Subsidence of the Texas coast: inferences from historical and late Pleistocene sea levels

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ABSTRACT

Changes in sea level observed at tide gauges are caused by actual changes in water level and by changes in elevation at the observing station. Recent research has focused on the relationship between climatic change and sea level, but vertical land movement can be just as important, particularly in subsiding sedimentary basins. The purpose of this study is to compare long-term rates of subsidence estimated from upper Pleistocene strata along the central Texas coast with historical subsidence rates from the same area obtained from geodetic surveys and tide gauge data. This comparison shows that historical subsidence rates are much greater than long-term averages and are equal or greater than actual sea-level change along the Texas coast south of Galveston Bay.

Long-term (~10^5 yr) subsidence rates were estimated by establishing the extent of marine, marine-influenced, and nonmarine strata within the upper Pleistocene Beaumont Formation in the Copano Bay area of the central Texas coast, and comparing the maximum elevation of in-place, marine-influenced deposits with published maximum sea level estimates of 5–8 m above mean sea level (MSL) from correlative, well-dated coral terraces from stable and uplifted areas. In-place, shell-bearing horizons deposited at or below sea level occur no higher than 2 m MSL in the Copano Bay area, suggesting that there has been no more than 6 m of subsidence since the probable time of deposition during the Sangamon interglacial at ~120 ka. The long-term, average subsidence rate for this part of the Texas coast is thus 0.05 mm/yr or less.

Historical subsidence rates were obtained by:

1. calculating relative elevation changes between National Geodetic Survey first-order leveling surveys conducted in the early 1950s with those conducted in the late 1970s to early 1980s;
2. normalizing the relative elevation differences between surveys to annual rates of change relative to an arbitrarily chosen benchmark;
3. referencing these lines to sea level at three tide gauges; and
4. comparing calculated rates of relative sea-level (RSL) rise along the lines with estimates of eustatic sea-level (ESL) rise. Rates of RSL rise for the Texas coast south of Galveston Bay were generally 4–8 mm/yr; locally, rates were as high as 23 mm/yr. These rates are significantly higher than global averages of ~1 mm/yr. Much of the difference is probably caused by subsidence of the Texas coastal zone at rates of 1–22 mm/yr, or 20–440 times the long-term average of 0.05 mm/yr. The highest subsidence rates were found locally where there has been historical water-level decline in shallow aquifers. Lower subsidence rates of 3–7 mm/yr occur regionally where groundwater decline is minimal or nonexistent. Increased subsidence over the long-term average in these areas may be caused by pressure decline in underlying oil and gas reservoirs.

Introduction

This study compares historical rates of subsidence and sea-level change, which together are termed relative sea-level (RSL) change, with long-term subsidence rates deduced from upper Pleistocene deposits of the central Texas coast (Fig. 1). Historical rates of RSL rise are of interest because they may be related to climatic change (natural and human-induced). Rising sea level threatens human investments in industry, residence and recreation in coastal zones throughout the world and affects coastal wetlands, which are a vital link between marine and terrestrial ecosystems. It has been suggested in many studies that increasing concentrations of “greenhouse” gases (principally carbon dioxide, methane, and chlorofluorocarbons) will cause climatic warming that...
will, in turn, raise global (eustatic) sea level by melting glacier and polar ice and by thermally expanding ocean water.

Particularly in major sedimentary basins such as the northwestern Gulf of Mexico, eustatic sea-level (ESL) rise is exacerbated by subsidence.

Rates of RSL rise measured at tide gauges along the Texas coast are higher than ESL rates (Swanson and Thurlow, 1973; Ramsey and Penland, 1989). The questions to be answered here are: (1) how much subsidence has occurred on a geological time scale, and at what average rate; (2) how

Fig. 1. Location of the study area and major physiographic and structural features. Structural elements from Ewing (1990).
does the long-term (average) subsidence rate compare with historical rates estimated from geodetic leveling and tide gauge data; and (3) how significant is the difference between the geological and historical subsidence rates, and what are the possible causes of the differences?

