Discriminating Quaternary Depositional Units on the Texas Coastal Plain Using Airborne Lidar and Near-Surface Geophysics

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ABSTRACT

Depositional units preserved on coastal plains worldwide are an important repository of information about large-scale climate change that has occurred during more than 20 Quaternary glacial-interglacial cycles. In general, the lateral and vertical complexity of these depositional units and their response to climatic and sea-level change are poorly understood, making it difficult to place historical and anticipated future climate and sea-level change in a natural geologic context. Mapping Quaternary siliciclastic depositional units on low-relief coastal plains historically has been based on aerial photographs. Accuracy and detail have been hindered, however, by lack of exposure and low relief. High-resolution airborne lidar surveys, along with surface and borehole geophysical measurements, are being used to identify lateral and vertical boundaries of stratigraphic units on the Texas Coastal Plain within upper Quaternary strata. Ground and borehole conductivity measurements discriminate sandy barrier island and fluvial and deltaic channel deposits from muddy floodplain, delta-plain, and estuarine deposits. Borehole conductivity and natural gamma logs similarly distinguish distinct depositional units in the subsurface and identify erosional unconformities that likely separate units deposited during different glacial-interglacial stages. High-resolution digital elevation models obtained from airborne lidar surveys reveal previously unrecognized topographic detail that greatly aids mapping of subtle surface features such as sandy channels, interchannel deposits, and accretionary features on barrier islands that formed during the last interglacial period. An optimal mapping approach for coastal-plain environments employs (1) an initial lidar survey to produce a detailed elevation model; (2) selective surface sampling and geophysical measurements based on preliminary mapping derived from lidar data and aerial imagery; and (3) borehole sampling, logging, and analysis at key sites selected after lidar and surface measurements are complete.

INTRODUCTION

The Texas Coastal Plain is underlain by a complex assemblage of fluvial, deltaic, estuarine, and marine-influenced deposits that make up two principal Pleistocene formations (Fig. 1): the younger Beaumont Formation and the older Lissie Formation (Hayes and Kennedy, 1903; Sellards et al., 1932; Price, 1934, 1958; Metcalf, 1940; Doering, 1956; Arnow, 1971; Brewton et al., 1975; Brown et al., 1987). These two formations record depositional, erosional, and weathering events associated with more than 20 full or partial glacial-interglacial cycles recorded in ice and sediment cores worldwide (e.g., Shackleton and Opdyke, 1973, 1976; Imbrie et al., 1984; Lorius et al., 1985; Robin, 1985; Lisiecki and Raymo, 2005). Surface, borehole, and geophysical data from many sources suggest that the strata within these two formations represent multiple episodes of deposition, erosion, and soil formation.
Much of the original mapping of geological units on the Texas Coastal Plain was based on interpretation of early aerial photography, agricultural usage, low-resolution topographic maps, and limited exposures. In this paper, we employ (1) high-resolution topography as determined from an airborne lidar instrument (elevations accurate to a few centimeters) to map the subtle topographic expressions of Quaternary depositional and erosional features; (2) ground-based conductivity measurements to distinguish and delineate the lateral extent of sand-rich and clay-rich depositional units at and near the surface; and (3) subsurface sampling and borehole-based gamma activity and electrical conductivity measurements to determine vertical lithologic boundaries, erosional unconformities, and buried soil horizons that are generally below the resolution of surface and airborne geophysical approaches. We are using these data to produce geologic maps of the coastal plain and to eventually better understand the relationship between depositional units, unconformities, and soil horizons within these two formations to the numerous climatic and sea-level cycles that occurred during their deposition. This paper focuses on recent data acquired on the central Texas coast in the Copano Bay and Corpus Christi Bay area (Fig. 1).

**METHODS**

We combined high-resolution topographic data acquired using an airborne lidar instrument, surface and borehole geophysical measurements, and select surface and borehole sediment samples to help delineate the lateral and vertical extent of Quaternary lithologic units on the central Texas Coastal Plain. Airborne lidar data were acquired in the Copano Bay area between January and March 2014 using a Chiroptera airborne lidar instrument (Airborne Hydrography AB) operating at a laser pulse rate of 120 kHz and a flight height of 800 to 900 m. GPS data from survey-area base stations were combined with aircraft-based global positioning satellite (GPS) and inertial navigation-system data to produce highly accurate instrument trajectories that, when combined with laser orientation and travel-time information, allowed determination of absolute surface reflection positions accurate to within a few cm. Laser returns were binned to produce a high-resolution digital elevation model (DEM) of the area using a 1 × 1 m cell size.

