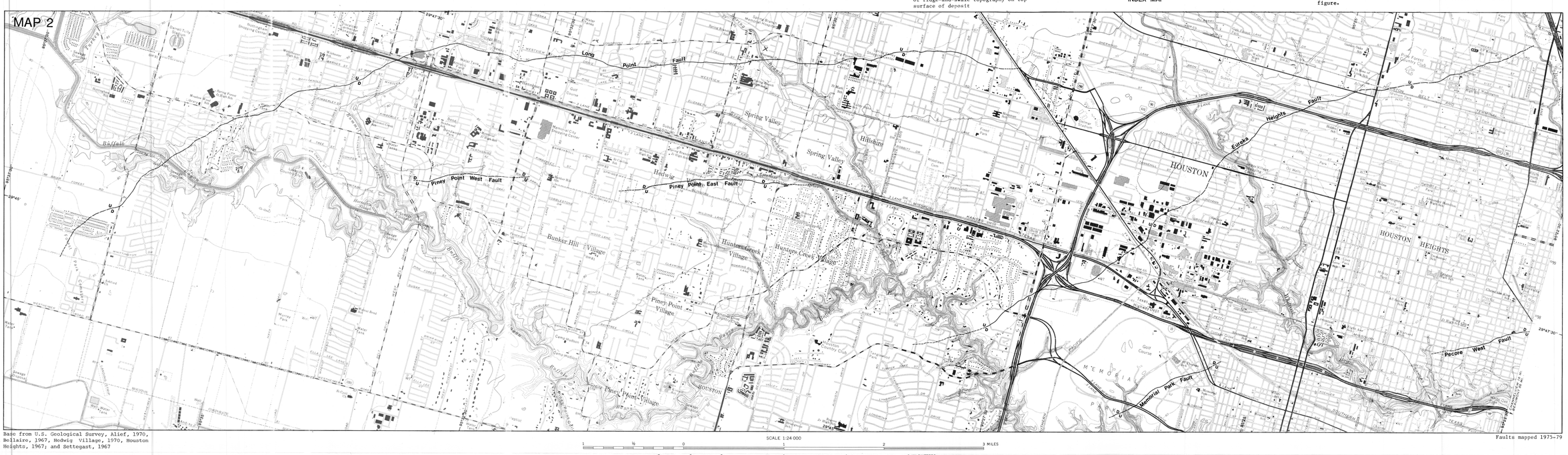
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MISCELLANEOUS FIELD STUDIES
MAP MF-1136

FAULTS, HOUSTON METROPOLITAN AREA, TEXAS

MAP OF THE CLODINE FAULT AND RENN SCARP, HOUSTON METROPOLITAN AREA, TEXAS



MAP OF THE LONG POINT, PINEY POINT EAST, PINEY POINT WEST, EUREKA HEIGHTS, MEMORIAL PARK, AND PECORE WEST FAULTS, HOUSTON METROPOLITAN AREA, TEXAS

DISCUSSION

Abstract

Hundreds of residential, commercial, and industrial structures in the Houston metropolitan area have sustained moderate to severe damage owing to their locations on or near active faults. Paved roads have been offset by faults at hundreds of locations, buried pipelines have been distorted by fault movements, and fault-induced gradient changes in drainage lines have raised concern among flood-control engineers. Over 150 faults, many of them moving at rates of 0.5 to 2 cm/yr, have been mapped in the Houston area; the total number of faults probably far exceeds this figure.

This report includes a map of eight faults, in north-central and western Houston, at a scale useful for land-use planning. Seven of the faults are known to be active and have caused considerable damage to structures built on or near them. If the eighth fault is active, it may be of concern to new developments on the west side of Houston. A ninth feature shown on the map is regarded only as a possible fault, as an origin by faulting has not been firmly established.

Seismic and drill-hole data for some 40 faults, studied in detail by various investigators, have verified connections between scarps at the land surface and growth faults in the shallow subsurface. Some scarps, then, are known to be the surface manifestations of faults that have geologically long histories of movement. The degree to which natural geologic processes contribute to current fault movement, however, is unclear, for some of man's activities may play a role in faulting as well.

Evidence that current rates of fault movement far exceed average prehistoric rates and that most offset of the land surface in the Houston area has occurred only within the last 50 years indirectly suggest that fluid withdrawal may be accelerating or reinitiating movement on pre-existing faults. This conclusion, however, is based only on a coincidence in time between increased fault activity and increased rates of withdrawal of water, oil, and gas from subsurface sediments; no cause-and-effect relationship has been demonstrated. An alternative hypothesis is that natural fault movements are characterized by short-term episodicity and that Houston is experiencing the effects of a brief period of accelerated natural fault movement. Available data from monitored faults are insufficient to weigh the relative importance of natural vs. induced fault movements.