The study area consists of the Texas coastal zone between Galveston Bay and the Rio Grande (Fig. 1). This area encompasses parts of three structural zones: the Rio Grande Embayment, the San Marcos Arch and the Houston Diapir Province (Dodge and Posey, 1981; Ewing, 1991). In these zones, greater sediment thicknesses in the Rio Grande Embayment and the Houston Diapir Province attest to higher rates of subsidence than in the arch. Even over the arch, ~ 2 km of fluvial to marine sediment has accumulated since the Late Oligocene (Dodge and Posey, 1981).

The Copano Bay area of the central Texas coast (Fig. 1) was chosen for detailed stratigraphic study in order to estimate average subsidence rates since the late Pleistocene. Historical rates of subsidence and RSL rise were determined between Galveston Bay and the Rio Grande.

Methods

Long-term (10^5 yr) subsidence rates for the Copano Bay area were estimated as follows:
(1) a lithologic model of upper Pleistocene strata was constructed using surface and subsurface data;
(2) depositional environments were interpreted on the basis of physical properties of sediments, including texture, color, competence and accessories;
(3) areal and vertical extent of marine-influenced deposits was established, from which the highest elevation of in-place, marine-influenced deposits was identified;
(4) the maximum elevation of marine-influenced deposits was assumed to be a conservative estimate of maximum paleo sea level during deposition; and
(5) this paleo sea level was compared with maximum paleo sea levels reported for the same period from well-dated stable and uplifted coral terraces in other parts of the world. The difference in these elevations is an estimate of subsidence since deposition.

Data used to construct a stratigraphic model of the Copano Bay area included foundation borings, water wells, soil cores, surface exposures and aerial photographs (Fig. 2). Detailed descriptions were obtained from 121 foundation borings taken from the surface to depths of as much as 40 m by the Texas Highway Department and the U.S. Navy during construction of roads, bridges, and port facilities. More than 100 descriptions of strata from similar depths were made by geologists during an extensive Works Project Administration (WPA) water-well drilling program in the late 1930s and early 1940s. Several soil cores were taken to depths of as much as 5 m to verify WPA descriptions and to provide samples for further study. Interpretations of depositional environ-

Fig. 3. Location of National Geodetic Survey leveling lines and National Ocean Survey tide gauges used in this study.
ments for the near-surface sediments were also based on aerial photographs and surface exposures along eroding bay shorelines.

Historical subsidence rates for the Texas coast from Galveston southward were estimated by combining geodetic leveling data with tide gauge data (Fig. 3). Regional first-order leveling across the Texas coast, conducted by the National Geodetic Survey (NGS) in the 1950s and again in the late 1970s and early 1980s, were used to quantify relative vertical movement between benchmarks. Regional lines were combined to make longer lines by using common benchmarks; vertical movement at each benchmark was referenced to an arbitrarily chosen benchmark. Small differences in elapsed time between surveys were compensated for by calculating annual rates of movement and using those rates for comparison.

To remove the shortcoming of rates of vertical movement referenced to an arbitrary datum (which itself is moving vertically at an unknown rate) the geodetic data were tied to three tide gauges, one at each end of the regional line and one near the center. Rates of differential vertical movement predicted for these gauges from leveling data were compared with annual rates of RSL rise calculated from tide gauge data collected over the same period in which the leveling data were collected. The geodetic network was then referenced to sea level at each of the three gauges. Each gauge provided an independent estimate of RSL change at the benchmark chosen as a datum, and, by extension, to every benchmark in the network. Calculated rates of RSL rise across the geodetic network were then compared with estimates of ESL rise. The difference is an estimate of the subsidence rate.

Geodetic data, collected by the NGS, consisted of unadjusted first-order profiles. These are reversed profiles having a maximum allowable elevation difference of 4 mm multiplied by the square root of the distance traversed (1–2 km) between forward and reverse runs (Bates and Jackson, 1987). A composite, 525-km-long profile was constructed along the coast between Algoa and Harlingen (Fig. 3) by combining a 330-km-long profile between Algoa and Robstown for the period 1951–1978 with a 195-km-long profile between Robstown and Harlingen for the period 1951–1981. Three coast-normal profiles connect the coast-parallel profile to National Ocean Survey tide gauges at Port Isabel (877-9770), Rockport (877-4770), and Galveston (877-1450). The Harlingen to Port Isabel segment (85 km) was surveyed in 1951 and 1982, the Sinton to Port Aransas segment (52 km) in 1959 and 1978, and the Algoa to Galveston segment (43 km) in 1978 and 1987.

