Land Subsidence Near Oil and Gas Fields, Houston, Texas[a]

by Thomas L. Holzer[b] and Robert L. Bluntzer[c]

ABSTRACT

Subsidence profiles across 29 oil and gas fields in the 12,200-km^2 Houston, Texas, regional subsidence area, which is caused by decline of ground-water level, suggest that the contribution of petroleum withdrawal to local land subsidence is small. Despite large volumes of petroleum production, subsidence at most fields was not increased by oil and gas withdrawal. Local increases of subsidence were detected at only six fields—Alco-Mag, Chocolate Bayou, Goose Creek, Hastings, Mykawa, and South Houston. With the exception of the 1-m subsidence from 1917 to 1925 at Goose Creek, differential subsidence across oil and gas fields was smaller by a factor of two or more than subsidence caused by aquifer compaction. At four fields—Barbers Hill, Cedar Bayou, Humble, and Pierce Junction—subsidence was substantially less than in the surrounding area. Except for Cedar Bayou, these fields are associated with shallow salt domes that partly occupy the aquifer system; for the three fields, subsidence during the periods of record came to less than half the subsidence in the surrounding area.

In addition to land subsidence, faults with an aggregate length of more than 240 km (150 mi) have offset the land surface in historical time. Natural geologic deformation, ground-water pumping, and petroleum withdrawal have all been considered as potential causes of the historical offset across these faults. The minor amount of localized land subsidence associated with oil and gas fields, however, suggests that petroleum withdrawal is not a major cause of the historical faulting, at least by a differential compaction mechanism.

INTRODUCTION

From 1943 to 1973, approximately 12,200 km^2 (4,700 mi^2) of land within the greater Houston, Texas, area subsided more than 0.15 m (0.5 ft) (Gabrysch and Bonnet, 1975). The area of subsidence (Figure 1) is one of the two largest subsidence areas in the United States, the other area being in the San Joaquin Valley, California (Poland *et al.*, 1975). Although the subsidence in Houston unquestionably is caused principally by man-induced water-level declines, a contribution from oil and gas withdrawal has been suggested by many investigators (*e.g.*, Van Siclen, 1966; Gabrysch, 1969; Kreitler, 1977); the relative contribution, however, is uncertain. The principal evidence for a contribution from oil and gas withdrawal is the subsidence of approximately 1 m (3.3 ft) that took place from 1917 to 1925 at the Goose Creek oil field (Figure 1) and specific examples of differential subsidence centered at oil and gas fields in the Houston area. The temporal and areal association of the subsidence at Goose Creek with the development of the oil field (Pratt and Johnson, 1926) and the fact that the subsidence there occurred before major water-level declines began confirm that the subsidence there was related to petroleum exploitation. The three other fields in the Houston area where differential subsidence has been reported also have simultaneously experienced subsidence caused by water-level declines: Chocolate Bayou, Mykawa, and South Houston (Figure 1) (*e.g.*, Winslow and Doyel, 1954; Yerkes and Castle, 1969; Gustavson and Kreitler, 1976; Kreitler, 1977). With the possible exception of the Chocolate Bayou field, differential subsidence at these three fields is significantly less than the amount of subsidence that can be reasonably attributed to aquifer compaction.

Petroleum withdrawal has caused subsidence at more than 28 fields worldwide. They include the Saxet field in the southwest Texas Gulf Coast (Yerkes and Castle, 1969; Gustavson and Kreitler, 1976); more than 21 fields in California (Yerkes and Castle, 1969); four fields at Lake Maracaibo, Venezuela (Nunez and Escojido, 1977); the Groningen gas field, the Netherlands (Schoonbeek,

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[b]U.S. Geological Survey, 104 National Center, Reston, Virginia 22092.

[c]Texas Department of Water Resources, P.O. Box 13087, Austin, Texas 78711.

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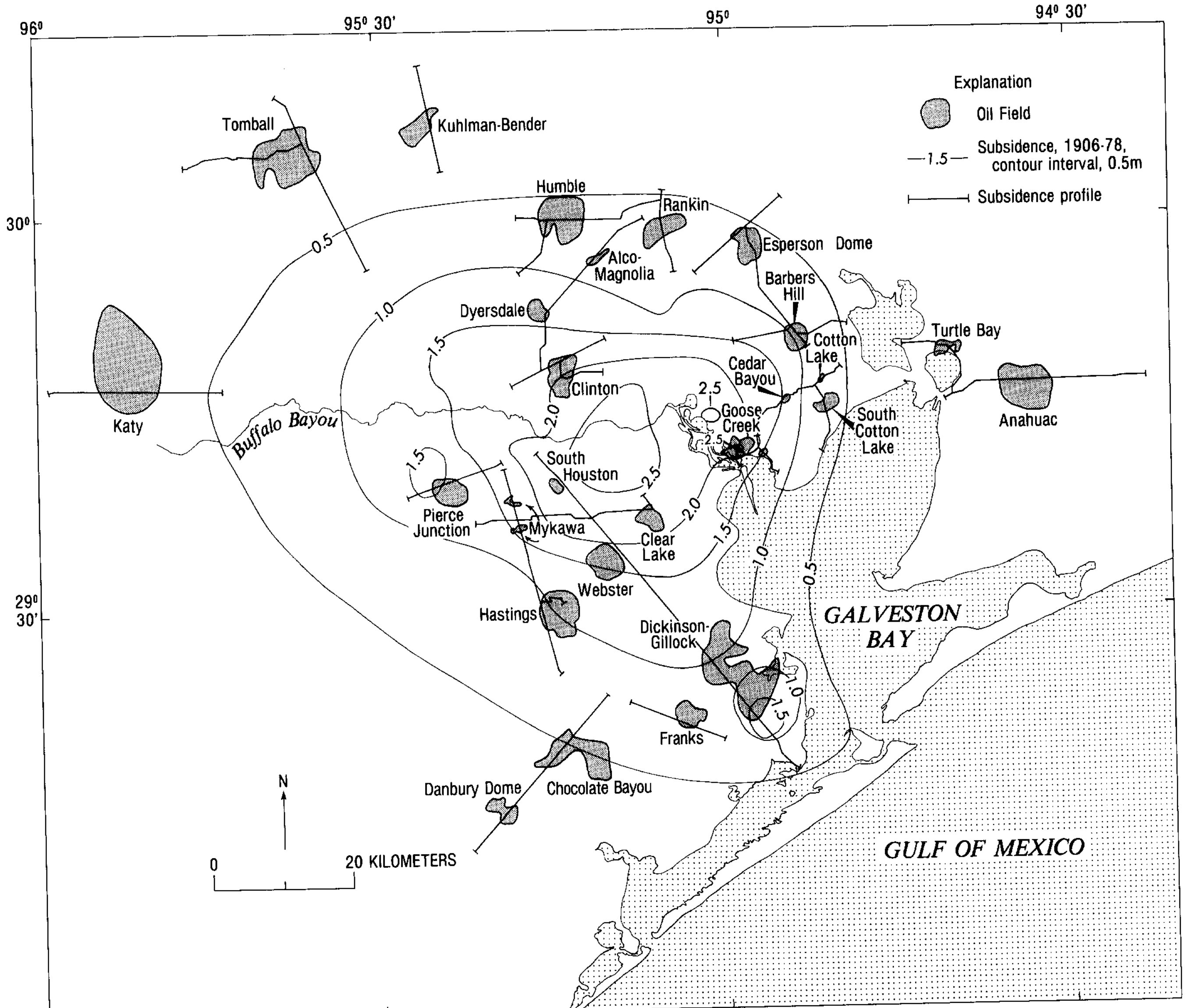