Introduction

This report has a dual purpose--to provide maps of faults in parts of north-central and western Houston at a scale useful to land-use planners, and to provide a limited discussion of "the Houston fault problem" (Van Siclen, 1967) for the interested reader. The use of scientific terminology has been held to a minimum, but where such use is unavoidable the appropriate term is followed by an asterisk (*) and is defined in the glossary.

Many readers of a companion report on faults* in the southeastern Houston area (Verbeek and Clanton, 1978) expressed a wish for amplification of the section on geologic significance of faults. This was particularly true among those in land-use planning, construction, engineering, and allied disciplines, who have periodic need of geologic information but who cannot routinely consult all of the geologic literature for relevant papers. Accordingly, this report provides a short summary of the geology of faults and a brief overview of the possible causes of current fault movement.

Active faults near Houston were first recognized over fifty years ago, when Pratt and Johnson (1926) reported sudden displacements of the land surface within the Goose Creek oil field near Baytown. By 1973, after much discussion of the subject in the geologic literature (for example, Gray, 1958; Weaver and Sheets, 1962; McClelland Engineers, 1966; Van Siclen, 1967; Sheets, 1971; Reid, 1973), some 52 faults had been recognized in the Houston metropolitan area. Aggregate length of known faults was then reported at 220 km (Reid, 1973). More recent studies (Clanton and Amsbury, 1975; St. Clair and others, 1975; Verbeek and Clanton, 1978; this report plus additional unpublished data) have increased those numbers to well over 150 faults having an aggregate length of more than 500 km.

Hundreds of residential, commercial, and industrial structures in the Houston metropolitan area have sustained moderate to severe damage because of their locations on or near active faults. The total number of active faults in this region is not known, but some idea of the scope of the problem can be gained from this report and a previously published map (Verbeek and Clanton, 1978) of faults in southeastern Houston (fig. 1). Together the two maps cover about 750 km^2, or about 20 percent of the Houston metropolitan area, yet even within this restricted area 100 faults with a combined length of over 230 km have been recognized. More than half of the faults mapped show clear evidence of movement during historic times. The actual percentage of active faults is probably much greater, because the opportunity to assess recent movement (based on damage to manmade structures) is lacking for large tracts of undeveloped land. Additional areas in and near Houston have comparable fault densities (for example, Jacinto City and areas to the north, as well as Baytown and much of southern Houston; see fig. 2), but other areas, such as downtown Houston, appear to be relatively unaffected.

The total socioeconomic impact of faulting is large (Sheets, 1971), yet public awareness of this natural hazard has grown slowly. Fault-related problems grow worse as the region rapidly develops into neighboring highly faulted areas. Even where the presence of a fault has been a matter of public record for years, as it has for the Long Point, Piney Point, and Eureka Heights faults (McClelland Engineers, 1966), new construction commonly takes place near or directly on the fault trace.*

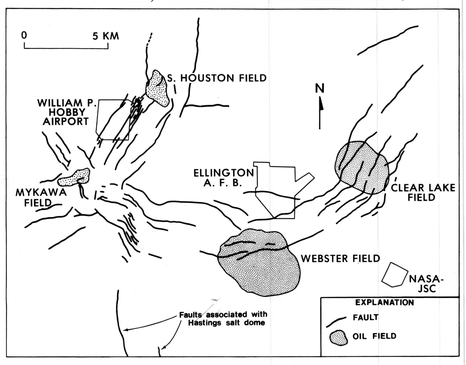


Figure 1.--Faults in southeast Houston metropolitan area (modified from Verbeek and Clanton, 1978). All faults shown have been mapped at land surface; many are demonstrably active.

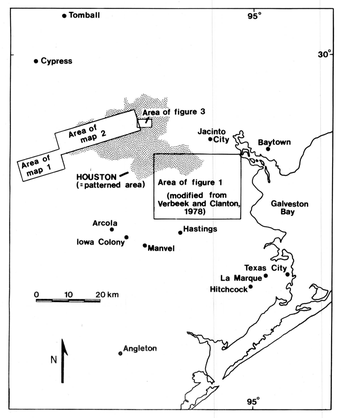


Figure 2.--Houston and vicinity, showing areas covered by published 1:24,000-scale fault maps. Additional faults have been mapped in or near every incorporated area (solid circles) shown on figure.

EXPLANATION

U/D FAULT--Solid line when position certain on the basis of field and photographic evidence; long dashed line when exact position uncertain, commonly the result of modification of the landscape; short dashed line when fault is located on basis of weak field and photographic evidence; short-dashed and queried line when inferred. U, upthrown side; D, downthrown side

POINT BAR DEPOSITS NEAR OYSTER CREEK--Dotted lines depict general pattern of ridge-and-swale topography on top surface of deposit

INDEX MAP

Mapping Technique and Limitations

Techniques in Developed Areas

The approximate locations of four of the faults shown on map 2 were known from the published works of McClelland Engineers (1966) and Van Siclen (1967). Their published maps, however, are at scales that are difficult to adapt to local studies; for purposes of land-use planning all four faults were compiled in detail (at a scale of 1:12,000). Two of the faults, the Long Point and Eureka Heights faults, are among the longest and, by virtue of their location, the most destructive faults in Houston. All seven faults shown on map 2 were mapped primarily by tracing an associated zone of damage through developed areas.

