Iron-Stained Quartz as Record of Recent Reworking of Older Sediment by Natural and Anthropogenic Processes, Rio Grande Delta, Texas

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ABSTRACT

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The iron-coated quartz grain record in the Rio Grande deltaic plain in southern Texas, determined from petrologic study of surface and core samples, does not show the distribution pattern typically observed in other deltas. The iron-stained grain distribution patterns in this delta are highly irregular in both time and space, and do not display low proportions (<10%) of coated grains in surficial and Holocene subsurface deltaic sections versus distinctly higher proportions (to over >20%) of stained grains in underlying Pleistocene alluvial strata. Intermediate (>10%) to large (>20%) amounts of partially plus fully coated quartz particles are measured in most surficial samples of 10 sampled deltaic depositional environments and in Holocene core sections. This is a result of (1) pre-dam fluvial transport of older, iron-stained material from Rio Grande basin areas to the Holocene cover of the delta and its Gulf of Mexico margin, (2) erosion and recent reworking landward of iron-stained sediment from Rio Grande delta terrains now submerged on the inner and mid-shelf, (3) possible *in situ* formation of iron-coated grains in the lower valley and delta proper, and (4) intensified post-depositional reworking of the deltaic plain and upper Holocene sections by human activity during the past century. We suggest that anthropogenic activity has now replaced natural processes, especially fluvial transport, as the primary means of mixing older material onto the younger surficial Rio Grande deltaic plain. The delta's present sediment cover is interpreted as a 'palimpsest' comprising admixtures of reworked modern and relict material, particularly in areas where formerly buried sediment continues to be artificially exposed and modified. We anticipate that the proportion of iron-coated grains will remain high at the Rio Grande deltaic surface as human activity continues to replace natural fluvial transport as the dominant process.

ADDITIONAL INDEX WORDS: *Cores, dams, Holocene, depositional environments, human activity, irrigation, navigation, Pleistocene, population growth, sediment cut-off, water shortage.*

INTRODUCTION

Sediment cores and the surficial cover of modern deltas in different climate and geographic settings usually record marked petrologic differences between Holocene fluvio-marine deposits and underlying late Pleistocene alluvial sequences. Such lithostratigraphic differentiation is normally achieved by study of petrologic and soil attributes in examined sedimentary sections (FISK, 1944; KOLB and VAN LOPIK, 1966; KANES, 1970; NELSON and BRAY, 1970; KALMAR, 1975; KOLB and DORNBUSH, 1975; MECKEL, 1975; COLEMAN and ROBERTS, 1988; CHEN and STANLEY, 1993; AUTIN, 1996). This type of information is useful in helping measure the extent of reworking and mixing of late Quaternary sediment of different age and origin in surficial Holocene deltaic sections as a result of natural transport processes and human activity.

One method used to identify displaced Holocene, late Pleistocene and older sediment in surficial deltaic plain sediment is by quantitative measurement of clear, non-coated quartz particles of sand size versus partially and fully iron-stained quartz grains. Investigation of several deltaic systems has shown that significantly different proportions of clear, partially iron-stained and fully coated quartz grains separated from surficial and core samples serve to distinguish Holocene deltaic deposits from underlying Pleistocene alluvial sections (STANLEY *et al.*, 2000). Where previously examined, such quartz staining differences are recognized in sediment deposited in diverse climatic and geographic settings, in deposits subject to various transport processes and dispersal distances, and in sediment of different lithologies and sand-grain textures. Two modern examples are the Nile delta in the warm to hot, arid setting of Egypt and the Ganges-Brahmaputra delta in the humid tropical region of India and Bangladesh. In both depocenters, samples of Pleistocene sediment show consistently higher proportions of both partially and fully stained quartz types than samples collected in overlying Holocene deposits.

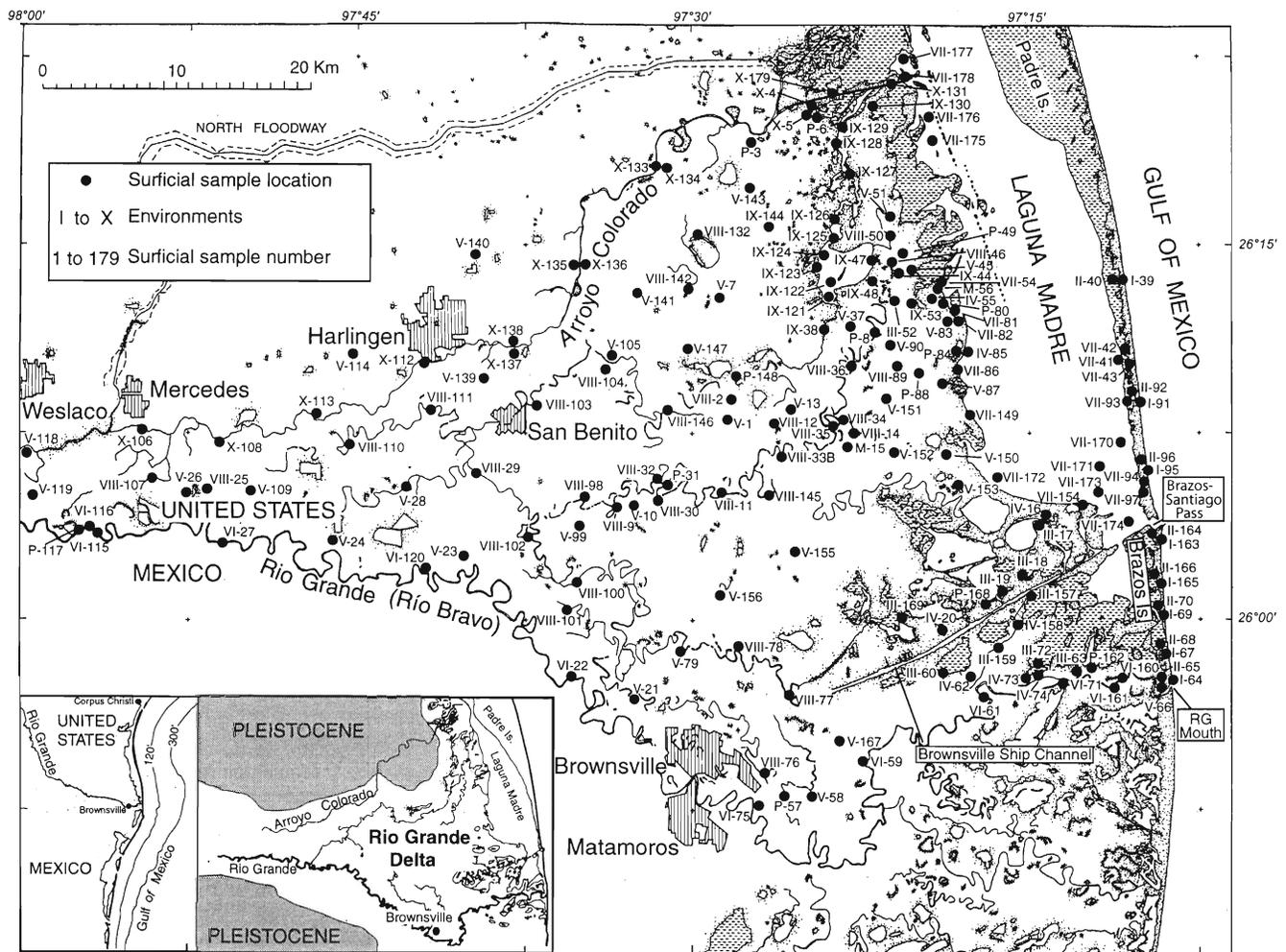While the stained quartz method is a generally valuable