Fig. 1. Map of approximate regional subsidence, 1906-1978 (adapted from Gabrysch, 1980), showing oil fields investigated and subsidence-profile locations in the Houston, Texas area.

1977); and the Po Delta gas field, Italy (Poland and Davis, 1969). The maximum subsidence reported is 8.8 m (29 ft) at the Wilmington field in Long Beach, California.

Previous evaluations of the contribution of petroleum withdrawal to land subsidence in the Houston area have focused on the four fields mentioned above. Subsidence can be evaluated, however, for at least an additional 25 of the more than 110 fields in the Houston area. The basis for these additional evaluations are leveling surveys which began in 1906 and which were performed intermittently by the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey) in order to establish and maintain the Houston part of the National Geodetic Control Network. The present investigation evaluates these additional leveling data for the relative contribution from oil and gas withdrawal to land subsidence. Evaluations are based on leveling lines that either cross through or pass near the oil fields.

The relative contribution from oil and gas withdrawal to land subsidence may also be relevant to historical surface faulting in the Houston area. More than 86 faults, with an aggregate length of 240 km (150 mi), have historical offset (E. R. Verbeek, written commun., 1982). Because these surface faults are temporally and areally associated with the land subsidence, a man-induced contribution to historical fault offset is likely (*e.g.*, Van Siclen, 1967; Kreitler, 1977; Verbeek and Clanton, 1981); the relative contributions from ground-water withdrawal, oil and gas withdrawal, and natural geologic deformation, however, are uncertain. That there is some contribution from oil and gas withdrawal is suggested principally by faulting that was associated with the 1917-25 subsidence at Goose Creek. In addition, many of the historically active surface faults in the Houston area are located either within or near the boundaries of oil fields. Presumably, the relative contribution from oil and gas withdrawal to historical faulting may be inferred from the extent to which oil and gas withdrawal has contributed to land subsidence. A mechanism for that connection was proposed by Yerkes and Castle (1969), who suggested that faulting is caused by changes in horizontal stress that are induced by differential compaction.

METHODOLOGY

Oil and gas fields in the Houston area that could provide potentially useful leveling data were identified by comparison of maps of oil and gas fields (Whico Oil/Gas and Marine Gulf Coast Atlas, 1981) with leveling lines depicted on Geodetic Control Diagrams (National Geodetic Survey, 1969, 1970). Both sets of maps are published at approximately the same scale, 1:250,000. After identification of fields with potentially useful leveling data, each field was examined at a scale of 1:24,000 in order to ascertain the locations of bench marks relative to the field boundaries. Then fields were selected which had bench marks located within at least 1 km (0.6 mi) of the field boundary. The decision to include fields for which geodetic control lies outside but near the field boundary was based on the theoretical consideration that compaction at depth causes subsidence of the land surface that extends beyond the surface projection of the compacting zone (Geertsma, 1973). Because the average depth of production in the Houston area is approximately 2 km (1.2 mi), differential subsidence should be detectable in data from leveling lines that pass within 1 km (0.6 mi) of a field's boundary. Such an assumption was made tacitly by previous investigators who attributed differential subsidence near the Mykawa (Kreitler, 1977) and South Houston (Winslow and Doyel, 1954) fields to oil and gas withdrawal; at both fields, differential subsidence cited by these investigators was calculated on the basis of leveling lines that lay outside the boundaries of the fields. Once fields with adequate bench mark coverage had been identified, the record of relevelings was examined to determine whether meaningfully detailed subsidence profiles could be computed. Serendipity was required because of the wide spacing of bench marks relative to field dimensions and the destruction of bench marks.

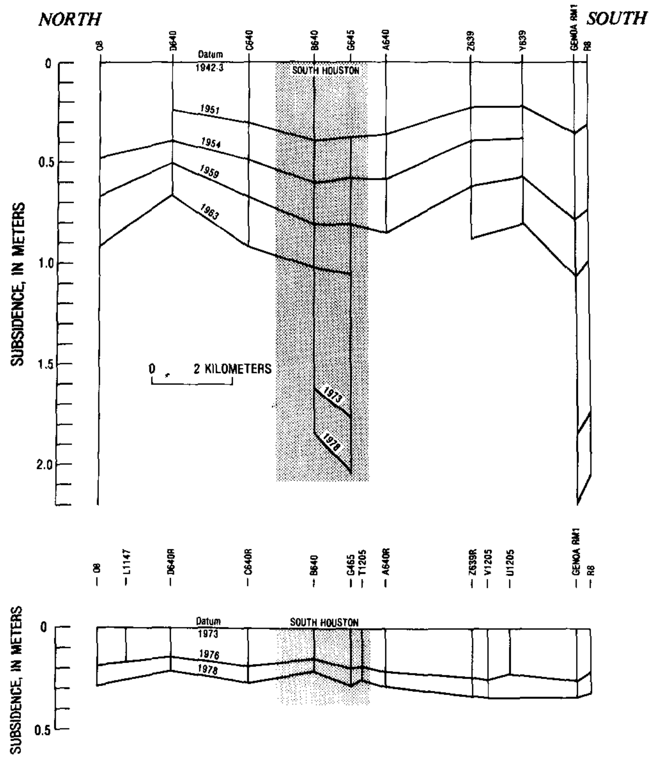

Fig. 2. Subsidence profiles near the South Houston field (see Figure 1 for profile location). Boundaries of field are projected.

