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Quantifying rates of coastal subsidence since the last interglacial and the role of sediment loading

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ABSTRACT

The rate of sea-level rise is expected to increase over the next century. In many areas, increasing rates of sea-level rise are exacerbated by subsidence. In order to develop proper mitigation strategies for coastal change, better estimates for the rates of subsidence are needed. In this study we outline a strategy for calculating long-term subsidence rates for coastlines based on the differential elevations of modern shorelines and their last interglacial (LIG) equivalent geomorphic features. We apply this strategy to the LIG shoreline of the USA Texas coast. We first obtained optically stimulated luminescence ages of features long conjectured to be LIG, but, until now have remained undated. We use a digital elevation model to calculate the difference in elevations between the modern and MIS5e shorelines. This difference is corrected for glacial-hydro-isostatic adjustments to the Texas coast over the last 120 ky. Our analysis shows spatial variability in the rate of subsidence that increases seaward and at locations closer to the Brazos/Colorado delta. The lowest rates of subsidence were 0.03 mm/yr at the most inland site. The highest rates were 0.09 mm/yr near the modern Brazos/Colorado Delta. The spatial pattern of subsidence suggests that most of the long-term vertical motion along the Texas coast is due to sediment loading. The rates of subsidence along the portions of the Texas coast are equal to, and in some places greater than, glacial-isostatic adjustments (GIA), thus highlighting the importance of other vertical motions such as sediment loading when using sea-level data to constrain GIA models even in the absence of active tectonics. In addition, these rates are two orders of magnitude less than modern rates of relative sea-level rise recorded at tide gauges along the Texas coast, highlighting the importance of Holocene compaction and fluid withdrawal in accelerating rates of subsidence along the Texas coast.

1. Introduction

Current IPCC projections of sea-level rise over the next century range from 0.18 to 0.59 m, threatening many low-lying coastlines across the globe (IPCC, 2007). In many areas this problem will be exacerbated by subsidence caused by either Holocene compaction (Bloom, 1964; Kaye and Barghoorn, 1964; Penland and Ramsey, 1990; Long et al., 2006; Törnqvist et al., 2008; Horton and Shennan, 2009; van Asselen et al., 2011), anthropogenic-related subsidence due to groundwater and petroleum extraction (White and Morton, 1997), or tectonic subsidence (Dokka, 2006; Dokka et al., 2006). Deciphering the relative contributions of sediment loading, compaction, and tectonic movements on relative sea-level change remains an important step for planning proper mitigation strategies over the next several centuries. One area that is particularly vulnerable to subsidence and sea-level rise is the northern Gulf of Mexico (Gornitz et al., 1994; Blum and Roberts, 2009; Syvitski et al., 2009; Fig. 1). Tide gauge records indicate highly variable subsidence rates across the region. Establishing long-term (pre-historic) average subsidence rates provides a better understanding of those factors influencing this variability and for placing anthropogenically induced subsidence into context. In this study we calculate the long-term subsidence rates for the Texas coast along the northwestern Gulf of Mexico based on the differential elevations of modern barrier islands and their LIG equivalent geomorphic feature. We first obtained optically stimulated luminescence (OSL) ages of onshore coastal deposits that have long been interpreted to be LIG in age (Price, 1933; Shepard and Moore, 1955; Morton and Price, 1987; Otvos, 2005) but, until now, have remained undated. As we were not able to obtain specific marker beds from the LIG shoreline from our cores, we use the difference in elevation between the LIG shoreline and the modern barrier island shoreline as a proxy for the difference in relative sea levels between the LIG and

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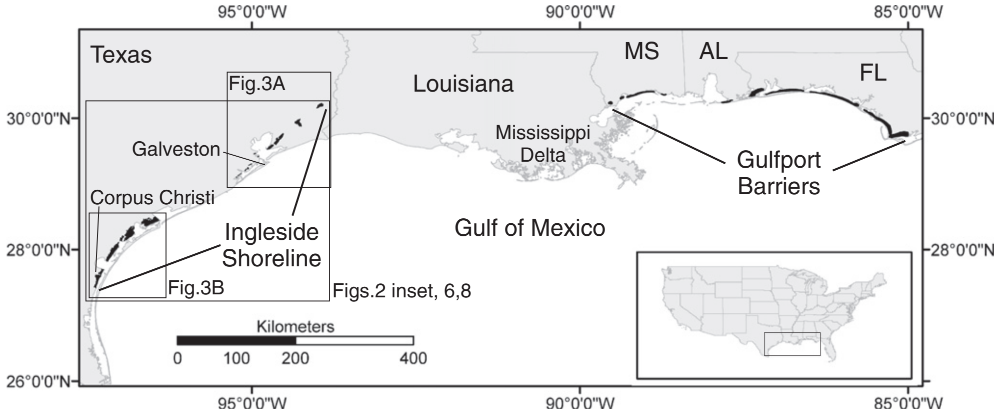

Fig. 1. Map of the northern Gulf of Mexico and general location of the study area and other sites discussed in the text. The black shade in the map represents the Ingleside Shoreline and other LIG shorelines along the northern Gulf of Mexico.

today. For this calculation we use a digital elevation model (DEM) to determine the average elevation of the modern and LIG shorelines as well as the spatial variability in the LIG shoreline elevations. These differences are corrected for glacial-hydro-isostatic adjustment (GIA) contributions to determine the long-term subsidence for the northwestern Gulf of Mexico over the last full glacial cycle.