Tide gauge data used in this study consist of monthly means of hourly tide-level measurements taken at Port Isabel, Rockport, and Galveston Pier 21 between 1948 and 1986 (Lyles et al., 1988). To facilitate comparison between gauges, only months during which all gauges were operating were used to calculate average annual rates of RSL rise. This restriction caused data gaps for 1955–1962, 1975 and 1984–1985.

**Results**

**Late Pleistocene subsidence rates**

The Copano Bay area of the central Texas coast was chosen for study because upper Pleistocene strata representing nonmarine and marine-influenced environments (including fluviatile, deltaic, lagoonal-estuarine and barrier-strandplain) are relatively well exposed there. The strata of interest for determining long-term subsidence rates are components of the Beaumont Formation and consist of three predominantly fluviatile units [informally named the Willow Creek, St. Mary's and San Patricio units (Fig. 4)] and a predominantly marine-influenced unit (Ingleside unit). The units interfinger, with some deltaic or estuarine sediments occurring within the fluviatile units and some alluvium occurring within the Ingleside section.

The uppermost depositional units within the Beaumont Formation (Fig. 5) represent the final phase of Pleistocene coastal plain aggradation. The fluviatile units are relatively fine grained and are composed of fine sandy channel deposits separated by clay or sandy clay floodplain or marsh deposits (Aronow, 1971; Brown et al., 1976; McGowen et al., 1976). The units generally thicken
gulfward, from 2–4 m near the inland contact with older Pleistocene fluvial deposits of the Lissie Formation to 5–8 m near the surface contact with the Ingleside unit (Paine, 1991). The fluvial and marine-influenced units occur on an unconformity marked by soil development on older, underlying deposits.

The Ingleside unit (Fig. 4) is a sandy, shore-parallel deposit that was interpreted as a late Pleistocene barrier complex by Price (1933), an interpretation supported by later work showing a Pleistocene lagoon landward of the barrier segment near Copano Bay (LeBlanc and Hodgson, 1959; Bernard and LeBlanc, 1965). The unit was reinterpreted north of the study area as a regressive strandplain deposit based on prominent ridge-and-swale topography and the presence of a soil horizon, rather than lagoonal deposits, at its base (Wilkinson et al., 1975a,b). A core that penetrated the Ingleside unit south of Copano Bay showed that the Ingleside is at least in part transgressive there (Shideler, 1986). Near Copano Bay, elevations at the base of the Ingleside range from −3 to −28 m MSL; total thickness of the unit varies between 8 and 31 m. It generally consists of a basal, fine-grained, marine-influenced section that is overlain by the main Ingleside sand body. This coarsening-upward transgressive sequence results from the landward migration of
Ingleside equivalent lagoonal or estuarine facies and barrier facies during a period of rising sea level. At and following the maximum transgression, the lagoons or small bays were filled with deltaic and fluvial deposits of the Willow Creek, St. Mary's and San Patricio units and the Ingleside began a regressive phase (Paine, 1991).

The extent of marine influence, both lateral and vertical, is critical to estimates of maximum sea level during deposition of these units. For the Willow Creek unit, for example, there is no direct evidence of marine influence (in-place marine shell horizons or shell-free estuarine deposits) where the elevation at the basal unconformity is above ~3 m MSL. This basal elevation occurs ~10 km inland from exposures of the marine-influenced Ingleside unit. The highest shell horizon encountered in the Willow Creek unit was reported at ~2 m MSL in a foundation boring much closer to the Ingleside unit. Between this elevation and ~3 m MSL, similar deposits (but without shell) are encountered. Marine influence in the Ingleside unit is clearer; shell horizons were reported in descriptions of borings and wells as high as 2 m MSL. Similar in-place horizons of the brackish-water oyster *Crassostrea virginica* are exposed along the inland margin of the Ingleside at 0.5 m MSL and below. On the microtidal Texas coast (normal tidal range less than 1 m), the occurrence of these shell horizons and correlative shell-free host deposits indicate that maximum sea level during deposition was ~2 m MSL.