Subsidence profiles were based on adjusted elevation data provided by the National Geodetic Survey. Most of the elevation data utilized in the present investigation are based on leveling to First-Order standards. For these surveys, the estimated standard deviation in the measured elevation difference between any two bench marks K kilometers apart has decreased from 2 mm $(K)^{1/2}$ in 1906 to 0.5 mm $(K)^{1/2}$ in 1978 (Vanicek *et al.*, 1980).

The method for constructing profiles is illustrated in Figure 2 with the South Houston field. The leveling line is tangential to the northeast boundary of the field (Figure 1). This line was established in 1906, 29 years before the field was discovered. The wide spacing and destruction of some of the original bench marks, however, precluded the use of the 1906 leveling as a datum. The earliest datum with resolution near the field is from the leveling of 1942-43, when new and more closely spaced bench marks were established. Although the line was either partly or completely releveled six times between 1942-43 and 1978, bench mark destruction frustrates the use of a 1942-43 datum after 1963. However, reset and new bench marks make it possible to use a new datum based on the 1973 releveling. Thus, differential subsidence across the South Houston field can be evaluated only for the two periods 1942-43 to 1963 and 1973 to 1978. Another aspect of the construction of profiles, which also is illustrated in the South Houston example (Figure 2), is the use of releveling data involving bench marks set after the date of the datum. Note in the profile with the 1942-43 datum (Figure 2) that bench mark G645 was set in 1951. By adding the subsidence of G645 to the 1951 profile, improved resolution of subsidence near the field can be obtained.

Profiles for most fields extend at least 6 km (3.7 mi) in both directions from the boundary of the field. For a few fields, however, profiles extend outwards from the field in only one direction. Regional and differential subsidence were determined after visual inspection (Figure 3). If differential subsidence was associated with the field, then its magnitude was estimated by first interpolating the regional subsidence near or at the field from the subsidence at the ends of the profile, and then subtracting the interpolated regional subsidence from the observed subsidence. By this convention, differential subsidence is positive wherever observed subsidence exceeds the regional subsidence.

Production, production depth and area, geologic structure and nearby historical surface faulting were also compiled for each field (Table 1). Hydrocarbon-production data were obtained from annual reports of the Texas Railroad Commission; salt-water production data are not collected by the Commission and thus are unavailable. Oil-production data are given in Table 1 for only crude oil; condensate from gas wells is not included. Usually, the volume of the latter has been insignificant relative to the former. Gas-production data are given only for dry gas; casing-head gas from oil wells is not included. Gas-production data were not reported to the Texas Railroad Commission before 1939. For many of the fields listed in Table 1, both oil- and gas-production data include production from additions to the fields. For example, production from Alco-Mag West is included in the production data for Alco-Mag. The only additions excluded were those that were substantially removed from both the main field and the leveling line. The "average production depth" given for each field is an average weighted by oil production by depth.

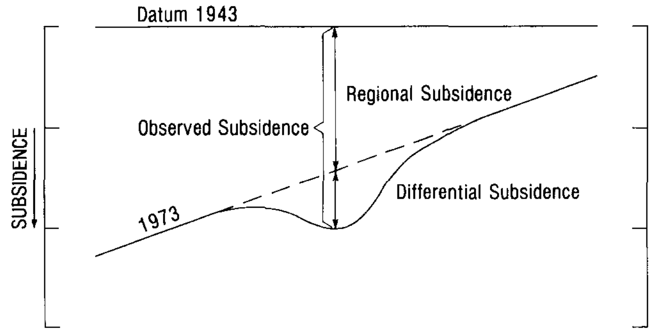

Fig. 3. Definitions of differential, regional, and observed subsidence.

Determination of the size and the precise location of each field was particularly troublesome because published maps of field boundaries at scales of 1:250,000 and smaller commonly were not consistent and did not agree with maps at