Ground-based conductivity measurements were acquired in January and March 2014 using a Geonics EM31 instrument in vertical and horizontal dipole orientations. This frequency-domain electromagnetic (EM) induction instrument operates at a primary frequency of 9800 Hz with a transmitter and receiver coil separation of 3.7 m and a dipole moment less than 1 ampere-m². Exploration depth is 3 m or less in horizontal dipole mode and 6 m or less in vertical dipole mode. At three sites, we acquired time-domain EM (TDEM) data using a terraTEM instrument (Monex GeoScope) with a 40 × 40 m transmitter and receiver loop, 3 to 8 ampere transmitter current, and turnoff times ranging from about 14 to 27 µs. TDEM data can be used to determine subsurface conductivity profiles to depths of 100 m or more.

Four boreholes were drilled to depths of about 30 m in the Nueces River valley upstream from Corpus Christi Bay in July 2012. Sediment was described and sampled during drilling at 1.5-m intervals using a split-spoon sampler. Upon reaching total depth, the boreholes were temporarily cased using PVC pipe and logged using spectral gamma and induction tools (2SNA–1000–S and 2PIA–1000, Mt. Sopris Instruments).

We acquired surface and borehole sediment samples in the study area for textural analysis and comparison with surface- and borehole-based geophysical measurements. In the laboratory, a representative fraction (0.2 to 0.5 g) was taken from each sample and placed in a plastic test tube. Sediments were dispersed by adding 5 percent sodium hexametaphosphate solution, shaken for 24 to 48 hr, and passed through a 2-mm (#10) sieve. The particle-size distribution of the passing suspension was determined by laser light diffraction using a Mastersizer 3000 (Malvern Instruments Ltd.) laser particle size analyzer, cycling through the measurement five times to improve size-distribution statistics.

**GEOMORPHOLOGY FROM HIGH-RESOLUTION DEM**

We used results from the 2014 airborne lidar survey of the Copano Bay area to produce a high-resolution DEM (Fig. 2) that we then used to examine subtle topographic features and guide placement of boundaries between distinct lithologic units of the Beaumont Formation (sandy paleochannel features with subtle positive relief and mud-rich overbank or interchannel deposits in intervening topographic lows).

Lidar-derived elevations range from near sea level to about 18 m above sea level in the study area. In general, the land surface slopes toward the Gulf of Mexico to the southeast. Pleistocene Beaumont Formation muddy and sandy deposits occupy the higher elevations in the study area. This upland surface is incised by valleys cut by rivers such as the Mission River, which has built a Holocene delta in Mission Bay, and the Aransas River, which has built a Holocene delta in its valley at the western edge of Copano Bay (Fig. 2).
Prominent, elongate local highs (labeled H1 through H6 in Figure 2) enter the study area from the north, west, and southwest. These highs on the uplands generally correlate with previously mapped sandy paleochannel facies in the Beaumont Formation. Their topographic expression revealed from lidar allows these features to be more accurately mapped and verified by subsequent sampling and geophysical measurements (Fig. 3). Other significant features can be seen in the high-resolution topographic data. A curvilinear, coast-parallel scarp (labeled S in Figure 2) extends from the Pleistocene upland north of Mission Bay through the Mission River delta in the Holocene valley, marking the likely position of a previously unrecognized fault with evident recent movement. Sharp topographic boundaries on the southeast margin of a locally high feature in the southwest part of the map (H6, Fig. 2) may represent a former bay margin associated with a bay landward of the Ingleside barrier island formed during the most recent interglacial period at about 100,000 yr ago.