2. Geological setting

2.1. Subsidence in Texas

According to the tide gauge at Pier 21 in Galveston, Texas, the rate of relative sea-level rise is between 6.3 and 6.5 mm/yr (www.psmsl.org, last accessed Nov. 30, 2012; Paine, 1993; Kolker et al., 2011; Fig. 2). Similar average rates of relative sea-level rise are found across the Texas coast (www.psmsl.org). These rates of relative sea-level rise are the sum of global increases in the volume of water in the ocean (both due to ice loss and steric changes), local variations due to GIA-induced changes, local steric changes (e.g. local wind regimes), and local and regional subsidence. Constraints on any one of these variables can be used to help determine the others.

Independent rates of the long-term subsidence for the region are needed to isolate the magnitude of land-level changes from any one cause and provide context for modern anthropogenically-influenced rates. In Texas a large component of the modern subsidence has been attributed to withdrawal of hydrocarbons and groundwater (Kreitler, 1977; White and Tremblay, 1995; White and Morton, 1997; Morton et al., 2006; Kolker et al., 2011). Locally, rates of subsidence have reached as high as 60 mm/yr (Gabrysch and Bonnet, 1975). Some of the subsidence is magnified as it is accommodated along growth faults (White and Morton, 1997). In many locations, displacement along these growth faults is visible in LIDAR surveys at the surface (Engelkemeir and Khan, 2008). Our study areas were chosen to avoid areas of high anthropogenically-driven subsidence rates such as the northwestern portions of Houston, Texas and west Galveston Bay.

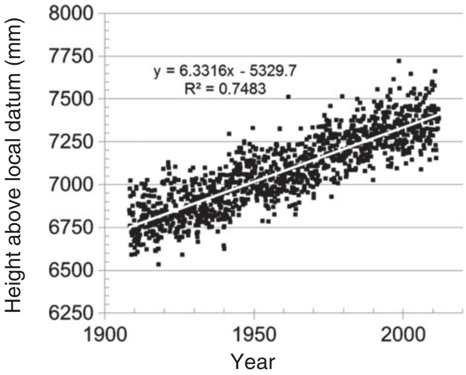

Fig. 2. Plot of tide-gauge elevations for Galveston, Texas Pier 21 tide gauge (from www.psmsl.org) illustrating the relative rate of sea-level rise experienced at Galveston, Texas for the period 1908–2012. The rate of relative sea-level rise calculated for this study (6.33 mm/yr; slope of the line shown) was derived from a simple linear regression of all the data.

Paine (1993) conducted one of the first attempts at determining the 10^3–10^5 year scale average subsidence rates for the Texas coast using the Ingleside Shoreline. However, at the time of his work, corrections were not available for the GIA components of land-level changes and since his study several new records of the LIG sea levels have been produced (e.g. compilation by Kopp et al. (2009); Muhs et al. (2011); Dutton and Lambeck (2012); and Kopp et al. (2013)). In addition, no absolute ages were available for the Ingleside Shoreline nor was Paine (1993) able to examine the variability of the LIG shoreline elevations along coastal Texas. Paine (1993) used the highest elevation of a shell hash of 2 m above present mean sea level as the datum to assign the maximum elevation of sea level during deposition of the Ingleside Shoreline and obtained a total subsidence of 6 m since the LIG equating to a long-term average subsidence rate of 0.05 mm/yr for the central Texas coast.

2.2. LIG sea levels

The LIG, 120 ka, also known as marine isotope stage 5e (MIS5e), represents the most recent deglacial period prior to the Holocene when global sea levels were close to present levels (Chappell and Shackleton, 1986; Dutton and Lambeck, 2012). Hence, according to some models of global warming (e.g. Otto-Biesner et al. (2006)), the LIG has been viewed as a possible analog for future sea-level scenarios. The highest global mean sea level during this period reached at least +4 m (the minimum of the range favored by Tarasov and Peltier (2003)) and is unlikely to have exceeded +9 m (Cuffey and Marshall, 2000; Kopp et al., 2009; Lambeck et al., 2012; Dutton and Lambeck, 2012; Kopp et al., 2013). Locally, the LIG sea levels may depart from these globally averaged values because of GIA contributions and vertical tectonic displacements. A study of LIG coral reefs in the southern tip of Florida has led to estimates that sea levels for the eastern Gulf of Mexico (uncorrected for GIA) were between +6.6 and +8.3 m (Muhs