Table 1. Oil Field Statistics and Differential Subsidence

Oil field name	County	Date of discovery	Leveling epoch	Differential subsidence (m)	Regional subsidence (m)	Historical faulting	Average production depth (m)	Range of production depths (m)	Oil production: Total (to 1/1/79) (m^3)	Oil production: During leveling epoch (m^3)	Gas production: Total (to 1/1/79) (10^3 m^3)	Gas production: During leveling epoch (10^3 m^3)	Area (hectares)	Potential subsidence: Total (m)	Potential subsidence: During leveling epoch (m)	Structure	Depth to salt or caprock (m)	Oil field name
Alco-Mag	Harris	1954	1954-1978	0.10	0.34	No	2426	2405-2455	516,433	516,433	1,530,546	1,528,706	291	0.18	0.18	–		Alco-Mag
Anahuac	Chambers	1935	1953-1959	0	0.08	–	2181	2149-2674	42,078,511	5,595,356	6,719,964	940,484	3,189	1.32	0.18	Domal anticline		Anahuac
Barbers Hill	*Chambers*	*1916*	*1943-1964*	*−0.26*	*0.32*	–	*2195*	*1923-2477*	*20,107,509*	*6,162,814*	*221,367*	*46,155*	874	2.30	0.71	Shallow salt dome	107	Barbers Hill
Cedar Bayou	Chambers	1939	1954-1978	−0.35	0.94	Yes	2189	2189	9,873	0			106	0.01	0	–		Cedar Bayou
Chocolate Bayou	Brazoria	1940	1943-1978	0.12	0.50	–	2926	2666-4097	6,351,833	5,997,057	47,761,097	46,794,860	7,392	0.09	0.08	Faulted anticline		Chocolate Bayou
Clear Lake	Harris	1938	1942-1954	0	0.38	Yes	1879	1815-1879	3,652,944	2,054,187	7,565,407	5,622,967	360	1.01	0.57	–		Clear Lake
Clear Lake			1959-1964	0	0.21	Yes				299,347		292,517			0.08			Clear Lake
Clinton	Harris	1937	1943-1978	0	1.62	Yes	1739	1125-2048	719,038	669,825	2,371,693	2,100,568	809	0.09	0.08	Faulted domal anticl.		Clinton
Cotton Lake	Chambers	1936	1954-1978	0.03	0.49	Yes	1929	1922-1941	397,739	296,007	0	0	61	1.14	0.49	–		Cotton Lake
Danbury Dome	Brazoria	1930	1943-1959	0	0.05		1455	605-2955	3,276,443	1,678,891	1,381,044	1,074,008	2,566	0.13	0.07	Intermed. salt dome	1508	Danbury Dome
Dickinson-Gillock	Galveston	1934	1943-1978	0	0.80	Yes	2755	2407-2998	19,990,184	15,148,997	9,227,708	8,052,410	6,377	0.31	0.24	Faulted domal anticl.		Dickinson-Gillock
Dyersdale	Harris	1940	1943-1978	0	1.17	No	1567	1498-2831	3,167,551	3,041,694	550,723	550,723	554	0.57	0.55	–		Dyersdale
Esperson Dome	Liberty	1929	1943-1964	0	0.22	Yes	2639	1859-2903	7,796,049	3,699,740	736,236	241,575	368	2.12	1.01	Deep salt dome	1881	Esperson Dome
Franks	Galveston	1955	1951-1978	0	0.42	No	2925	2745-3502	1,820,529	1,820,529	2,202,814	2,202,814	1,093	0.17	0.17	–		Franks
Goose Creek	Harris	1916	1917-1925	1.0	0	Yes	1404	1402-1497	21,203,491	7,675,112	3,530		1,404	1.51	0.55	Faulted domal anticl.		Goose Creek
Goose Creek			1936-1959	0	0.65	Yes				5,686,773					0.41			Goose Creek
Hastings	Braz.-Galv.	1934	1918-1978	0.23	0.82	Yes	1892	1890-3041	97,114,971	97,114,971	1,325,777	1,325,777	2,602	3.73	3.73	Faulted domal anticl.		Hastings
Humble	Harris	1905	1942-1978	−0.29	0.44	Yes	1096	831-1659	26,420,618	6,541,562			1,619	1.63	0.40	Shallow salt dome	213	Humble
Katy	Har-Wal-Ft.B.	1935	1906-1978	0	0.40	No	2025	2010-2094	3,156,085	3,156,085	229,569,072	229,569,072	14,165	0.02	0.02	Broad anticline		Katy
Kuhlman-Bender	Harris-Mont.	1948	1932-1978	0	0.19	No	1777	1771-1817	776,425	776,425	284,011	284,011	1,036	0.07	0.07	Stratigraphic trap		Kuhlman-Bender
Mykawa	Harris	1929	1943-1978	0.30?	1.33	Yes	2017	1483-2644	1,220,652	488,096	277,580	262,647	372	0.33	0.13	Deep salt dome	2164	Mykawa
Pierce Junction	Harris	1921	1959-1978	−0.60	1.05	Yes	1524	579-2199	13,959,371	1,801,237	453,577	266,807	1,813	0.77	0.10	Shallow salt dome	192	Pierce Junction
Rankin	Harris	1946	1943-1978	0.04	0.42	No	2515	2399-2530	1,154,116	1,154,116	215,323	215,323	324	0.36	0.36	–		Rankin
S. Cotton Lake	Chambers	1937	1959-1973	0	0.22	Yes	1989	1989	1,017,342	149,812	134,480	39,491	992	0.10	0.02	Fault		S. Cotton Lake
South Houston	Harris	1935	1943-1963	0.31	0.74	Yes	1459	1407-1463	6,444,353	4,192,212	258,997	88,742	615	1.05	0.68	Intermed. salt dome	1337	South Houston
South Houston			1973-1978	0	0.28	Yes				295,344		21,715			0.05			South Houston
Tomball	Harris	1933	1935-1978	0	0.26	Yes	1683	1676-1930	17,844,455	17,542,340	9,292,316	9,292,316	3,290	0.54	0.53	Broad anticline		Tomball
Turtle Bay	Chambers	*1935*	*1936-1978*	0	0.25	–	*2021*	*1986-2179*	*2,070,122*	*2,069,668*	*558,359*	*558,359*	*441*	*0.47*	*0.47*	*Domal anticline*		*Turtle Bay*
Webster	Harris	1936	1943-1964	0	0.63	Yes	1859	1859-2877	80,691,212	41,560,761	23,203	21,452	1,105	7.30	3.76	Deep salt dome	3179	Webster

larger scales. The most reliable maps are the plats in the files of the Texas Railroad Commission; these show well locations at scales that range from 1:3,600 to 1:24,000. For most fields, boundaries defined by circumscribing wells shown on 1:24,000-scale U.S. Geological Survey topographic quadrangle maps agree with boundaries inferable from plats. Even with these maps, however, precise delineation of field boundaries remains subjective because many of the fields are ringed by abandoned wells from which total production was small. The field boundaries shown in Figure 1 are based principally on plats; they include all wells that have produced in the given field.

At two locations, fields recognized as separate by the Texas Railroad Commission are grouped together because they shared common boundaries where traversed by the leveling lines. These fields are the Dickinson, Gillock, and South Gillock fields listed together as the Dickinson-Gillock field, and the Kuhlman and Bender fields listed together as the Kuhlman-Bender field.

RESULTS

In Table 1, analyses of the subsidence profiles are summarized alphabetically by oil field. Examples were observed of both positive and negative differential subsidence, but typically observed subsidence was dominated by the regional-subsidence component.