Figure 1. Map showing locations of 177 sites in the Texas sector of the Rio Grande delta. Each site is identified by depositional environment (I–X) and locality (1–177). Inset maps show the configuration of the arcuate deltaic depocenter spanning southern Texas and northeastern Mexico on the western Gulf of Mexico margin.

tool for paleogeographic and stratigraphic purposes, several scenarios are envisioned where the iron-coated quartz record would not clearly distinguish Holocene from Pleistocene deltaic deposits. Such examples could include: deltas that, during most of the Holocene, received a large input of older, reworked iron-stained material by downvalley transport to the Holocene plain; or those subject to soil development and/or geochemical groundwater conditions leading to *in situ* development of staining during accumulation of the Holocene section; or deltas where significant amounts of Pleistocene material have been mixed artificially with Holocene sediment by human activity; or depocenters influenced by two or more of these conditions. To date, however, no specific studies have been made of the stained-quartz record in such deltaic settings.

To examine this problem in more detail, we selected the Rio Grande (abbreviated RG) delta located in the western Gulf of Mexico (inset, Figure 1). This sytem was chosen for

several reasons: (1) until its recent damming, the fluvial sediment load deposited on the deltaic plain included significant proportions of petrologically diverse, oxidized reddish-brown material (references in MORTON and PRICE, 1987; CHURCH, 2000; PEREZ-ARLUCEA et al., 2000) transported by downvalley fluvial and aeolian processes (BROWN et al., 1980); (2) nearshore processes carry significant amounts of older reworked particles, including stained grains, from the shelf landward to the coast (CURRAY, 1960; VAN ANDEL, 1960; GARNER, 1967; HERBER, 1981; MAZZULLO and WITHERS, 1984); (3) frequent river avulsion and flood-related processes have extensively eroded and redistributed Holocene sediment in the deltaic cover above Pleistocene alluvial deposits (FULTON, 1976); and (4) the surficial cover of the lower valley and delta has been extensively modified by man during the past century (BROWN et al., 1980; DAY et al., 1981; U.S.-MEXICO BORDER XXI PROGRAM, 1998).

On the basis of the above-listed factors influencing RG del-

taic sedimentation, we would expect an irregular and poorly-defined distribution pattern of iron-coated particles in the RG delta's surficial cover. Moreover, it is possible that the stained-quartz record in this delta could help to gauge the extent of recent to ongoing sediment reworking and mixing by both natural processes and anthropogenic activity. The present study thus assesses the combined effect of natural transport and human-influenced displacement on quartz-stain attributes in surficial sediment of 10 different modern environments between the RG lower valley and coastal margin of the RG delta in Texas (Figure 1).

NATURAL PROCESSES AND HUMAN ACTIVITY

The RG, or Río Bravo as it is called in Mexico, flows from the Rocky Mountains of Colorado, southward across New Mexico, and then defines the Texas-Mexico border from Ciudad Juárez-El Paso to the western Gulf of Mexico. The river, 3030 km in length, has a drainage basin of 472,000 km², and relatively few major tributaries (most are in New Mexico). In the Gulf, the RG has built the second largest (7770 km²) Holocene fluvial-marine deltaic system, after the Mississippi (Figure 1).

The RG delta, spanning southernmost Texas and Tamaulipas State in northeastern Mexico, presents morphological features typically associated with low elevation, wave-dominated, small tidal range deltas (cf. COLEMAN and WRIGHT, 1975; GALLOWAY, 1975; ELLIOTT, 1978). The delta's Gulf Coast margin, largely erosional and smoothly arcuate, is bordered by a broad expanse of sandy deposits that, in the southern Texas sector, includes an extensive barrier island system, including Padre and Brazos islands (LE BLANC, 1958; FISK, 1959; MORTON and PIEPER, 1975; MORTON and McGOWEN, 1980; WEISE and WHITE, 1980). Behind these barriers lies a broad, shallow lagoon system comprising Laguna Madre, Laguna Atascosa and many smaller wetlands and temporarily flooded algal and salt flats (LOHSE, 1952; RUSNAK, 1960; WHITE et al., 1986; MORTON et al., 2000). A similar, almost symmetrical, barrier and lagoon system has also formed on the coastal margin of the delta in Mexico (inset in Figure 1).

The delta is located in a temperate to hot, semi-arid region receiving an annual average rainfall of only about 650 mm that is concentrated primarily in spring and late summer/fall. Most coastal environments are affected by these seasonal variations, including saline to hypersaline conditions in Laguna Madre and wind-tidal flats (with algal mats common); some flats are locally bordered by silt-rich, elongate mud dunes (PRICE, 1958; PRICE and KORNIKER, 1961). The coastal and lower deltaic environments are periodically affected by powerful tropical storm and hurricane surges that drive Gulf and Laguna Madre waters landward. For example, from 1900 through 1974, 37 hurricanes affected the Texas coast (BERRYHILL, 1975), flooding low-relief terrains. At least 5 destructive events struck the RG region during a 37-year period (1910–1947) in the first-half of last century (HAYES, 1967). Subsequently, hurricanes 'Beulah' in 1967 and 'Allen' in 1980 caused significant changes that have lasted for decades; 'Bret', the most recent of such events (August 1999), resulted in only minor modification of the delta (R. MORTON, 2000,

personal communication). Geologic, geographic, climatic, pedologic, sedimentologic, stratigraphic and other attributes of RG terrestrial and its coastal-related environments and deposits are summarized in numerous publications (references in LE BLANC, 1958; BROWN et al., 1980). Previous petrologic analyses of RG sediment in the lower delta and its contiguous coastal margin have been consulted for the present investigation (BULLARD, 1942; CURRAY, 1960; VAN ANDEL, 1960; HERBER, 1981). Also useful are studies of Late Quaternary RG deltaic sections submerged offshore in the Gulf of Mexico (BERRYHILL, 1975; BERRYHILL et al., 1976, 1987; MAZZULLO and WITHERS, 1984; MARTON and PRICE, 1987; BANFIELD, 1998).

Examination of >100 lithologic logs of U.S. Army Corps of Engineer borings (unpublished, Galveston District) indicates that the Holocene cover of the RG delta is generally <25 m thick, even at the coast where delta thickness tends to be greatest. It is of note that the Holocene section in this system is considerably thinner than that of most other modern world deltas of equivalent water discharge, sediment load, age and size (STANLEY and WARNE, 1994; STANLEY, 1997). This may be a response, at least in part, to geographic change in earlier Holocene time, when the climate was cooler and wetter and the RG had a higher discharge and greater sediment supply. A major change from deltaic progradation to retrogradation is believed to have taken place several thousand years ago, as precipitation decreased and the river drained an increasingly more arid region (R. MORTON, 2000, personal communication).