Fault damage may take a variety of forms, but all damage is due to the same cause--"sinking" of the downthrown side of a fault relative to its upthrown side*. Rigid structures, such as paved surfaces and slab foundations, break along the traces of faults and become progressively more offset as movement continues. Gently inclined fault scarps are the most visible aspect of fault movement, but inasmuch as typical fault surfaces are inclined at angles of 60°-75° from a horizontal plane (Van Siclen, 1967), any movement on the fault must be accompanied by horizontal extension as well (fig. 4).

Damage due to faulting may locally mimic damage due to other causes (such as unstitched clays, general deterioration of structures with age, or substandard construction practices), but usually is distinguishable by the following characteristics:

1. Damage to cultural features is significantly more severe within a narrow (1 to 10-m width), rectilinear to gently curvilinear zone than in adjacent areas.
2. The zone of damage is parallel to and coincident with a topographic slope--the fault scarp*--that separates two blocks of land of different elevations. Together the fault scarp and associated zones of damage define a linear feature which may be traceable for a 2,000 times greater than its width.
3. The degree of affected structures is consistent with vertical offset of the land surface as deduced from the fault scarp. For example, if the land surface is lower on the south side of a fault, observed damage to buildings, roads, and so forth must be consistent with south-side-down movement on the fault.

Observations of fault damage provide information on the exact location of a fault for only short segments of its length--that is, only at those locations where fault displacements have been built and show clear evidence of offset along the fault. The fault scarp, however, connects discrete zones of fault damage and thereby establishes a reliable and continuously mappable fault trace. Although the fault scarp may be modified by erosion or locally obliterated by man's activities, the elevation difference between the upthrown and downthrown blocks remains to suggest the approximate trace of the fault (fig. 5).

Faults in urban areas were investigated at every location where they were crossed by public roads. As additional detail was desired, more detail was required, permission was obtained to trace faults across selected residential lots and through commercial and industrial complexes. Normally, however, visual inspection from a public road right-of-way established the fault trace through private property. The faults shown on map 2 could thus be traced on a nearly continuous basis.

Techniques in Undeveloped Areas

Typical fault scarps in the Texas Gulf Coast range in height from about 0.2 to about 1.5 m--very low compared to fault scarps in many other areas of the United States. Scarps in the Texas Gulf Coast commonly are subtle and stand out as prominent, relatively abrupt topographic features within the otherwise much flatter and more gently rolling landscape characteristic of much of the region. At many locations a fault scarp is the dominant feature of the local landscape.

Faults in undeveloped areas, such as those depicted on map 1, are commonly visible on aerial photographs as sharp, gently curvilinear to rectilinear boundaries between two areas that differ in tone or texture. Large-scale (1:10,000 to 1:40,000) black-and-white or color-infrared photographs are particularly well suited for this purpose. Tonal contrasts on photographs reflect, among other things, fault-associated vegetation and soil-moisture contrasts in the field. The topographically low, downthrown side of a fault, which catches and holds much of the surface runoff from adjacent areas during periods of rainfall, commonly supports a different plant community than is found on the upthrown side. In extreme cases, shrubs, small trees, and prairie grasses dominate the upthrown side, whereas the downthrown side is a marsh and supports only those plants that can grow in a permanently wet environment. In winter, when bare ground is visible through remnants of the previous season's growth of annual plants, tonal contrast between the dark, relatively wet soils of the downthrown side and the lighter and better drained soils of the upthrown side may be particularly evident--often more so than the fault-related vegetation contrasts of the growing season. During extended periods of little rainfall, however, soils on both sides of the fault will dry out and photographic evidence of the fault may all but disappear.

The seasonal nature of vegetation changes and the dependence of moisture contrasts on recent rainfall necessitate examination of aerial photographs for a specific season. Flights (ideally from different years) as practical if a reliable fault map is to be prepared. Field examination of each linear feature tentatively identified as a fault from aerial photographs is essential--photos provide a powerful but not sufficient tool for positive fault identification. Repeated visits to the field are advisable, and at least one such visit should take place in winter or early spring, after a heavy rain, when ponded water and minimal vegetation may enhance the visibility of subtle fault scarps.

Additional work (by drilling, or trenching across the scarp) will be needed to further define this feature.

Each feature shown on maps 1 and 2 was examined along nearly the entire mappable length of its scarp, both on the ground and from a helicopter. Repeated visits to the field were made to document seasonal vegetation and moisture changes, and much field work was carried out in winter, when minimal vegetation maximized visibility of topographic features.

All faults mapped in the field were plotted initially on 1:12,000-scale aerial photographs and later reduced to the publication scale of 1:24,000.