The age of these uppermost Beaumont Formation units is not rigorously established. Some have argued for a middle to late Wisconsin date (29 ka) for the Ingleside unit on the basis of radiocarbon dates on shell (Shideler, 1986). Others studying the same samples do not rule out the possibility that contamination by younger radiocarbon has caused erroneously young dates (Cronin, 1986). Climatic data for the Wisconsin glaciation suggests maximum sea levels no higher than ~40 to ~50 m MSL during the Wisconsin interstadial at ~30 ka (Mörner, 1971). Shallow seismic reflection studies of the northwestern Gulf of Mexico continental shelf indicate that the interpreted mid-Wisconsin coastal ravinement surface, developed by landward shoreface migration during sea-level rise, pinches out at ~20 m MSL (Suter et al., 1987).

Perhaps the most reliable age information currently available for the Ingleside unit is that it was deposited when sea level was as high or higher than present. A preponderance of global data from raised and stable coastal terraces indicates that the last time sea level was above present level was during the Sangamon interglacial stage (Fig. 6), which is here considered equivalent to oxygen isotope stage 5e. Uranium series dates on corals from these terraces range from ~120 to 135 ka (Veef, 1966; Ku, 1968; Bloom et al., 1974; Moore and Somayajulu, 1974; Chappell and Veef, 1978; Harmon et al., 1979; Muhs, 1983; Chen et al., 1991).

Fig. 6. Late Quaternary sea level, glacial stages and oxygen isotope stages. Modified from Moore (1982).

Estimates of the height of sea level during the Sangamon interglacial, calculated from absolute elevations on "stable" platforms and from corrections for uplift rates on raised terraces, range from 4 to 10 m MSL, although most estimates are between 5 and 8 m MSL (Osmond et al., 1965; Matthews, 1973; Ku et al., 1974; Harmon et al., 1983; Hendey and Volman, 1986; Chen et al.,
1991). Deposits with direct marine influence have been encountered no higher than 2 m MSL in the Ingleside unit and in the distal parts of the uppermost fluvial units of the Beaumont Formation, implying that there has been no more than ~6 m of subsidence in the Copano Bay area since deposition. Using the most likely age of 120 ka for these deposits yields a long-term subsidence rate of 0.05 mm/yr or less; even the youngest age suggested for these deposits (29 ka, Shideler, 1986) yields long-term rates no higher than 0.2 mm/yr.

**Historical subsidence rates**

Comparisons of first-order leveling profiles along the Texas coast between Algoa and Harlingen show that there was substantial differential movement between 1951 and 1978–1982 (Fig. 7). Rates of movement, relative to benchmark F46 at Sinton, Texas, ranged from 6.1 mm/yr of relative uplift to 15.9 mm/yr of relative downwarp. Areas that moved rapidly downward relative to F46 include Algoa (as much as 13.5 mm/yr) and Palacios (as much as 15.9 mm/yr). Despite its location in a structural trough (Rio Grande Embayment), the southern part of the Texas coast between Sinton and Harlingen was relatively stable. Rates of vertical movement in this area ranged from ~2 to 4 mm/yr upward relative to F46.

Leveling lines connecting the Algoa to Harlingen line with tide gauges at Port Isabel, Rockport, and Galveston Pier 21 (Fig. 3) were used to

<table>
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<tr>
<th>Tide gauge</th>
<th>Vertical movement relative to F46</th>
<th>RSL rate 1948–1986</th>
<th>RSL rate 1951–1982</th>
<th>RSL rate relative to F46</th>
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<tr>
<td>Galveston Pier 21</td>
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<td>6.5</td>
<td>8.2</td>
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<td>Rockport</td>
<td>+ 2.2</td>
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<td>5.4</td>
<td>7.6</td>
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<tr>
<td>Port Isabel</td>
<td>+ 2.7</td>
<td>3.4</td>
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estimate the differences in rates of RSL rise that should be observed at the gauges and to check the accuracy of the surveys. Rates of vertical movement between Harlingen and Port Isabel were between 2.7 and 5.2 mm/yr upward relative to F46; at the Port Isabel gauge, the rate was 2.7 mm/yr (Table 1). For the mid-coastline between Sinton and Port Aransas, rates of movement ranged widely from 5 mm/yr downward to 10 mm/yr upward relative to F46. The benchmark nearest the tide gauge at Rockport moved upward at 2.2 mm/yr relative to F46. Along the upper coast, vertical movement between Algoa and Galveston was between 7.4 mm/yr downward to 3.3 mm/yr upward relative to F46. At the Galveston Pier 21 gauge, the land surface moved 2.3 mm/yr downward relative to F46 (Table 1).