It is also likely that the relatively thin Holocene section is a function of low accomodation space and conditions that affect deposition specific to this delta: the seaward-directed slope of the deltaic plain, for example, is among the lowest recorded for modern deltas (4 to 24 cm/km; LE BLANC and HODGSON, 1959; MORTON and McGOWEN, 1980); low isostatic and compactional rates have resulted in low land subsidence (BROWN et al., 1980; HERBER, 1981); and this coastal sector is characterized by relative tectonic stability (MORTON and McGOWEN, 1980; MORTON and PRICE, 1987). Flooding on the low gradient of the deltaic plain is associated with unusually high channel sinuosity values (commonly to >2.0, and locally to >3.0) measured for channels of the modern Rio Grande and resacas; these values are higher than for most other studied deltas (sinuosity measured by A.J. JEFFERSON, 1999, Smithsonian Research Training Program unpublished report). Such conditions indicate high river avulsion and migration rates of deltaic distributary channels spreading Holocene sediment laterally across the deltaic plain (FULTON, 1976). It is conceivable that somewhat straighter distributaries may have formed on the lowermost sector of the deltaic plain, but that these were subsequently eroded by the landward retreating shoreline (R. MORTON, 2000, personal communication).

In addition to the above responses to paleoclimatic change, the RG delta has been subject to increasing environmental degradation as a result of accelerated population growth and agricultural and industrial practices (U.S.-MEXICO BORDER XXI PROGRAM, 1998). Within the past 100 years, effects of anthropogenic pressure began to surpass those of natural

processes (BROWN *et al.*, 1980), and interaction of the two parameters has now completely modified original sedimentation patterns on the modern deltaic surface. Emplacement of a permanent rail line in 1904 was a major factor contributing to rapid population increase and intensified agricultural development on both sides of the border in the lower RG valley (DAY *et al.*, 1981). Fresh water, originally needed primarily for agriculture (field crop and livestock range account for nearly two-thirds of the delta study area) is now increasingly used for municipal expansion and industrialization (*maquiladora* plants) along both sides of the international border. Large-scale irrigation and drainage projects presently redirect most natural fresh water flow on the deltaic plain, as do structures emplaced for flood control (such as the North Floodway) and byways for navigation (Brownsville and Harlingen ship channels, Brazos-Santiago Pass, Arroyo Colorado).

Deltaic sedimentation was rapidly, and almost completely, modified as a direct response to marked reduction of river flow and sediment cut-off due largely to dams emplaced on the RG river in the early to mid-20th century (VAN METRE *et al.*, 1997). Among the most important of these structures are Elephant Butte Dam and its reservoir in southern New Mexico (emplaced in 1916), Falcon International Dam and its reservoir in the lower valley between Nuevo Laredo and Brownsville, Texas (in 1954), and Amistad International Dam and its reservoir at Del Rio, Texas (1969). Closest to the RG delta is Falcon Dam, positioned about 440 km up-river from the Gulf·Coast. By 1959, the annual sediment load in the lower valley had already been seriously diminished (to only 1.4 million tons), and then was decreased abruptly after 1961 (VAN METRE *et al.*, 1997) largely as a consequence of further entrapment in the 3 major dam reservoirs and expansion of river water diversion structures.

Mid- to late Holocene climatic and paleogeographic changes and recent entrapment by dams, admittedly significant factors, do not explain the thoroughly altered nature of modern RG deltaic sedimentation regime. In our view, the major critical factor reducing both water and sediment on the depocenter proper has been the very recent, near-complete redirection of water upriver and on the deltaic plain proper by the dense and complex network of water irrigation and drainage channels. Just in the Texas sector of the delta alone, the total length of large waterways, canals and ditches, most bordered by levees, exceeds 2000 km; it is these high-relief features that now preclude widespread flooding and fluvial sediment accretion on the deltaic plain. It is readily apparent that the closely-spaced network of artificial water structures and roadways across the entire Texas portion of the delaic plain have now completely altered the original water flow and distribution system (BAKER and DALE, 1964; TEXAS WATER DEVELOPMENT BOARD, 1977; BROWN *et al.*, 1980; U.S. GEOLOGICAL SURVEY, 1992).

Among aspects of present concern in the semi-arid RG lower valley and delta are decreased access to sufficient supplies of fresh water, salinization, and substantially increased dispersal of pollutants leading to decreased soil quality. In addition, drought conditions in this region during the past 6 years have further reduced essential water resources at a time of much increased need. As a result of the above factors, and especially the extensive anthropogenic modification of the RG river system, little—and, at certain times of the year, no—water is now discharged from the delta mouth to the Gulf (BROWN *et al.*, 1980; DAY *et al.*, 1981; U.S. GEOLOGICAL SURVEY, 1992). In a number of respects, the altered RG system is similar to that of Egypt's Nile delta, also artificially modified and located in an arid setting (STANLEY and WARNE, 1998).

METHODS

A total of 177 sites were selected in 10 different deltaic environments in southernmost Texas during the period 2 to 17 March 1999 (Figure 1). Each site location is coded by two sets of numbers, *i.e.* by depositional environment (I–X) and site position (1–177). Sediment samples examined here were collected at 164 of these localities. The other 13 sites, occupied specifically for mollusc collection (n = 2) and photography (n = 11), are indicated by the symbols P and M in Figure 1.

The following 10 environments were sampled: I, marine beach along the Gulf Coast (n = 8 samples); II, coastal dune along the Gulf Coast (n = 8); III, wind-tidal flat (includes algal flats and some typical playas) in the lower delta, near Laguna Madre (n = 10); IV, mud (largely silt) dune, generally bordering salt flat (n = 8); V, deltaic plain surface proper (n = 36); VI, modern Rio Grande channel on the deltaic plain (n = 11); VII, Laguna Madre (n = 21); VIII, relict deltaic distributary channels (in this region termed *resacas*; LE BLANC and HODGSON, 1959; FULTON, 1976; BROWN *et al.*, 1980), either dry or water filled (n = 32); IX, other wetlands on the delta surface, including Laguna Atascosa and Cayo Atascosa (n = 16); and X, Arroyo Colorado channel and banks along the northern margin of the RG delta (n = 14).

Calculated proportions of non-pigmented clear (transparent or translucent) and of iron-coated (partially and fully stained) quartz grain types in each of the 164 samples are of primary interest here. Stained-grain data averaged for each of the 10 environments are listed in Table 1. This measure is achieved by binocular microscope counts of at least 300 quartz grains randomly selected from the sand-size fraction (63–2000 μm) in each sample. The color of stained quartz grains was recorded using standard color codes (MUNSELL COLOR, 1975). Munsell color readings were determined using moist samples under fluorescent light. The stained-quartz grain method used here is detailed by STANLEY *et al.* (2000).

Additional petrologic information was obtained for the 164 surficial sediment samples, and results averaged for the 10 environments are presented in Table 1:

- Two replicate grain-size analyses were performed on each sample with a Coulter Counter laser particle analyser (LS200). From the two size runs, the following were averaged: relative percent of sand (63–2000 μm), silt (0.5–63 μm) and clay (<0.5 μm); mean, median and modal grain size; and standard deviation, kurtosis, and skewness of the size curve.
- Total organic matter (by weight %) was obtained by removing water from the samples, followed by combustion at 650°C for 5 hours.