Positive differential subsidence was associated with six fields: Alco-Mag (1954-1978), Chocolate Bayou (1943-1978), Goose Creek (1917-1925), Hastings (1943-1978), Mykawa (1943-1978), and South Houston (1943-1963). Profiles across five of these fields are shown in Figures 2, 5, and 6. For the sixth field, Goose Creek (1917-1925), the

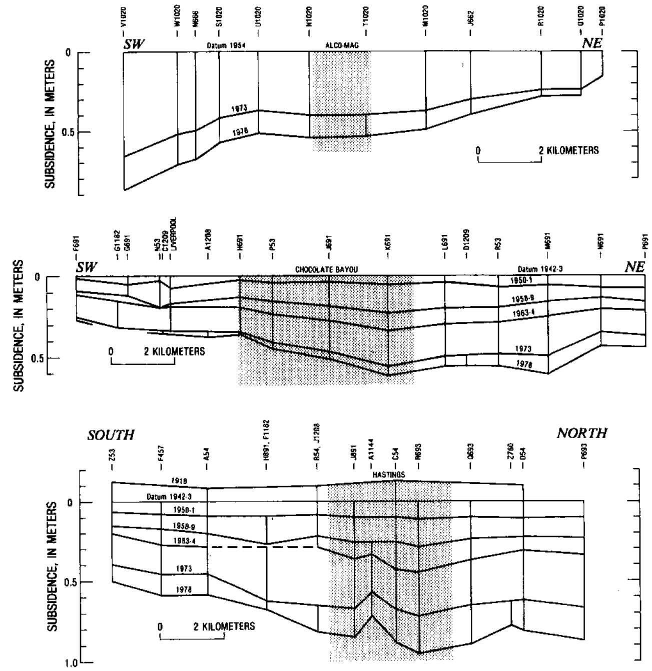

Fig. 5. Subsidence profiles across Alco-Mag, Chocolate Bayou, and Hastings fields (see Figure 1 for profile locations).

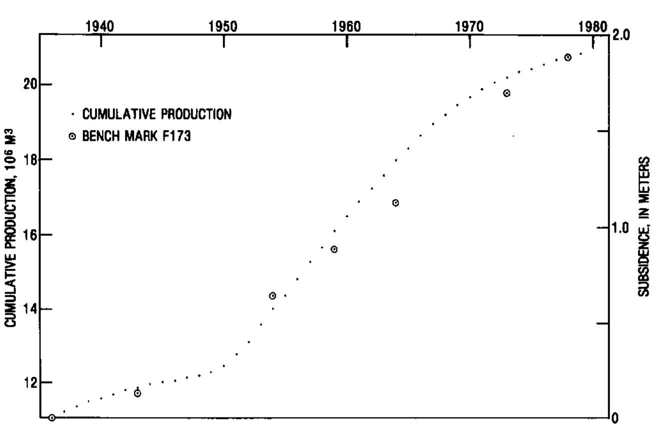

Fig. 4. Cumulative production from Goose Creek field, 1936-78, and subsidence of bench mark F173, 1.4 km north of field.

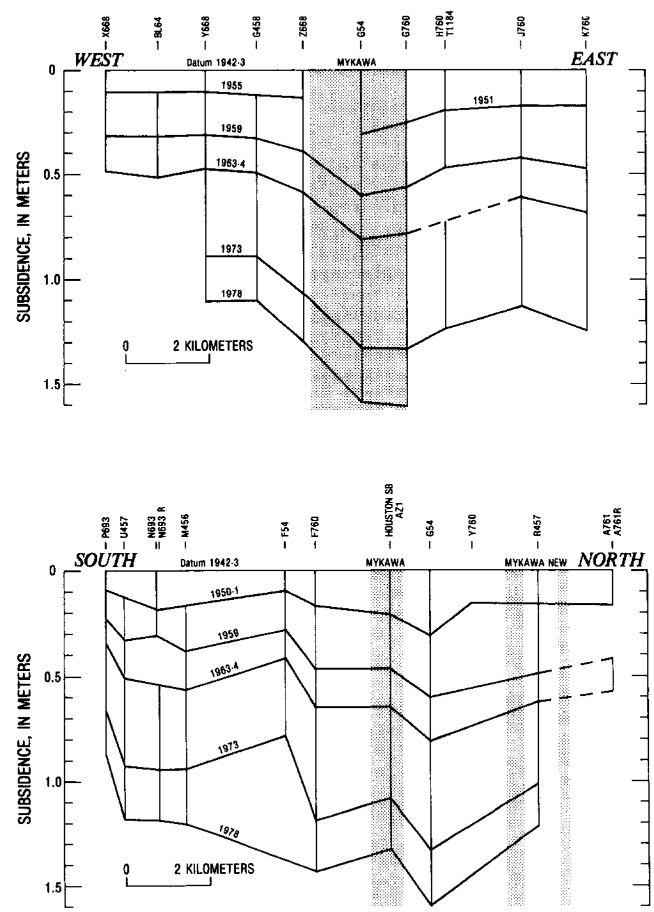

Fig. 6. East-west and north-south subsidence profiles near Mykawa field (see Figure 1 for profile locations). Boundaries of field in east-west profile are projected.