Limitations of Maps

Effective and proper use of these maps is in part contingent upon awareness of their limitations. This report should be viewed only as a preliminary study of faulting*; more detailed site-specific studies are warranted in areas where faulting could prove detrimental to anticipated land use.

Four of the faults shown on map 2--the Long Point, Piney Point East, Eureka Heights, and Memorial Park faults--have been mentioned previously in the geologic literature (for example, Weaver and Sheets, 1962; McClelland Engineers, 1966; Van Siclen, 1967). The other faults on map 2 are named here, but perhaps in the course of a reconnaissance study of faults in the Houston Gulf Coast. Only a limited detail was required, permission was obtained to trace faults across selected residential lots and through commercial and industrial complexes. Normally, however, visual inspection from a public road right-of-way established the fault trace through private property. The faults shown on map 2 could thus be traced on a nearly continuous basis.

Identification of faults in undeveloped areas is complicated by the fact that no associated scarp may exist, because of recent recent movement and thus confirm the identity of the mapped feature as a fault. Topographic features locally resemble fault scarps form by a number of natural processes, and care must be taken not to interpret apparent features as faults. Presence or absence of a fault may, under favorable circumstances, be confirmed by well-log correlation, but for most areas of nearby control points from which one can determine exact map positions requires accurate portrayal of the scarp on maps. Unless the position of a scarp is apparent from aerial photographs, because of a visible change in vegetation or soil tone from the upthrown to the downthrown side, the geologist must simply estimate the position on the map. These uncertainties affect, to varying degrees, the two features depicted on map 1. Locational uncertainties were reduced by examination of numerous sets of aerial photographs, in conjunction with careful field inspection of both scarps in the vicinity of the mapped traces of the Clodine fault and the Renn scarp (map 1) do not have the accuracy of faults shown on map 2. We therefore stress again that this report, by its very nature, depicts faults in considerable detail, detail. For site-specific studies where the location of a fault must be known to within the nearest few meters, subsurface data must commonly be acquired and used in conjunction with surface evidence to pinpoint a fault, and the fault's location must then be surveyed to required standards of accuracy.

A final and serious limitation to any fault map of the Houston area is the inability of geologists to determine, on the basis of current fault activity, which faults will be active in the future.

Discussion of faults in Houston area
Environmental Aspects of Faulting

The consequences of active faulting are many and, almost without exception, costly and undesirable. Visible fault damage was an aid to mapping throughout our work, but no special study of the impact of faulting was attempted. Nevertheless, some generalities, based on observations and measurements along nearly 300 km of active faults, can be made.

Rigid structures such as highways, runways, and building foundations, where built astride active faults, commonly display the consequences of differential vertical movement and horizontal extension. Breakage occurs as the sinking ground surface on the downthrown side no longer supports the structural load. Maximum damage normally occurs on and immediately adjacent to the fault scarp, within a zone that is typically 2-3 m wide, but which may vary in width from less than 1 m to more than 10 m. To either side of this zone, some limited fault-related failure may be seen in brittle material, but the most visible effect of fault movement here is tilting. The amount of tilt progressively decreases away from the fault scarp and is, for most faults, minor at distances of 20-30 m from the scarp. Surveying data, however, suggest that detectable amounts of tilt may be found as much as 70 m away from some faults. The effects of faulting are not identical on both sides of a fault; typically the downthrown block shows more damage, and the zone of distortion and tilting are wider, than for corresponding zones on the upthrown side.

Some effects of faulting beneath buildings include foundation failure (and attendant geotechnical infiltration of water), tilting of floors, distortion of window and door frames, leaking roofs, and extensive damage to facing materials and interior walls. The road network in the Houston area has also been damaged by faulting at hundreds of locations, some of which have required repair at intervals as frequent as every 2 years. Airports have fared little better; the faulted runways at both William P. Hobby Airport and at Ellington Air Force Base (fig. 1) require nearly constant maintenance.

It should be noted that dip-slip movement* along any nonvertical fault must generate both vertical offset and lateral separation at the surface. Most faults in the shallow subsurface are inclined at angles of 60°-75° relative to a horizontal plane (Van Siclen, 1967), which indicates that the value for the horizontal component of movement ranges from about one-fourth to one-half the value of the vertical movement (fig. 4). Repair of damaged structures, or the design of new structures that must bridge an active fault, should therefore take both components of movement into account.

Fault-related damage to residential, commercial, and industrial facilities, and to the road and railroad network, but perhaps of no greater importance than more subtle effects of faulting, buried pipelines, for example, must experience the same kinds of distortion as do streets and buildings at the surface, but subsurface damage is rarely seen. It is thus probable that other, perhaps active, faults are present. Blank areas on the map are most appropriately regarded as insufficiently mapped rather than unfaulted.