Table 1. *Petrologic data averaged for 164 samples collected in ten (I–X) depositional environments in the Texas sector of the Rio Grande delta.*

PARAMETER	I. Beach	II. Coastal sand dune	III. Wind-tidal flat	IV. Mud dune	V. Delta plain	VI. Rio Grande	VII. Laguna Madre	VIII. Resaca	IX. Other wetland	X. Arroyo Colorado
Clear quartz	76.32	76.39	88.47	84.50	86.48	86.25	86.43	88.17	90.10	88.17
Partially stained qtz.	17.89	18.98	9.02	12.79	10.75	10.62	11.08	9.68	8.18	9.68
Fully stained qtz.	5.79	4.63	2.51	2.72	2.77	3.13	2.49	2.15	1.72	2.15
Sand	99.26	100.00	36.58	37.11	18.81	42.62	56.89	31.78	47.04	31.78
Silt	0.45	0.00	44.90	46.89	60.41	40.99	28.59	49.27	34.83	49.27
Clay	0.29	0.00	18.52	16.00	20.78	16.39	14.53	18.94	18.13	18.94
Mean (in microns)	205.96	201.44	66.09	61.10	47.42	103.28	163.00	96.23	106.78	96.23
Organic matter	1.45	1.33	10.52	8.49	10.32	8.80	10.04	13.22	10.83	13.22
Light mineral	95.18	93.47	80.16	85.16	71.70	84.39	82.66	67.42	86.87	67.42
Heavy mineral	1.43	3.91	4.77	4.21	4.64	5.16	4.57	4.72	3.18	4.72
Mica	0.15	0.00	0.99	1.20	0.66	1.24	0.26	0.80	0.15	0.80
Pyrite	1.30	1.00	0.44	1.46	1.35	1.63	0.69	0.93	0.36	0.93
Gypsum	0.04	0.00	0.67	0.26	2.10	0.46	0.39	0.60	0.17	0.60
Lithic fragment	1.34	1.54	4.40	1.85	11.16	3.44	1.04	5.29	1.69	5.29
Aggregate	0.04	0.00	2.95	2.03	4.50	0.60	0.80	2.38	1.47	2.38
Plant matter	0.00	0.07	2.43	0.00	1.16	0.23	4.43	11.34	1.20	11.34
Foram benthic whole	0.04	0.00	0.53	1.02	0.38	1.17	1.53	0.33	2.00	0.33
Foram benthic frag.	0.31	0.00	0.47	2.15	0.33	1.02	0.91	1.61	0.47	1.61
Gastropod whole	0.00	0.00	0.03	0.15	0.00	0.00	0.00	0.07	0.03	0.09
Gastropod fragment	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.12	0.00	0.12
Pelecypod whole	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00
Pelecypod fragment	0.00	0.00	0.00	0.00	0.00	0.00	0.49	0.37	0.18	0.37
Ostracoda	0.00	0.00	0.05	0.51	0.05	0.03	0.26	0.82	0.50	0.82
Sponge spicule	0.07	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.02
Shell other	0.11	0.00	2.12	0.00	1.91	0.63	1.87	3.19	1.77	3.19

- A second sand-size fraction was separated from each sample for compositional identification of at least 300 randomly selected grains with binocular microscope. Relative percentages of the following 14 components in this fraction were calculated: (1) *inorganic* = light mineral, heavy mineral, mica, pyrite, gypsum, lithic fragment (rock lithologies other than quartz), aggregate; (2) *organic* = plant matter, foraminifera, gastropod (complete and broken), pelecypod (complete and broken), ostracod, spicule, and other shell.
- Compositional analyses using a binocular microscope were also obtained for the coarsest (>2000 μm) fraction, where present in the 164 samples; this granule fraction most commonly comprises plant, molluscan shell and fragment, lithic fragment and calcareous concretion.

For comparison with surficial samples, a study was made of 82 core samples applying the same methodology as described above. Samples were obtained from 10 cores collected by the U.S. Army Corps of Engineers in the RG delta study area (Figure 2). These cores, ranging to a depth of ~18 m below mean tide level, included the following: 5 cores along the Brownsville Ship Channel (coded BS89-41, -45, -52, -56, -57), 3 cores in Brazos Island Harbor and near the Brazos-Santiago Pass (BI95-116, -117, -118), and 2 cores along the Arroyo Colorado near Harlingen, Texas (AC90-184, -189). Petrologic parameters measured in core samples are identical to those examined in surficial samples. Of the 82 core samples, 63 had a sufficient sand fraction (>1.5%) to conduct both stained grain and sand counts. The range of values for the 2 quartz grain types (clear grain, partially plus fully iron-stained grains) and for the 3 textural parameters (relative

percentages of sand, silt, clay) measured for the 63 core samples are listed in Table 2.

To help evaluate sediment provenance, 8 samples were collected well up-valley from the delta, in and along the present RG channel, north of El Paso, Texas (courtesy of T. Church, in November 2000). This river channel sampling area comprises a 60-km stretch between Radium Springs and Anthony, in southern New Mexico. Proportions of the two quartz particle types and 3 textural parameters in the modern river samples are given in Table 3.

Complete textural and compositional data for each surficial (n = 164), core (n = 82) and modern RG channel (n = 8) samples are listed in tables available from the authors.

OBSERVATIONS

General Petrologic Distributions

To help interpret recent RG deltaic sedimentation patterns, petrologic parameters of RG surficial samples are averaged for each of the 10 deltaic environments (Table 1). This approach, for example, serves to distinguish sand of Gulf beach from dune (the latter has a higher heavy mineral content). Moreover, the petrology of these 2 sand-rich coastal environments (I, II) clearly differs from the 8 other deltaic environments (III–X) that are mud-rich (primarily silt plus clay) and constitute the majority of examined delta samples. However, petrologic parameters measured in the 8 mud-rich facies record considerable overlap and do not serve to effectively distinguish each specific deltaic environment (Table 1). Petrologic attributes of the sand-size fraction from these samples, to differentiate among various mud-rich facies, are un-
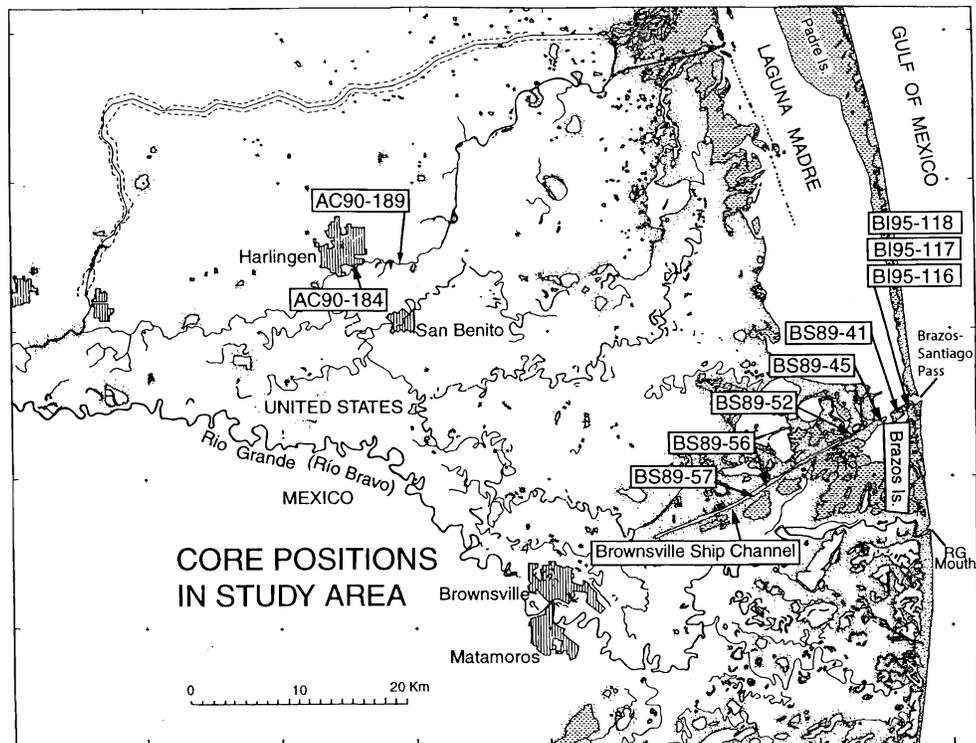
Figure 2. Map showing locations of 10 Rio Grande delta cores sampled for this study.