LITHOLOGY FROM SURFACE GEOPHYSICS

Preliminary geologic mapping accomplished through interpretation of aerial photographs and DEMs can be verified and refined with surface geophysical measurements. We acquired ground conductivity measurements using an EM31 instrument at 83 sites within the study area and augmented those shallow-focused measurements with deeper TDEM soundings at three locations (Fig. 3). We used the ground conductivity measurements as a local proxy for sand or clay content; higher conductivities were interpreted to be associated with clay-rich Pleistocene interchannel or overbank deposits (Qbc, Fig. 3), whereas low conductivities tended to occur on the subtle topographic highs where we mapped sandier Pleistocene paleochannel deposits (Qbs, Fig. 4). Low conductivities were also measured in the southeast corner of the study area, where the sand-rich deposits associated with a Pleistocene barrier island (the Ingleside barrier, Qbi, Fig. 4) extend into the map area.

Horizontal and vertical dipole apparent-conductivity measurements made using an EM31, while useful for distinguishing distinct surficial geologic units and determining boundaries between them, provide little infor-
Information about thickness of these units. Conductivity profiles determined from TDEM soundings can be used to estimate the thickness of surficial units and perhaps the lithology and depths of underlying units. TDEM sounding 2, located on the Pleistocene barrier island, recorded a transient response to 2 ms after turnoff and yielded a four-layer model with a low fitting error of 1.6 percent root mean square (rms). At this site, a low-conductivity (79 mS/m) layer extended from 3 to 31 m below the surface, likely representing the sand-rich core of the barrier island. At TDEM site 1 (Fig. 3), near the margin of an interpreted sandy paleochannel within the Beaumont For-

Figure 2. Digital elevation model (1-m$^2$ cell size) of the Bayside and Mission Bay quadrangles, Copano Bay area, constructed from airborne lidar data acquired in 2014. Areas labeled H1 through H6 indicate local elevation highs that correspond to sandy Pleistocene channel courses. Feature S denotes a scarp where there is an abrupt elevation change.
information, a three-layer conductivity model yielded a fitting error of 1.4 percent rms. Here, a 2.4-m-thick, relatively resistive (41 mS/m), likely sand-rich paleochannel unit of the Beaumont Formation overlies a highly conductive (728 mS/m), likely clay-rich overbank or interdistributary unit that is 20-m thick. Below that, a more resistive (220 mS/m) unit of unknown thickness likely represents another sandy unit deeper in the Beaumont Formation.

Figure 3. Geologic map of the Bayside and Mission Bay quadrangles showing Quaternary fluvial, deltaic, and marine-influenced deposits mapped on the basis of geomorphic character expressed in a DEM produced from airborne lidar data, aerial photographs, and ground-based electrical conductivity measurements acquired using EM instruments. Map adapted from Paine and Collins (2014a, 2014b).
Borehole samples, measurements, and direct observations can provide a more detailed view of the subsurface and can reveal critical geologic information, such as the presence of buried soil horizons, that cannot be obtained from surface topographic, remote sensing, or geophysical measurements.

Data from four boreholes drilled across the Nueces River valley upstream from Corpus Christi Bay (Fig. 1) illustrate the complementary nature of geophysical measurements and direct geological observations. In borehole ND-06, drilled to a depth of about 30 m on the floor of the Nueces River delta at a surface elevation of 1.5-m

**VERTICAL BOUNDARIES FROM BOREHOLE GEOPHYSICS AND SAMPLING**

**Figure 4.** Geologic map of the Bayside and Mission Bay quadrangles showing the spatial relationship between interpreted sandy channel deposits of the Beaumont Formation (Qbs) and highly resistive electrical-conductivity measurements acquired using a Geonics EM31 in vertical dipole orientation.
msl, it is evident that the gamma log (Fig. 5a) correlates quite well with clay content in borehole samples acquired at 1.5-m intervals. High gamma counts (20 counts per second or higher) correspond to high clay contents, suggesting that the gamma log is a reliable proxy for clay content and can be used to distinguish sand-rich and clay-rich units. In this example, unit thicknesses determined from the gamma log range from 1 m or thinner to greater than 5 m, showing both abrupt lithologic boundaries as well as gradational ones. The conductivity log (Fig. 5b) has character similar to the gamma log and textural trends in the upper 15 m; higher conductivities in the upper half of the log correlate with higher gamma counts and higher clay content. Below 15 m, apparent conductivity decreases significantly and does not correlate well with gamma or textural trends. The most likely interpretation is that the upper part of the conductivity log is influenced by highly saline pore water at a nearly constant concentration. At depths greater than about 17 m, pore-water salinity progressively diminishes with depth; the concentration reduction likely dominates the conductivity response. It is evident from this example that there are limitations to using conductivity measurements exclusively to develop an accurate subsurface lithologic framework.