Because rates of RSL rise can be calculated at the tide gauges for the period encompassing the leveling surveys, differences in the rates of RSL rise can be compared with differences in rates of vertical movement at each of the gauges. Additionally, rates of RSL rise at each tide gauge can be used to convert rates of vertical movement along the geodetic network to an estimate of the rate of RSL rise at each benchmark. This operation reveals whether rates of RSL rise observed at tide gauges are anomalously high and represent only small geographic areas (local anomalies) or whether they are representative of larger geographic areas in the Texas coastal zone.

Mean sea level data collected from the three tide gauges between 1948 and 1986 are strongly correlated (Fig. 8). Because month-to-month variations are of the same magnitude as the net RSL rise over the period of interest, only data for months during which all gauges were recording were used. Linear regression equations for the 1951–1982 period yield rates of RSL rise of 4.6 mm/yr at Port Isabel, 5.4 mm/yr at Rockport and 8.2 mm/yr at Galveston Pier 21 (Table 1).
Differences between these rates are near those estimated from the leveling data (Table 1; Fig. 9), which supports the validity of the leveling data and allows RSL rise to be estimated for the entire geodetic network.

Estimates of rates of RSL rise across the network could be made from any of the three gauges, but each would give a slightly different rate. The Port Isabel gauge was chosen for these estimates (Fig. 10) because: (1) the dates of leveling surveys between Harlingen and Port Isabel agreed most closely with those between Algoa and Harlingen; (2) estimates of relative vertical movement at Port Isabel did not require extrapolation from a benchmark several kilometers away as did the estimate for the Rockport gauge; and (3) relative vertical movement between Harlingen and Port Isabel was not as variable as it was on the other two coast-normal lines.

Rates of RSL rise between Algoa and Harlingen, calculated from the Port Isabel tide gauge, range from ~2 to 23 mm/yr, with most of the coast undergoing rates of 4–8 mm/yr. Most of the rates are similar to those observed at the tide gauges, which suggests that the gauges are good regional indicators of RSL. Some areas, nevertheless, are undergoing much higher rates of RSL rise. The question of how much rise along the Texas coast is due to subsidence and how much is due to ESL rise can be answered by comparing the observed rates with estimates of ESL rise.

There have been numerous studies of historical sea-level trends worldwide. Although no tide gauge can be considered truly stable (Mörner, 1976; Clark et al., 1978), estimates of the eustatic component fall within a narrow range. One of the earliest studies was by Gutenberg (1941), who estimated an eustatic rate of rise of 1.1 mm/yr from tide gauges. Estimates made since then have ranged from 1.0 to 1.5 mm/yr (Gornitz et al., 1982; Barnett, 1983; Gornitz and Lebedeff, 1987), although Emery (1980) supported a considerably higher global average of 3.0 mm/yr. Attempts to remove postglacial isostatic movement and geographical bias from tide gauge records resulted in eustatic estimates as high as 2.4 mm/yr (Peltier and Tushingham, 1989).

Rates of RSL rise on the Texas coast exceed these estimates (Fig. 10), therefore, virtually the entire Texas coast subsided between the 1950s and early 1980s. In areas of low rates of RSL rise, the subsidence component was ~50% of the observed rise and amounted to only 1 or 2 mm/yr. In other areas undergoing extremely high rates of
RSL rise, the subsidence component approached 90% of the observed rate. For most of the coast, subsidence estimates range from 3 to 7 mm/yr, or 50–75% of the observed rate of RSL rise. These rates for the subsidence component are similar to the range reported for selected Texas tide gauges (Ramsey and Penland, 1989).

Comparison of late Pleistocene and historical rates

Differences between rapid historical rates and lower global rates of RSL rise have been attributed to the natural compaction of the thick sedimentary section beneath the Texas coastal plain (Swanson and Thurlow, 1973). Long-term subsidence rates, calculated for the Copano Bay area by comparing sea level during deposition of the Ingleside unit with global estimates of sea level during the last interglacial, do not exceed 0.05 mm/yr. This rate is undetectable in leveling surveys and by tide gauges and suggests that either there has been a recent large increase in the subsidence rate over much of the Texas coast or that estimates of ESL rise are too low by a factor of two or more.