der study using statistical correspondence (cluster) analyses (work in progress by G. Randazzo and others).

Examination of the relative percentage of sand in samples (Figures 3, 4) is useful to help interpret transport process (fluvial, coastal marine, wind) and dispersal energy level on the deltaic plain and associated coastal environments (ROYSE, JR., 1968; PETTIJOHN et al., 1973; ETHRIDGE et al., 1975; ELLIOTT, 1978). Moreover, we would expect that data on proportions of non-coated clear grains versus partially plus fully iron-stained quartz grains of sand size (Figure 5) could provide information on sediment provenance and sedi-

mentation changes through time (cf. STANLEY and HAIT, 2000).

Light minerals (Table 1), which generally include a large proportion of quartz, constitute the dominant compositional component of the sand fraction in the 164 surficial deltaic samples. The proportion of light minerals exceeds 70% in more than 80% of the surficial samples (Figure 4). Of note are the 11 modern RG fluvial samples, presumably representative of much of the sediment deposited on the deltaic plain, that contain a high light mineral fraction ranging from 79 to 93% (see three fields denoted in Figure 4). Particularly high

Table 2. *Minimum and maximum values of selected petrologic parameters compiled for core samples (n = 63) recovered in 10 borings in the Texas sector of the Rio Grande delta.*

PARAMETER	Range of values	Arroyo Colorado 90–184	Arroyo Colorado 90–189	Brazos Harbor 95–116	Brazos Harbor 95–117	Brazos Harbor 95–118	Brownsville 89–41*	Brownsville 89–45**	Brownsville 89–52	Brownsville 89–56	Brownsville 89–57
Clear quartz grains %	Min	83.0	71.4	82.2	81.9	77.8	—	—	73.1	75.1	73.8
	Max	97.4	84.9	91.9	95.6	89.5	85.9	87.0	94.2	93.6	86.7
Partially plus fully stained quartz %	Min	2.6	15.1	2.0	4.4	10.1	—	—	5.8	6.4	3.3
	Max	17.0	28.1	17.7	18.1	22.2	14.1	12.9	26.9	22.3	26.2
Sand %	Min	1.6	19.2	7.6	0.0	7.6	—	0.0	0.0	1.4	0.0
	Max	5.3	63.3	92.4	97.4	73.3	43.1	6.6	69.5	84.5	49.1
Silt %	Min	50.4	27.3	5.6	1.8	19.1	—	30.8	25.5	9.8	35.7
	Max	59.1	59.3	54.5	51.6	45.0	41.9	69.5	61.4	70.9	64.8
Clay %	Min	36.9	9.4	1.7	0.8	7.1	—	28.9	5.1	5.7	12.5
	Max	47.5	21.5	38.9	60.0	47.4	15.0	69.2	53.7	45.3	61.8

* = only one sample available
** = only one sample with a sufficient quantity of sand fraction

Table 3. *Proportions of clear and stained particles and of textural end-members in samples (n = 8) collected along a 60-km stretch of the modern Rio Grande channel in southern New Mexico, north of El Paso, Texas.*

PARAMETER	Rio Grande channel #1	Rio Grande channel #2	Rio Grande channel #3	Rio Grande channel #4	Rio Grande channel #5	Rio Grande channel #6	Rio Grande channel #7	Rio Grande channel #8
Clear quartz grains %	76.05	89.07	80.18	77.64	75.72	67.14	74.02	79.81
Partially plus fully stained quartz %	25.95	10.93	19.82	22.36	24.28	32.86	25.98	20.19
Sand %	87.89	84.64	69.85	98.14	85.51	87.89	93.36	94.00
Silt %	9.53	12.23	25.86	1.42	11.35	10.36	4.94	4.89
Clay %	2.58	3.13	4.29	0.44	3.14	1.75	1.7	1.11

Sample locations: #1, at edge of Rio Grande channel, 6 km north of Radium Springs; #2, top of river bank, 5 km north of Radium Springs; #3, upstream from small dam, Leasburg State Park; #4, bank of present channel, at Shalom Colony Rd bridge crossing Dona Ana; #5, bank of present channel, at city park Las Cruces; #6, top of present bank channel, at bridge crossing Mesquite; #7, top of present bank channel, at bridge crossing Vado; #8, bank of present channel, at bridge crossing Anthony.

percentages (86–98%) occur in beach and coastal dune settings, while low amounts (<10%) of light minerals are measured in only a few of the deltaic plain and resaca samples. Our analyses indicated the presence of sufficient quartz grains in this fraction for quantitative examination of all samples in the ten RG depositional environments.