A further complication in preparing this report and similar fault maps is that much of the evidence a geologist normally uses to map surface faults is absent in the Gulf Coast has been destroyed in developed areas. Only the most active and damaging faults, or faults whose scarps are of substantial height, are likely to be noticed during mapping of developed areas. Mapping of faults in such areas is a matter of recent construction, where even rapidly moving faults may not have had sufficient time to cause substantial damage. Faults in urban areas are thus likely to be always underrepresented on maps, regardless of the time available to map them. For those active faults that are found, however, the trace of the fault can commonly be determined from the distribution of the associated zone of damage.

Wherever possible, faults on the map are plotted to an accuracy within 1 mm, a distance that corresponds to 24 m on the ground. It is thus difficult to determine from the map alone whether a fault goes through or merely lies near a particular site, except for those parts of the map where individual faults are shown and where we can, therefore, depict faults in true relation to all cultural features. In so doing, however, minor inaccuracies are unavoidably introduced. The Eureka Heights fault, for example, need not significantly impair future development of the region. With prior knowledge of fault locations and responsible planning of engineered structures, any problem evident in existing areas can be avoided in future construction.

Rates of Fault Displacement in the Houston Metropolitan Area

The first and, to our knowledge, the only attempt to study short-term variations in fault movement was that of Reid (1973), who, in 1971, installed monuments on many points (Long Point, Piney Point East, and Eureka Heights) to measure both vertical and horizontal components of displacement across the scarps. Reid (1973, p. 87), the first 14 months of observation revealed the following:

(1) The annual rate of vertical separation ranged from 6.7 mm/yr at a monitored site on the Eureka Heights fault to 34 mm/yr at a site on the Long Point fault.

(2) The vertical separation was accomplished by individual creep events that ranged from 0.09 mm in one hour to 3.33 mm in 4 days.

(3) Individual creep events were separated by periods of inactivity that lasted from 4 to 60 days. In addition, Reid found that different parts of the same fault moved at different rates, and only occasionally could discrete movement events at one site be correlated with observed events at other sites.

The interpretation of these and additional data gathered from Reid's instruments since mid-1972 is complex and will not be discussed here. We point out only that fault movements are episodic on the scale of hours to days, at least for the few faults monitored by Reid.

Average rates of movement over periods of years can be determined "by dividing the vertical separation of the overlying paved surface by the number of years since its surface was constructed or relevelled" (Reid, 1973). This has been done by a number of workers (Gray, 1958; Weaver and Sheets, 1962; McClelland Engineers, 1966; Van Siclen, 1967; Reid, 1973). Most active faults surveyed showed average vertical displacements of between 0.3 and 2-3 cm/yr., with a maximum observed rate (Reid, 1973) of 10.3 cm/yr.

Long-term as well as short-term variations in fault movements have been documented, so the vertical separation from year to year at any particular location on a fault is likely to vary. Sections of some faults that have apparently been dormant for years may suddenly become active (illustrated dramatically by faulting at Goose Creek oil field; see account of Pratt and Johnson, 1926), and, conversely, other faults with a long history of damage to manmade structures may stop moving (Van Siclen, 1967). The same fault may be dormant at one location and active at another. There appears to be little assurance that identification of the most active segments of faults today will be of material assistance in estimating fault movements beyond the immediate future.

No special study of movement rates for any of the faults shown on maps 1 and 2 and figure 3 was attempted, but, on the basis of observed damage to structures of known age, vertical offsets of 1 cm/yr or more appear characteristic for much of the Long Point, Piney Point East, Eureka Heights, Memorial Park, Pecore West, and Pecore East faults.[2/] Movement rates have not been estimated for the Piney Point West fault, but it is active and has damaged structures built on it.

The Clodine fault is problematic, in that few manmade structures more than a few years old have been built across the fault. Opportunity to assess its rate of movement, if indeed it is active, is thus severely limited. The geologist must resort to old aerial photographs and old topographic maps for evidence of previous signs of the fault; he must inspect borrow ditches and irrigation canals for evidence of gradient changes caused by faulting; and he must examine every paved surface that crosses the fault, no matter how new, for signs of fault-related damage. The bits of evidence that we have gathered for the Clodine fault suggest that it is active, at a seemingly low but undetermined rate. We believe, however, that the various lines of evidence, even collectively, are far from diagnostic and present at best only a weak indication that the fault is active.

No manmade structures had been built on the Renn scarp at the time of our investigation; we therefore have no evidence by which to directly assess the possibility of movement.