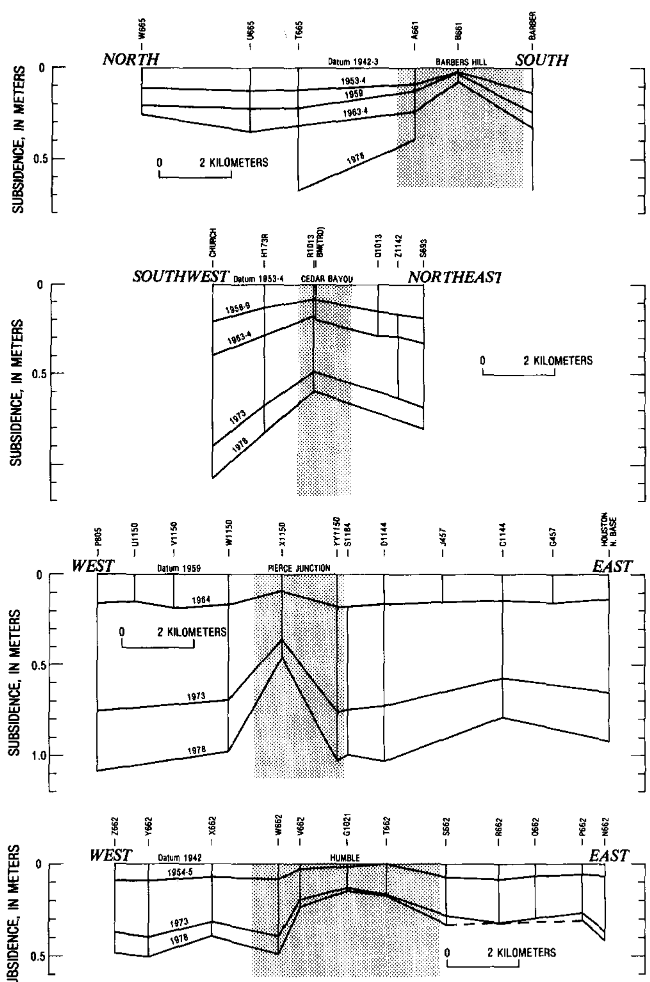

Fig. 7. Subsidence profiles across Barbers Hill, Cedar Bayou, Pierce Junction, and Humble fields (see Figure 1 for profile locations).

differential subsidence cited is based on the map published by Pratt and Johnson (1926, Figure 7). For one of the fields, Mykawa, two profiles (Figure 6) cross at a right angle. Differential subsidence of 0.30 m (1 ft) from 1943 to 1978 is well defined in the east-west profile, which comes no closer than 0.7 km (0.4 mi) of the northern boundary of the field. The differential subsidence, however, is not well defined in the north-south profile, which passes directly through the field. In fact, relevelings of the bench mark Houston South Base Azimuth (Houston SB AZI), which is within the boundary of the oil field, suggest that differential subsidence is either small or negligible. The actual magnitude of the differential subsidence in the profile through the Chocolate Bayou field also is uncertain because the differential subsidence is eccentric with respect to the field (Figure 5). The differential subsidence directly over the field (from bench mark H691 to L691) is approximately 0.12 m (0.39 ft); differential subsidence of the whole depression (from bench mark H691 to N691) is approximately 0.22 m (0.72 ft).

Negative differential subsidence, i.e., subsidence that was less than in the surrounding area, was associated with four fields: Barbers Hill, Cedar Bayou, Pierce Junction, and Humble (Figure 7). With the exception of Cedar Bayou, the subsidence at each of these fields was less than half of the subsidence in the surrounding area. The smallest subsidence was at Barbers Hill, where the subsidence at bench mark B661 was equal to only 19% of the regional subsidence.

Although the recognition of the presence or absence of differential subsidence in most profiles was a straightforward matter, the interpretations of the profiles at Dyersdale and Goose Creek (1936-1959) were uncertain because differential subsidence did not coincide with the area of the oil field, but was laterally offset from it. At these two fields, the centers of the localized subsidence depressions in the profiles, 0.23 and 0.55 m (0.75 and 1.80 ft), respectively, were outside but near (less than 1 km) the boundaries of the fields. The flanks of these depressions extended into the fields. Because the center of the depressions in the profiles were outside the field boundaries, the differential subsidence near each field is not included in Table 1. At Goose Creek, comparison of cumulative production with the subsidence history of the oldest surviving bench mark near the field appears to indicate a relation between the depression and petroleum withdrawal (Figure 4). The bench mark, F173, which was set in 1936, is 1.4 km (0.9 mi) north of the field's northern margin. However, ground-water pumping is also concentrated near Goose Creek field. A localized 1.6-m subsidence depression at the south end of the Dickinson-Gillock field (Figure 1) is clearly related to a localized cone of depression in the aquifer at Texas City (Petitt and Winslow, 1957; Gabrysch and Bonnet, 1975).

DISCUSSION

Subsidence caused by aquifer compaction is the most conspicuous aspect of the subsidence profiles across oil and gas fields in the Houston area. At all 29 fields, except Goose Creek (1917-25) and the four fields where differential subsidence was negative, the regional subsidence was the dominant component. Even at the six fields—Alco-Mag, Chocolate Bayou, Goose Creek (1917-25), Hastings, Mykawa, and South Houston (1943-63)—where local increases of subsidence were observed, the differential subsidence was equal to less than one-third of the observed subsidence. Thus, the present results support the conclusion of previous investigators that water-level declines are the predominant cause of land subsidence in the Houston area.

The most pronounced differential subsidence was observed across the four fields where observed subsidence was significantly less than the regional subsidence—Barbers Hill, Cedar Bayou, Humble, and Pierce Junction. The ratio of observed subsidence to regional subsidence at these fields ranged from 0.19 at Barbers Hill to 0.63 at Cedar Bayou. The differential subsidence across at least three of these fields probably is caused by local decreases in the thickness of aquifer system and resulting decreases in the aggregate thickness of compressible clay beds. Barbers Hill, Humble, and Pierce Junction fields are associated with shallow salt domes that lie partly within the aquifer system. Depths to the caprock on the tops of these domes are 107, 213, and 192 m (350, 700, and 360 ft), respectively. Each of these depths is much less than the depth to the base of the aquifer system near the dome—840, 460, and 750 m (1,750, 1,500, and 2,450 ft), respectively. The decreased thickness of the aquifer system above the Pierce Junction salt dome is illustrated by the cross section shown in Figure 8. On the basis of electric logs published by Glass (1953), the lower part of the aquifer system, defined by the base of the Evangeline aquifer, appears to be deformed near the Pierce Junction salt dome. This young deformation suggests that upward movement of salt may have continued into historical times and counteracted subsidence above