Sand Fraction Distribution

Grain-size analyses of RG delta samples record the presence of most textural types defined by FOLK (1954), including the clay, silt and sand end-members and most mixtures thereof. The relative percentage of sand in the 164 surficial
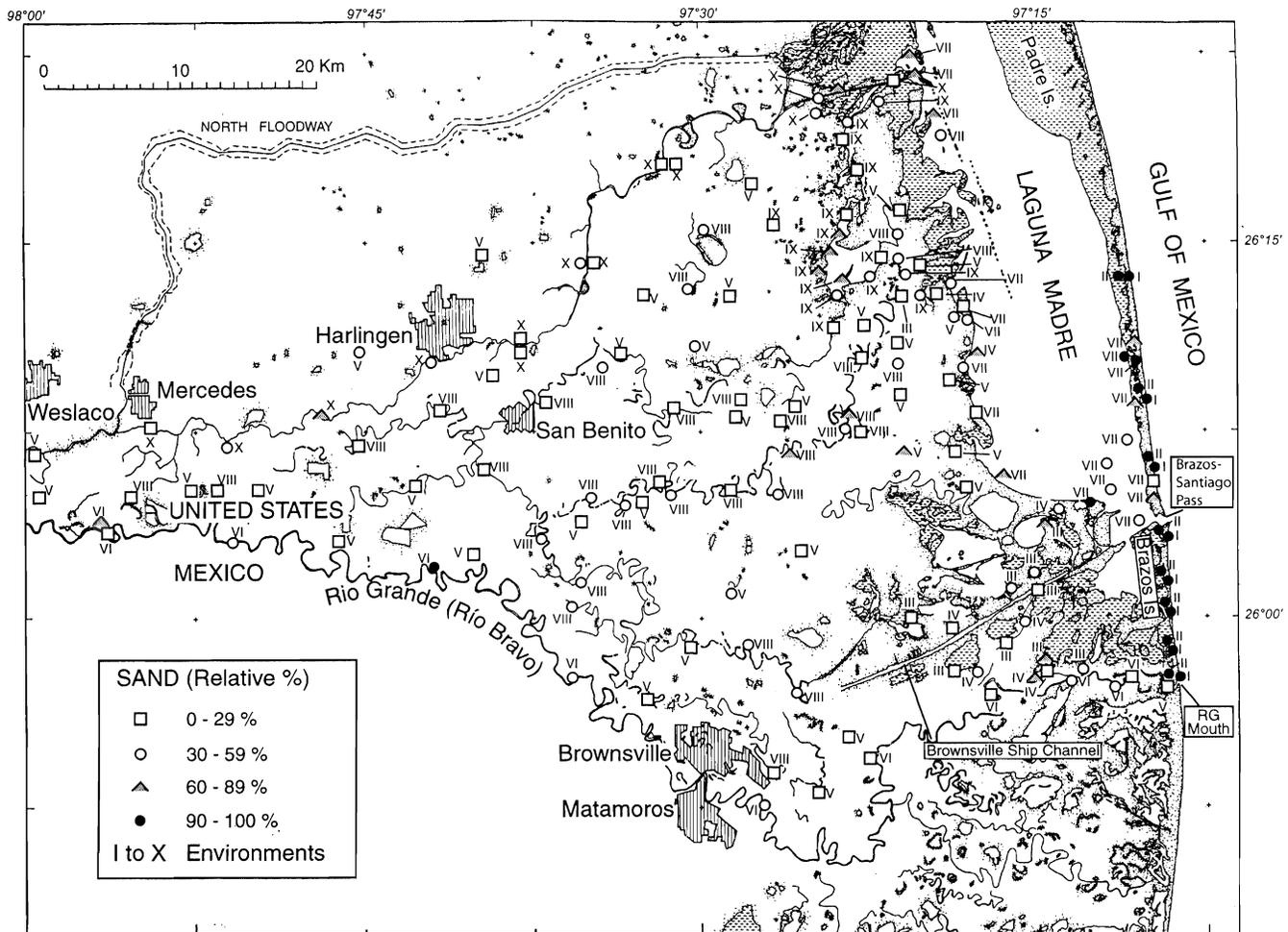

Figure 3. Distribution of four sand content categories in surficial sediment of the Rio Grande study area.
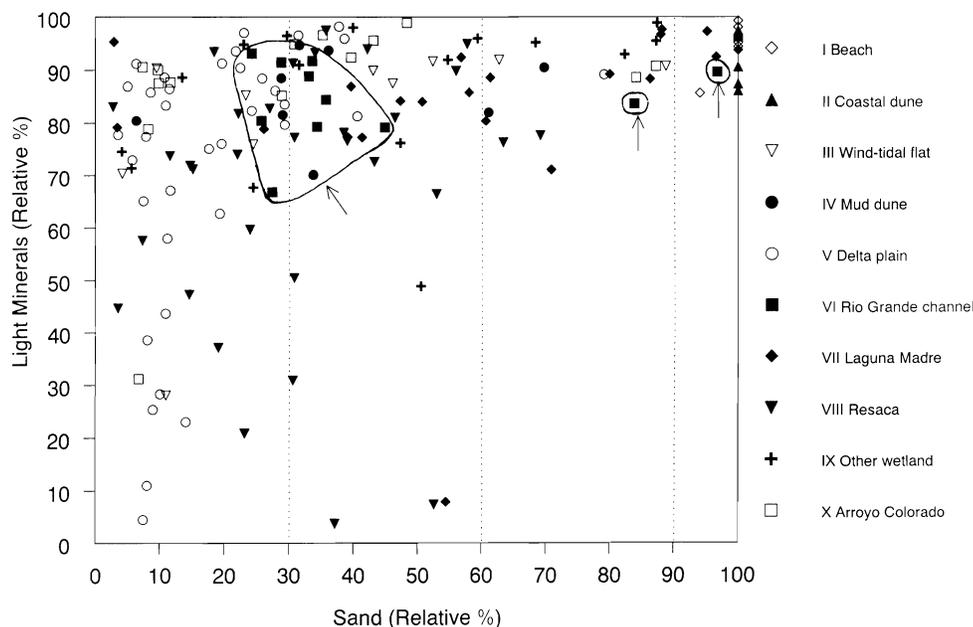
Figure 4. Proportions of light minerals (includes quartz) in the sand-size fraction versus percentages of sand; 4 sand content categories are shown by dotted lines. Note 3 fields (see arrows) occupied by the modern Rio Grande channel samples.

samples ranges from as little as 2.9 to 100% (Figure 3). On the basis of overall range and distribution of relative percentages of sand measured, each sample is assigned to one of four designated sand content categories (Figure 4): <30% sand (n = 70 samples), 30–59% (n = 51), 60–89% (n = 22) and >90% (n = 21). There is good correlation among sand-rich (>90%) samples from coastal environments I and II and their geographic distribution. In contrast, correlation is only moderate to poor among the 4 sand content categories and mud-rich (silt and clay) environments III to X (Figures 3, 4). Eight of the 11 RG channel samples, representative of the fluvial material transported to the deltaic plain, contain a sand content ranging from ~25 to 50%. The following observations are made (textural terminology according to FOLK, 1954):

- The prevailing textural category of surficial samples (in 43% of 164 samples) is the fine-grained (<30% sand) sediment facies that, for the most part, comprises silty mud, sandy silty mud and sandy clay. This category most commonly occurs in the lower valley and deltaic plain proper; it is also recovered in resacas and in the northern Atascosa lagoon.
- Samples (31% of the 164) with intermediate proportions (30–59%) of sand are somewhat less widely distributed. This category occurs mostly in sandy silt, muddy silty sand and sandy clay facies, along the RG channel and in some resacas, Arroyo Colorado, wind-tidal flats/playas and Laguna Madre. Samples in this category were also collected at a few sites on the delta plain proper.
- Samples (13% of the 164) that comprise a still higher proportion (60–89%) of sand are mostly in muddy sand

and silty sand facies. This category, more geographically restricted, was recovered at and near the mouth of Arroyo Colorado, on wind-tidal flats, on some beaches of Laguna Madre, and in a few resacas. A few isolated samples were also collected near the delta apex and RG channel.
- The coarsest grain-size category (with >90% sand) also accounts for 13% of all surficial samples. Most of these samples, comprising sand and silty sand facies, are concentrated in beach and dune of Brazos and Padre islands north of the RG mouth; one such coarse-grained sample was also collected along the RG channel in the delta proper.

