONS

1. The land surface of the Texas Coastal Zone is inscribed by faults and lineations, which are, in part, the result of the propagation of Tertiary faults through the unconsolidated Pleistocene and Recent sediments.
2. Lineations may be passive structural features representing either surface extensions of Tertiary faults or joint patterns.
3. Lineations are linear zones that can be several thousand feet wide.
4. Lineations are coincident with the surface trace of many subsurface faults that have been extrapolated to the land surface.
5. In the Houston-Galveston area of land subsidence and active faulting, lineations are coincident with several zones of active faults. Not all active faults are coincident with lineations.
6. Lineations are commonly coincident with zones of differential subsidence in the Houston-Galveston area.
7. Movement on some surface faults has been accelerated by a declining piezometric surface within the coastal aquifer system.
8. Lineations in nonsubsiding zones appear to be passive structural features that may pass along strike into active surface faults or zones of differential subsidence in areas of land subsidence.
9. Differential subsidence may be a precursor to active faulting because it represents a flexing of the land surface before fault rupture.
10. Lineations and subsidence profiles are valuable tools for identifying incipient faults in many areas.
11. Important questions arising from the data presented in this report cover subjects including the mechanisms of fault activation, the relationship of faults to hydrologic boundaries, the relationship of subsidence to phenomena other than ground-water withdrawal, the consequences of ground-water production from different sections of the Gulf Coast aquifers, and the possible effectiveness of a ground-water management program for the Houston-Galveston area. The Bureau of Economic Geology is conducting further studies in these areas.

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