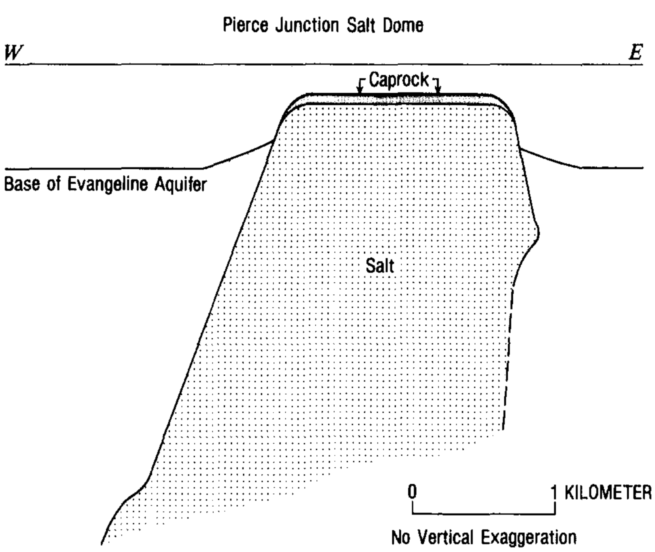

Fig. 8. Cross section of Pierce Junction salt dome (modified from Glass, 1953). Base of Evangeline aquifer is base of aquifer system.

the dome. The historical rate of uplift of 30 mm/yr, inferred from the differential subsidence data, however, is much greater than the average Pleistocene rate, which was less than 0.1 mm/yr. The possibility of episodic movement, of course, cannot be excluded. In contrast with the other fields, the Cedar Bayou field is not known to be underlain by a shallow salt dome, and so the decrease in subsidence there cannot be attributed to a local decrease in the thickness of the aquifer system caused by uplift of salt.

A causal relation between petroleum withdrawal and differential subsidence in specific areas in and around Houston is difficult to demonstrate except at Goose Creek (1917-25). Nevertheless, the leveling results are compatible with such a relation at five fields in addition to Goose Creek—Alco-Mag, Chocolate Bayou, Hastings, Mykawa, and South Houston.

The most direct approach for evaluating a potential relation between differential subsidence and petroleum withdrawal is to compare histories and magnitudes of differential subsidence with recorded measurements of reservoir pressure. Unfortunately, bottom-hole pressures are not regularly reported for most fields in the Texas Gulf Coast. We do know, however, that large pressure declines have been induced in at least two of the fields which have undergone differential subsidence. Winslow and Doyel (1954) reported a pressure decline of 2.45 MPa (356 psi) from 1943 to 1951 in the South Houston field, and Pratt and Johnson (1926) reported declines of 6.9 to 8.3 MPa (1,000 to 1,200 psi) in the Goose Creek field. The latter decline probably is atypical, because the pressure was dropped precipitously during initial exploitation.

It may also be relevant to the general absence of differential subsidence in the Houston area that effective water drives are prevalent in fields over salt domes where the top of the caprock is deeper than 1,830 m (6,000 ft) (Olcott, 1953). Such a condition would help maintain reservoir pressure and thereby minimize subsidence.

Because reservoir pressure data are inadequate to enable direct evaluation of the contribution of petroleum withdrawal to differential subsidence, volumes of both oil and gas production and production areas were compiled for each field (Table 1). The potential for subsidence is related in part to the ratio of the volume of produced fluid under reservoir conditions to production area. In actuality, water drives, gas or gas-solution drives, or secondary recovery counteract the tendency to

Table 2. Potential Subsidence

Ratio of oil production during leveling epoch to production area			
Greater than 0.5 m	*0.5 to 0.2 m*	*0.19 to 0.1 m*	*Less than 0.1 m*
Barbers Hill	Cotton Lake	Alco-Mag	Cedar Bayou
Clear Lake (1942-54)	Dickinson-Gillock	Anahuac	Chocolate Bayou
Dyersdale	Goose Creek (1936-59)	Franks	Clear Lake (1959-64)
Esperson Dome	Humble	Mykawa	Clinton
Goose Creek (1917-25)	Rankin	Pierce Junction	Danbury Dome
Hastings	Turtle Bay		Katy
South Houston (1943-63)			Kuhlman-Bender
Tomball			South Cotton Lake
Webster			South Houston (1973-78)

subside by maintaining reservoir pressures. Although the ratios preferably should include the large quantities of brine that commonly are produced in conjunction with the petroleum, it was impossible to do so, because data on the production and disposal of salt water were unavailable except for the year 1967. Gas production also was not included in the data used to calculate the ratio of produced fluids to area of production because we lacked reliable data for correcting gas volume to reservoir conditions. Accordingly, a very conservative estimate of potential subsidence was calculated by computing the ratio of oil produced to production area (Table 2). This estimated potential subsidence exceeds observed differential subsidence at most fields (compare Tables 1 and 2). The only field where observed differential subsidence exceeded potential subsidence was Chocolate Bayou, a field where large volumes of gas were also produced. Overall, estimated potential subsidence exceeds 0.1 m (0.3 ft) at 19 of the 26 fields. Of the nine fields whose potential subsidence is estimated to be greater than 0.5 m (1.6 ft), differential subsidence was detected at only three; estimated potential subsidence is greatest at Hastings and Webster fields, where it exceeds 3 m (10 ft).

Although the ratios given in Table 2 support a relation between petroleum withdrawal and differential subsidence at five of the six fields where differential subsidence has been observed, these ratios also raise the question of why differential subsidence is not more common. The question is not easily answered with available data. Three factors, however, including modest pressure declines, incompressibility of the reservoirs, and the ratio of depth to width of the compacting zone, may be important to the general absence of differential subsidence. As was noted above, the magnitudes of pressure decline cannot be seriously evaluated on the basis of available data although effective water drives are prevalent and probably counteract major pressure declines. The second factor, compressibility, also cannot be directly evaluated. Although the pressure declines at Goose Creek (1917-1925) were probably anomalously large, the subsidence there confirms that reservoirs are compressible to some extent. Another potentially important aspect at Goose Creek is that the average production depth was approximately 0.5 km (0.3 mi) shallower than the depth at most other fields (Table 1). In general, sediments are less compressible as depth of burial increases. An effect of production depth at other fields that evidence differential subsidence is suggested by Figure 9; differential subsidence tends to be larger as average production depth is shallower. However, the relation is not clear-cut, because some fields that do not evidence differential subsidence produce from depths that are comparable to the depths in other