Iron-Stained Grain Distribution

The distribution pattern of partially plus fully iron-coated quartz grains, measured in the sand-size fraction of each of the 164 surficial samples, is shown on the map in Figure 5. Pigments that coat quartz particles are most often composed of iron oxides, and commonly include goethite. The larger frequency of stained particles in Pleistocene sediment is attributed to oxidizing conditions that prevailed in subaerially exposed environments (DORN, 1998). Such coated quartz grains viewed under the binocular microscope are commonly yellow (2.5Y 8/6, 10YR 8/6) to red, brownish red and orange (10R 3/6, 10R 4/6, 10R 4/8). In contrast, Holocene deposits record a lower proportion of partially and fully stained quartz. The somewhat higher proportion of light brownish grey (2.5Y 6/2), pale brown (10YR 7/3) and light olive grey (5Y 6/2) particles is interpreted as deposition in settings affected by altering reductive and oxidative processes.
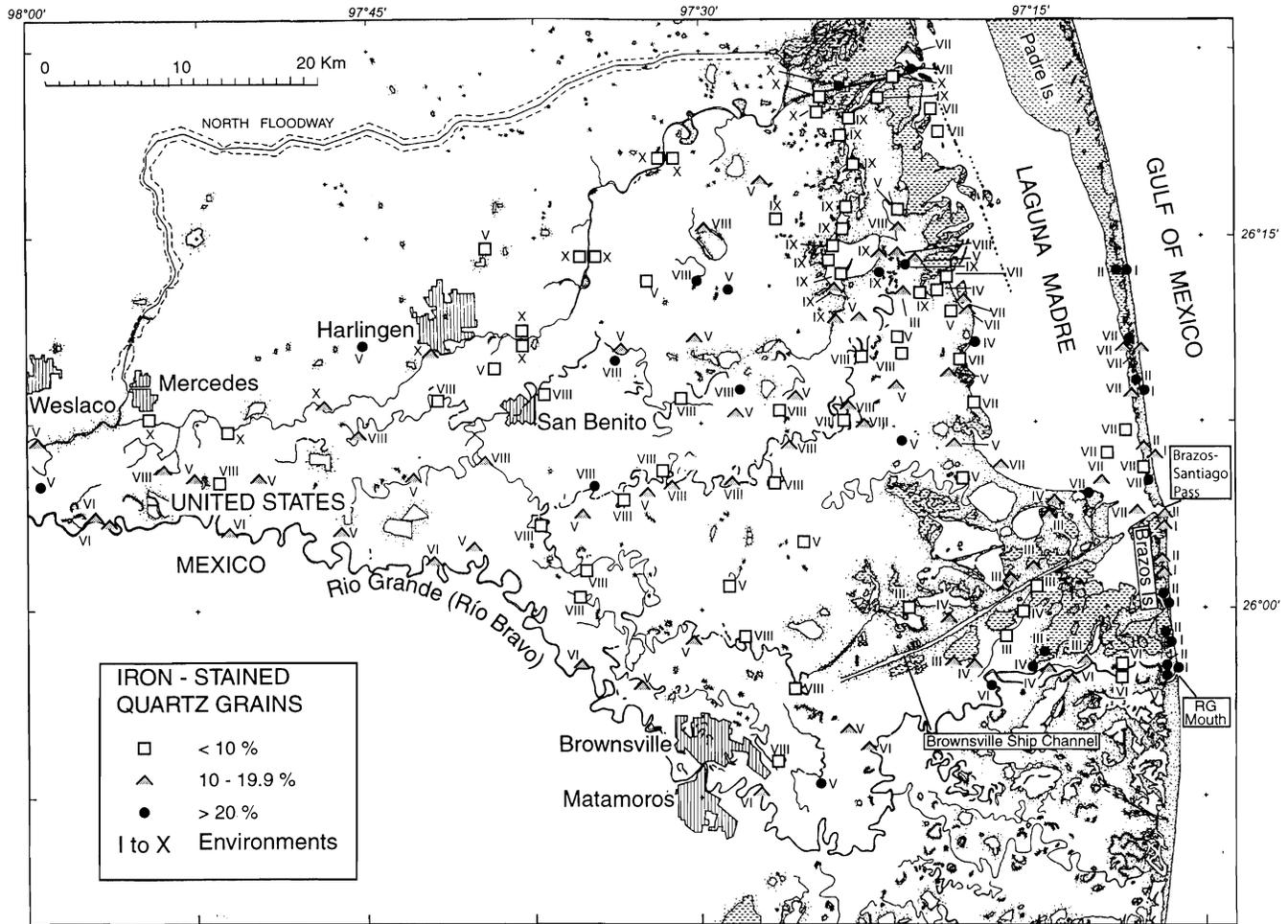
Figure 5.   Distribution of three iron-stained quartz grain categories in surficial sediment of the Rio Grande study area.

On the basis of the overall range and distribution of relative percentages measured (from 0.3 to 36.8%), three stained-grain sample groups are designated: <10% partially plus fully coated quartz (n = 64 samples), 10 to 19.9% (n = 69), and >20% (n = 31). Overall, there is poor correlation among these 3 groups, depositional environment, and geographic distribution in the delta:

• Samples (accounting for 39% of the 164) comprising the lowest proportions (<10%) of partially and fully stained grains are widely distributed between the uppermost delta and the coast, including delta plain proper and resacas, wind-tidal flats, other wetlands and some beaches along the landward margin of Laguna Madre.
• The most widely distributed sample group (42% of the 164) is characterized by an intermediate amount of iron-stained quartz grains (10–19.9%). Such samples are interspersed geographically with those characterized by lower proportions of stained grains, especially on the delta plain proper and in resacas. However, this stained-grain category was also sampled in the other 8 environments.

• Samples (19% of the 164) with highest proportions (>20%) of stained quartz were collected primarily on Gulf of Mexico beaches and dunes, several isolated wetland sites, and the coastal margin of Laguna Madre. Several samples of this stained-grain group, however, were also recovered locally in resacas, lower RG valley and adjacent delta plain.

INTERPRETATION OF CORE LITHOFACIES

Distinguishing Pleistocene from Holocene

The petrologic types described in the previous sections of this study are interpreted by means of comparison with (1) published descriptions of characteristic lithologic and stratigraphic attributes of Pleistocene and Holocene facies defined in the study area (TROWBRIDGE, 1932; DOERING, 1956; LE BLANC, 1958; HERBER, 1981; MORTON and PRICE, 1987), and (2) our field observations of mapped Pleistocene and Holocene surface exposures in the south Texas study area (cf. geologic maps in BROWN et al., 1980).

North of the RG delta proper, facies of the Beaumont For-

mation of late Pleistocene age are exposed along and north of the Arroyo Colorado (insert, Figure 1). These deposits commonly include sandy silt and silty clay interbedded with fine- to coarse-grained sand layers. The muds are gray, tan and light to dark brown and very stiff to hard (penetrometer readings to 4.0 or more); they commonly include calcareous nodules, are partially cemented and show iron-stained mottling patterns. Finer-grained units usually contain little to no shell and plant matter. Radiocarbon dates obtained for these sediment facies exceed 10,000 years B.P. (BANFIELD, 1998).