It is unlikely that estimates of ESL rise derived from global data sets are enough in error to account for the rapid rates of RSL rise calculated for the Texas coast. Even if estimates of ESL rise at the high end (2.4–3.0 mm/yr) are correct, rates of RSL rise over large areas of the Texas coast still exceed ESL rates by 1–5 mm/yr, which is 20–100 times the long-term subsidence rate.

Possible causes of increased subsidence rates

There are several possible sources of the increased subsidence observed along the Texas coast, including combinations of basinal subsidence, sediment compaction and subsurface fluid removal. Basinal subsidence and sediment compaction account for a small part of the observed subsidence rates, probably on the order of the long-term subsidence rates. Compaction of Holocene sediments is a major contributor to rapid subsidence rates in Louisiana (Ramsey and Penland, 1989), but tide gauges used in this study are situated on relatively thin Holocene deposits. Further, high rates of subsidence were observed along the leveling network in areas where Holocene sediments are absent or are but a thin veneer over Pleistocene deposits.

Groundwater withdrawal and concomitant compaction of water-bearing strata can explain increased subsidence rates locally (Gabrysch and Bonnet, 1975; Ratzlaff, 1982). At Algoa, where some of the highest subsidence rates were observed, water levels in a shallow aquifer declined 30 m between 1942 and 1972 (Paine, 1991). Higher subsidence rates over large areas and in areas where groundwater production is insignificant require other causes. One possible cause is pressure decline in Texas coastal oil and gas reservoirs. Production and regional depressurization in deep hydrocarbon reservoirs might produce broad areas of land-surface subsidence rather than the localized subsidence characteristic of shallow groundwater production. These reservoirs are more concentrated north of the Rio Grande valley (Galloway et al., 1983; Kosters et al., 1989), where increased regional subsidence rates are most pronounced.

Subsidence related to hydrocarbon production has been reported near Houston and Corpus Christi (Pratt and Johnson, 1926; Kreitler, 1978; Ratzlaff, 1982; Holzer and Bluntzer, 1984), but relatively low rates of subsidence expected from oil and gas production can be overwhelmed locally and masked by more rapid subsidence caused by groundwater withdrawal. It has been suggested that subsidence on the upper Texas coast can be attributed to hydrocarbon reservoir depressurization (Sharp and Germiat, 1990; Germiat and Sharp, 1990). It is possible that the historical increase in subsidence rates along much of the Texas coastal plain is caused by the same process.

Conclusions

On a geological time scale (10^5 yr), average rates of subsidence are 0.05 mm/yr or less for the central Texas coast. Relatively small differences in elevations of marine-influenced upper Pleistocene deposits elsewhere along the Texas coast suggest that this rate is a representative one.
On a historical time scale (decades), rates of vertical movement are much higher. Differential vertical movement between Galveston Bay and the Rio Grande, calculated from first-order leveling surveys conducted in the 1950s and in the late 1970s to early 1980s, ranged from 6 mm/yr upward to 16 mm/yr downward relative to an arbitrarily chosen benchmark in the central Texas coastal zone. Estimates of RSL rise across the leveling network were made by combining the leveling data with tidal data from three tide gauges. These estimates range between 2 and 23 mm/yr, but much of the coast ranges between 4 and 8 mm/yr. These rates are significantly greater than eustatic estimates of 1.0–1.2 mm/yr. Higher rates of RSL rise on the Texas coast are probably caused by subsidence, which, once the eustatic component is removed, range from 1 to 22 mm/yr.

It is clear that historical subsidence on the Texas coast far exceeds (by 20–440 times) average subsidence rates calculated over longer periods. Large, local excess subsidence (as much as 22 mm/yr) is found in areas of shallow groundwater withdrawal. Subsidence rates of 3–7 mm/yr occur in regions where groundwater use is minimal or nonexistent. For these regions, where subsidence rates exceed the long-term average by 60–140 times, other causes must be found. These areas are underlain by producing oil and gas fields; the excess subsidence observed might be related to declining fluid pressures in subsurface hydrocarbon reservoirs.

Finally, much effort has been expended in recent years to analyze the connection between climatic change and sea level. This study shows that other geological parameters can vary greatly, perhaps under human influence, and can exacerbate relative sea-level changes locally as much or more than can climatic change.

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