Relation Between Subsurface Faults and Scarps at Land Surface

Numerous faults beneath the Houston area, at depths of 1,000-4,000 m, have been delineated through study of well-log correlation lines. It is reasonable to assume, but difficult to prove, that most of these subsurface faults penetrate younger sediments at shallower depths, and that among them are some faults that have offset the ground surface to form recognizable scarps. Unequivocal demonstrations of this relationship (McClelland Engineers, 1966) are few in the published literature. Among unpublished studies, however, there is ample evidence that many faults recognized at land surface may be traced to appreciable depths; that is, that faults in the Houston area are not merely surface lines. Exploration for the Texas Medical Center and for a nearly 3,000 m by use of electric logs, but little subsurface information has been reported for the other faults.* All of the faults shown on maps 1 and 2, however, appear to be part of a larger group of east-northeast-trending faults, some of which have been studied recently by Van Siclen (1978) in the Addicks and Barker dam areas, north of and adjoining map 1. Of nine features tentatively identified as faults on the basis of surface evidence, eight for which subsurface confirmation was sought, seven were identified by Van Siclen as growth faults.

History of Faulting in the Houston Area and Causes of Current Fault Movement

The conclusion that some, and probably most, observed fault scarps at the surface are manifestations of natural geologic features leaves open the question of what factors promote current fault movements. Certainly natural processes must be considered, as was suggested by Reid (1973) in his discussion of movement on the Long Point and Eureka Heights faults. However, Reid also advocated large-scale pumpage of ground water as an additional, locally, fault-initiating or accelerating fault movements. Kreitler (1977) extended this view a step further by emphasizing the importance of fluid withdrawal (ground water and, locally, petroleum) as the prime factor governing fault movement; he suggested that most faults in areas of little fluid production are either inactive or are moving so slowly that few recognizable scarps have formed.

It would be inappropriate in this paper to discuss all aspects of this controversy. Only a few pertinent facts with which any hypothesis of faulting must be consistent are reviewed here:

1. Some faults are undeniably natural geologic features--that is, they were not inadvertently created by man, even though man's activities are possibly accelerating or reinitiating movement along them. Scarps due to prehistoric movement along the Long Point and Eureka Heights faults, for example, are readily visible on topographic maps based on surveys completed in 1915-16 (U.S. Geological Survey, Hillendahl sheet, 1915; Houston Heights sheet, 1922). The present land surface and uppermost sediments in the Houston area are geologically very young--their ages are measured in tens of thousands, not millions, of years--and knowledge that they were faulted by a natural process, before large-scale fluid extraction had affected much of the Houston area, suggests the probability that natural fault movement is locally continuing today.

2. Although some fault scarps are visible on topographic maps of 60 years ago, it is equally important to realize that most are not. Many scarps mapped in the Houston area today did not exist, or were present only in subdued form, in 1915-16. Most of the present scarp height of many faults, then, appears to have been produced through fault movements within only the last few decades.

3. The visibility of faults on aerial photographs of undeveloped areas has increased dramatically since 1930, when large-scale comprehensive coverage was first obtained. The amount of increase is far greater than can be attributed to the superior quality of modern cameras, films, and processing; it is probably attributable instead to recent growth in scarp heights.

4. If present rates of fault movement (commonly in the range of 0.5-2 cm per year; McClelland Engineers, 1966) were characteristic of the recent geologic past, we should, but do not, see many fault scarps tens of meters high. Present levels of fault activity evidently are far in excess of the prehistoric long-term average.

These facts collectively suggest that some limited faulting of the land surface in the Houston area took place in the recent geologic past, but that most significant offset of the land surface has occurred only within the last 60 years. Ascribing the apparent sharp increase in modern fault activity to fluid withdrawal is tempting, but this conclusion, however attractive, has not been proved. Critical data to test a possible relation between fluid withdrawal and fault movements for a meaningful number of faults are not presently available. The limited information so far acquired, from tiltbeams* monitoring ver.ical movements since 1971 on the Long Point and Eureka Heights faults, shows no evidence of correspondence between variations in fault displacement with water-level fluctuations in shallow wells for the first 2 years of record (Reid, 1973; Kreitler, 1977). This was considered by Kreitler (1977) as proof of non-correspondence and as an implied demonstration of the absence of any significant cause-effect link. The following 5 years of record, however, showed no such correspondence, casting doubt on proposals that fluid withdrawal is the dominant control of vertical movement, at least by the mechanism proposed by Kreitler (Gabrysch and Holzer, 1978). One alternative, that greatly increased rates of natural fault movement are at least partly responsible for the current high level of faulting in the Houston area, may at first seem an untenable suggestion. However, some faults show clear evidence (from well-log data) of episodic movement in the geologic past, and it is conceivable that the normally slow pace of natural fault displacement was punctuated by brief periods of greatly accelerated movements, at rates comparable to those observed today. We cannot discount the possibility that the Houston area is experiencing the effects of another such period.

To summarize, the cumulative weight of evidence would favor fluid withdrawal as the dominant factor in contemporary fault movements, but nearly all of the supporting evidence is based on a cause-and-coincidence between accelerated fault movements and large-scale production of subsurface fluids. No cause-and-effect relationship has yet been demonstrated.