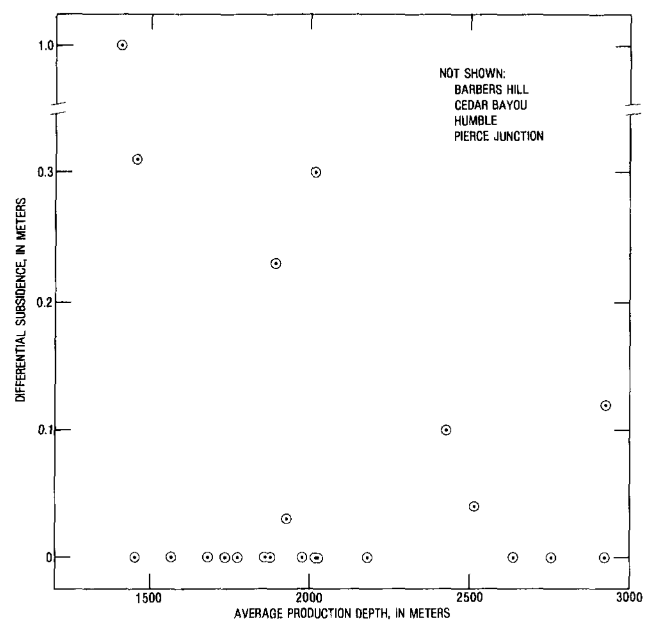

Fig. 9. Differential subsidence versus average production depth of oil fields in the Houston, Texas area.

fields that do evidence differential subsidence. Finally, the third factor, the ratio of the depth to width of the compacting zone, has an inverse effect on the magnitude of differential subsidence and may help explain why differential subsidence is not more common. For example, Geertsma (1973) estimated that for reservoirs underlying a horizontal disc-shaped zone of compaction, whose depth-to-radius ratio equals 1.0, maximum subsidence would be only 45% of the reservoir compaction. For the 26 fields listed in Table 1, the median ratio of the average depth of production to an equivalent radius of the producing area is approximately 1.0.

The importance of water-level declines to observed subsidence suggests the possibility that some differential subsidence may be related to ground-water withdrawal rather than petroleum withdrawal. Differential subsidence could be caused either by local cones of depression induced by concentrated pumpage, such as the 1.6 m subsidence depression at the south end of the Dickinson-Gillock field, or by local increases in the thickness of compressible materials within the aquifer system. The former mechanism may apply at the Hastings field, where Sandeen and Wesselman (1973, Figure 13) mapped a small cone of depression. The eccentricity of the differential subsidence at the Chocolate Bayou field may be caused by the complicating effect of a cone of depression centered at Alvin, 10 km (6 mi) to the north (see Sandeen and Wesselman, 1973, Figure 13). The paucity of water-level measurements, however, does not permit a rigorous test of this hypothesis at these two fields. The alternative mechanism of differential subsidence, local increases in the thickness of compressible material in the aquifer system, could be caused by structural movements during the deposition of stratigraphic units within the aquifer system. Although the stratigraphy of the aquifer system near Houston oil fields has not been analyzed in sufficient detail to evaluate this possibility, both shallow salt domes that pierce the aquifer system and preexisting faults that offset it (Kreitler *et al.*, 1977; Verbeek and Clanton, 1981) indicate that stratigraphic units within the aquifer system of the Houston area are structually disrupted. Because these structural disruptions took place at least partly during the deposition of the units in the aquifer system (Kreitler *et al.*, 1977), the thicknesses of the compressible strata might have been locally affected.

Fields at which historical surface faulting occurred inside or within 2 km (1.2 mi) of the field boundary are indicated in Table 1. Of particular interest are those fields that evidence both historical faulting and a negligible amount of differential subsidence. These fields include Clear Lake, Clinton, Dickinson-Gillock, and Webster, where some of the most closely spaced surface faults in the Houston area occur (Verbeek and Clanton, 1978; E. R. Verbeek, 1981, unpub. data). Thus, even though extensive surface faulting is areally associated with petroleum withdrawal at these fields, the historical offset does not appear to be caused by the petroleum withdrawal, at least by a differential compaction mechanism.

CONCLUSIONS

Subsidence profiles across 29 oil and gas fields in the Houston, Texas, subsidence bowl indicate local increases of subsidence at least at six fields—Alco-Mag, Chocolate Bayou, Goose Creek (1917-25), Hastings, Mykawa, and South Houston. Although ground-water withdrawal is undoubtedly the most important factor contributing to the subsidence at each field, oil and gas withdrawal may be partly responsible for the differential subsidence. Except for Chocolate Bayou, the volume of petroleum production at each field was sufficient to account for the differential subsidence. The volume of petroleum production, however, in general is not a reliable index for predicting differential subsidence because land within many fields with significant production did not evidence differential subsidence. At four fields, subsidence was less than in the surrounding areas. Three of these fields—Barbers Hill, Humble, and Pierce Junction—are associated with shallow salt domes that partly occupy the aquifer system and thin the aquifer system.

Although oil and gas production at six of the 29 fields investigated may have contributed to land subsidence, with the exception of Goose Creek (1917-25), the contribution of petroleum withdrawal relative to that from aquifer compaction appears to be small. At no field except for Goose Creek (1917-25) did the amount of differential subsidence exceed one-third of the regional subsidence.

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Thomas L. Holzer is Deputy Assistant Director for Research of the U.S. Geological Survey. He has been with the Survey since 1975. Formerly, he taught ground-water hydrology at the University of Connecticut. He received a B.S.E. in Geological Engineering from Princeton University, and an M.S. in Hydrology and a Ph.D. in Geology from Stanford University. He has published numerous articles on land subsidence and ground failure caused by ground-water withdrawal.

Robert L. Bluntzer is the Ground-Water Planning Coordinator in the Planning and Development Division of the Texas Department of Water Resources. He earlier was employed as a ground-water geologist and hydrologist with the Department. During the early 1960's he worked for Halliburton, Core Laboratories, and Schlumberger. He received his B.Sc. in Geology in 1960 from the University of Texas at Austin.