A cross section constructed from geophysical logs and data from sediment samples from the four Nueces Valley boreholes (Fig. 6) reveals geologic complexity that may reflect the influence of multiple periods of deposition, erosion, and soil formation that we expect to encounter in the Beaumont and Lissie formations on the lower Texas Coastal Plain. The section is constructed from the upland (Beaumont Formation) south of the valley (borehole ND–05) through two boreholes (ND–07 and ND–06) on the Nueces delta on the valley floor, and terminates on a fluvial terrace on the north side of the Nueces River valley (borehole ND–01). Each gamma log shows variations in count rates that are correlated to variations in clay content (similar to ND–06, Fig. 5). Sample descriptions from the boreholes include color, texture, and accessory information such as the presence of shell, carbonate nodules indicative of buried soil horizons, and soil slickensides indicative of vertisol development in clay-rich strata.

Using a combination of geophysical log character (gamma counts and conductivity), soil descriptions, and laboratory-measured textural information, the borehole data can be interpreted to suggest that Pleistocene deposits border and underlie more recent deposits that partly fill the Nueces River valley. Holocene fluvial, estuarine (shell bearing), and deltaic deposits (Qal, Fig. 6) extend from the valley floor near sea level to a depth of 10 to 15 m, where older deposits (Qb3–5, Beaumont Formation) with evidence of soil formation occur. On the upland south of the valley, two distinct buried soil horizons are evident at depths of 13 and 22 m, suggesting three episodes of deposition (Qb3, Qb2, and Qb1 from oldest to youngest, Fig. 6) separated by periods of possible erosion.
and weathering. Only one of these boundaries (Qb₁ to Qb₂, Fig. 6) is evident from the geophysical log alone. On the north side of the valley, a sandy fluvial terrace (Qt, Fig. 6) overlies older deposits interpreted to be part of the Beaumont Formation. It appears that the soil horizon atop the Beaumont Formation has been eroded, but a second soil horizon occurs at a depth of about 18 m. Buried soil horizons within the Beaumont Formation are also evident from borehole samples beneath the Holocene valley fill on the floor of the valley, where three distinct pedogenic carbonate nodule zones occur in borehole ND–06 and two in ND–07. Some of these boundaries correspond with lithologic boundaries that could be interpreted from gamma or conductivity logs (Q₁ to Qb and Qb₄ to Qb₂, Fig. 6), but others are not clearly interpretable from geophysical data alone.

Taken together, and assuming lateral equivalence of strata across the Nueces River valley, there is evidence for as many as seven distinct Quaternary geologic units. These include the Holocene fluvial, estuarine, and deltaic deposits (Q₅) that partly fill the valley, the elevated fluvial terrace sands (Qt) on the northern side of the valley, and the five units (Qb₁⁻₅) separated by soil horizons and unconformities within the underlying Beaumont Formation (Fig. 6).
CONCLUSIONS

Advances in airborne lidar and geophysical instrumentation have presented an opportunity to better understand the geologic complexity and heterogeneity within the two Quaternary formations that underlie the lower Texas Coastal Plain. High-resolution DEMs, aerial photographs, and surface geophysical measurements can help delineate surficial geologic units and perhaps provide a general lithologic framework for subsurface units. Borehole geophysical data provide more detailed information on subsurface lithologic units, but can miss important intraformation lithologic and pedologic boundaries that may correlate with major climatic and sea-level fluctuations known to have occurred during the Quaternary. An approach that combines (1) airborne lidar to produce high-resolution DEMs that can detect subtle topographic signatures of Quaternary depositional and erosional features; (2) surface geophysical measurements to identify dominant lithology and distinguish surficial geologic units; (3) borehole geophysical measurements to establish the character and detailed lithologic framework of subsurface units; and (4) direct geological observation of subsurface samples to identify key erosional and pedogenic features will likely be required to gain a more complete understanding of the relationship between Quaternary climatic and sea-level cycles and the depositional record on the Texas Coastal Plain.

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