Knowledge of the effects of fluid withdrawal is pertinent both to plans for future development and utilization of water supplies for the Houston area, and to the oil industry for recovery of petroleum. However, the mechanism(s) whereby fluid withdrawal may affect faulting in the Houston area is not understood, and, if fluid withdrawal does affect fault movements, the relative importance of ground water versus petroleum production remains unassessed. Moreover, knowledge that some fault movements are taking place along ancient and naturally occurring planes of weakness is insufficient assurance that new faults are not being created by stresses associated with fluid withdrawal. Until details of cause-and-effect relationships are understood, prediction of fault movements in the Houston metropolitan area must remain speculative.

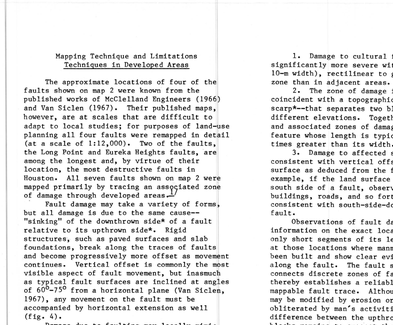


Figure 3.--Map of Pecore East and eastern portion of Pecore West faults. Map symbols and scale are same as for maps 1 and 2; see fig. 2 for location. Base from U.S. Geological Survey, Settegast 7 1/2-minute quadrangle, 1967.

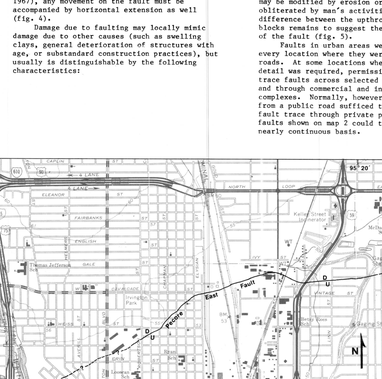


Figure 4.--Effect of fault movement on a rigid structure built on an active fault. A, original construction; B, structure damaged by fault movement. Both vertical offset and horizontal separation are necessary consequences of displacement. Rigid structures may literally be pulled apart as faulting proceeds.

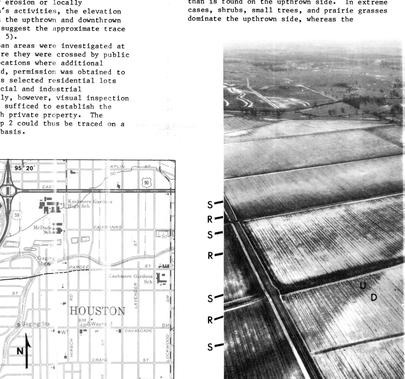


Figure 5.--Topographic profiles across a hypothetical fault in the Houston area. A, shortly after displacement of the land surface. Scarp is sharp and has a steep slope. B, the same fault scarp modified by erosion. Material eroded from the upthrown side is deposited near the base of the scarp. The scarp now has a rounded form and a relatively gentle slope. Location of the fault trace in the absence of structural damage can only be approximated. C, fault scarp after grading for construction or after preparation of a field for rice cultivation. The scarp is all but destroyed; only a gentle slope remains in its place. The elevation difference between the upthrown and downthrown fault blocks remains, but the location of the underlying fault can only be estimated within broad limits because of extensive modification of the original topography.

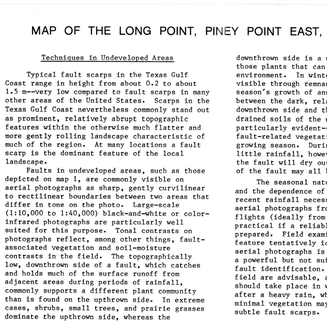


Figure 6.--Oblique aerial photograph (NASA photo S-78-26931) of western part of Clodine fault, looking southwest toward Figure Four Lake (map 1). R and S identify cliff-and-swale topographic features typical of point-bar deposits. A similar but younger point bar is visible on the inside bend of Figure Four Lake (arrow), a remnant of an old and now-abandoned stream channel.

Topographic details of the fault scarp visible on aerial photographs after a heavy rain, when water (light tones) occupies the swales of the point bar and the downthrown side of the fault is flooded. The slope that marks the fault may be followed readily through the fields, but the scarp has been all but destroyed by repeated plowing.

Similar relationships have been photographed at other locations along the 12-km length of this fault.

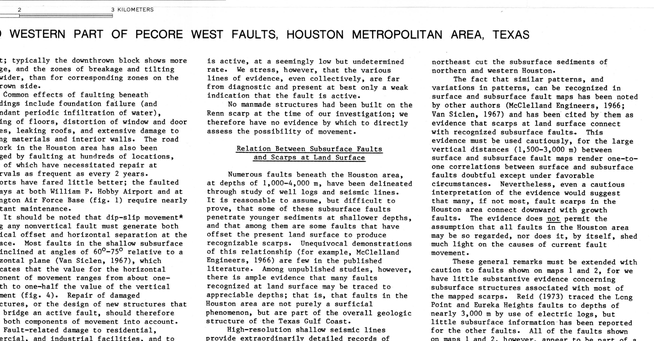


Figure 7.--Faults in northern and western Houston metropolitan area. Approximate traces of Addicks North and Addicks South faults are modified from St. Clair and others (1975) and Van Siclen (1978). An origin by faulting for the Renn scarp is suspected but has not been firmly established. Faults are labeled on topographically higher, upthrown side. IH = interstate highway.

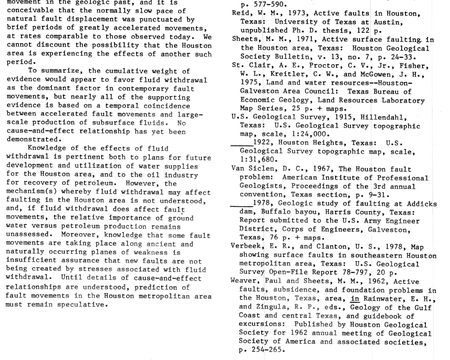


Figure 8.--Vertical section through a hypothetical fault in the Houston area. Land surface was originally level, but has since been displaced by movement along the fault. Note thickening of sedimentary layers on the downthrown side. This indicates that faulting occurred repeatedly over a long period of time, while the sediments were being deposited. Such faults are common in the Texas Gulf Coast.

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Glossary of Terms [3/]

Active fault--(1) A fault that has caused damage to manmade structures, or (2) a fault whose current rate of movement is sufficient to cause such damage, but where no manmade structures exist to document effects of movement.

Existing definitions of this term are both numerous and partly contradictory. By almost any of them, however, all faults that have been recognized at land surface in the Houston area are active, regardless of whether they have moved in historic times or not. We employ a more restricted definition in our discussion of the Houston area, and use active fault only as a term of convenience to signify those faults that are, in effect, an immediate hazard to property.

Dip-slip movement--Slip of one fault block, relative to the other block, by movement parallel to the dip of the fault. In any inclined surface, such as a fault in the Houston area, it is possible to draw an imaginary horizontal line, termed the strike of the fault, and to draw a second line perpendicular to the strike, termed the dip line. The angle by which the dip line deviates from horizontal is the dip of the fault; it corresponds to the inclination of the fault in nonscientific terms. If movement of one fault block relative to the other block occurs parallel to the dip line, it is termed dip-slip movement.

Downthrown side--The side of a fault that appears to have moved downward relative to the other side (fig. 8). Also called downthrown fault block.

Fault--A surface along which the nearly horizontal sedimentary layers beneath the Houston area are broken and offset (fig. 8).

Fault trace--The line defined by the intersection of a fault surface with the land surface.

Growth fault--A fault along which movement occurs as sediments are deposited on and above the fault scarp. Continued movement and sedimentation over an extended period of time causes the oldest and lowermost sediments to be offset the most and causes the amount of offset to decrease upward within younger deposits (fig. 8). Such faults are common in the Gulf Coast.

Point bar--A low, arcuate ridge of sand deposited by a stream on the inside of a bend, or meander, in its course. A series of such ridges, separated by intervening troughs, may be deposited along some meanders.

Scarp--A relatively steep face or slope of considerable linear extent, irrespective of origin. Some scarps are formed directly by movement along a fault surface; the scarp separates two blocks of land that were originally at the same or nearly the same elevation but which now are at different levels due to faulting. Note that in discussing the exposed surface of a fault, usually modified to some extent by erosion on the upthrown side and deposition on the downthrown side (figs. 5 and 8).

Tiltbeam--A device for measuring the vertical component of motion along an active fault. One end of the tiltbeam rests on a section of the upthrown side, the other on the downthrown side, and the beam is leveled. The vertical component of movement since the last releveling can be calculated from the length of the beam and the amount by which it deviates from a horizontal (level) line.

Upthrown side--The side of a fault that appears to have moved upward relative to the other side (fig. 8). Also called upthrown fault block.

1/ Not until after the base map had been printed was it apparent that the Pecore fault extended westward into the area of map 2. A map of the eastern part of this fault is included here as figure 3.

2/ The October 1978 pipeline explosion near Pearland, which claimed seven lives, was unrelated to movement on any known fault. The nearest fault mapped by Verbeek and Clanton (1978) is about 0.4 km from, and parallel to, the pipeline.

3/ Parts of the Long Point and Eureka Heights faults appear to be particularly active; some sections of the Long Point fault have averaged more than 2 cm/yr of vertical offset over the last 20 years.

4/ The same is true of other salt domes (Hastings, Manvel, Blue Ridge, Clinton) in the Houston area (Verbeek and Clanton, unpub. data, 1975-1979).

5/ Some definitions presented here have been extracted and modified from the American Geological Institute "Glossary of Geology" (Gary and others, 1974).

FAULTS IN PARTS OF NORTH-CENTRAL AND WESTERN HOUSTON METROPOLITAN AREA, TEXAS

By
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1979