Based on comparison with the above descriptions, we identified material of Pleistocene age in some Corps of Engineer core sections analyzed in this study (Figure 2), primarily in lower parts of borings to recovered depths of 18 m. As in Beaumont surface exposures, these strata comprise mostly dark grayish brown (10YR 4/2), brown (10YR 5/3, 10YR 5/4, 10YR 3/2) and dark grey (10YR 4/1, 10YR 5/1) silt-rich mud units that locally include calcareous nodules. Iron-oxide coated grains range in color from pale and dark yellowish orange to more vivid orange and reddish brown. Cored sediment, comparable to surface exposed Pleistocene Beaumont facies described above, is usually very stiff to hard and characterized by penetrometer values that approximate or exceed 4.0 (unpublished core records, U.S. Army Corps of Engineers, Galveston District). Proportions of sand in such samples are highly variable (0.0 to >90%; Table 2), and sedimentary structures identified in these core facies indicate aqueous (probably fluvial) and wind-blown origins.

Elsewhere in the study area, cored sections recovered above the Pleistocene sequence locally comprise a grey to tan sand layer that ranges to 6 m in thickness (BROWN et al., 1980; their figure 20) or several thinner sand strata (MORTON and PRICE, 1987, their figure 11). This laterally extensive sand-rich section, positioned beneath mid- to upper Holocene deltaic strata (the latter dated as younger than ~7000 years B.P.; FULTON, 1976; PRYOR and FULTON, 1978), is interpreted as a late Pleistocene to early Holocene transgressive sand facies (cf. SCRUTON, 1960).

Most of the deltaic plain surface of late Holocene age is characterized by gray and tan to brown, silt-rich deposits (BECK and HENDRICKSON, 1928; RETZLER et al., 1945; FULTON, 1976). The subsurface Holocene section (in excavations and cores) comprises tan and light brown to grey and olive, soft to stiff mud-rich facies interbedded with thin silt and sand strata. These Holocene deposits may include variable amounts of shell and plant matter (usually higher proportions than in Pleistocene sections) and, locally, evaporite (caliche) layers.

Core analysis shows a seaward increase in thickness of the Holocene deltaic section: from <5 m on the margins of the RG lower valley, delta apex and near Arroyo Colorado, to ~25–30 m in some areas underlying distributary channels and the Gulf coast, including areas of southern Laguna Madre and seaward of Brazos-Santiago Pass inlet at the Gulf of Mexico (LE BLANC, 1958; FULTON, 1976; MORTON and PRICE, 1987; unpublished Corps of Engineers core logs). Farther offshore, on the inner to mid-shelf, seismic profiles and cores reveal thinning of the Holocene section to ~15 m or
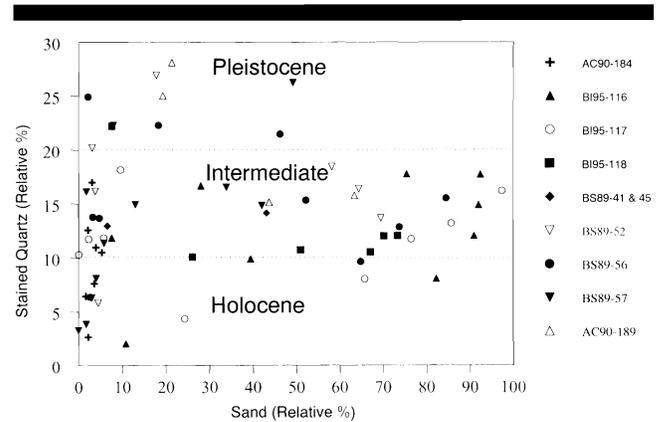

Figure 6. Relative percentages of iron-stained quartz grain versus sand plotted for 63 Rio Grande delta core samples. Superposed on the diagram are three stained-grain fields: <10% stained quartz grains identifies samples of Holocene age; intermediate values of 10–19.9% stained quartz in samples of reworked, but unspecified, age and origin; and >20% stained quartz helps identify Pleistocene core samples. Explanation in text.

less (BERRYHILL, 1975; BERRYHILL et al., 1976, 1987; BANFIELD, 1998).

We note that iron-stained grains, in both Holocene and Pleistocene sections and in the modern RG channel (on the delta plain and up-valley from the delta), are generally similar, i.e. red to brownish red (10YR 3/6, 10YR 4/6, 10YR 4/8), yellow (2.5Y 8/6, 10YR 8/6) and orange in color as viewed with a binocular microscope.

Identifying a Third (Intermediate) Lithofacies

Petrologic analyses of RG core samples are plotted on a diagram showing relative percentages of iron-coated quartz grains versus sand (Figure 6). Two end-member lithofacies are observed. Very stiff to hard mud samples from strata in the lower part of some borings, interpreted as Pleistocene, record proportions of partially plus fully stained grains that usually exceed 20%, and sand values ranging to ~50%. In contrast, some RG sediment samples in the upper part of borings, interpreted here as Holocene, comprise lower proportions of partially plus fully stained grains (to <10%) and of sand (to <10%). These two subsurface end-member facies correlate well with Pleistocene and Holocene units identified in the field.

The problem in the RG delta, as recorded by Figure 6, is that most such plots of core samples do not occupy distinct Holocene or Pleistocene end-member fields. Rather, the largest group of RG core samples is characterized by petrologic attributes that differ from, but are intermediate with, the two depositional sequences identified above as Pleistocene and Holocene. This is unlike the pattern of distinctly higher proportions of stained grains and sand in Pleistocene than in overlying Holocene deposits as observed in the late Quaternary record of the Nile, Ganges, Yangtze and Mississippi depocenters (COLEMAN, 1982; COUTELLIER and STANLEY, 1987; CHEN and STANLEY, 1993; STANLEY and HAIT, 2000; STANLEY et al., 2000).
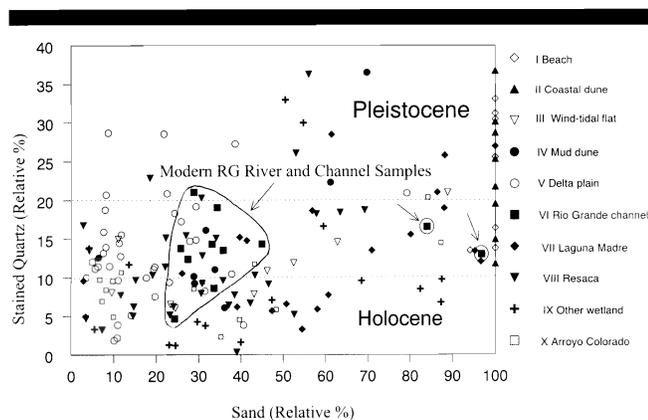
Figure 7. Relative percentages of iron-stained quartz grain versus sand plotted for 164 surficial samples collected on the Rio Grande deltaic plain. Superposed on the diagram are three stained grain fields: <10% stained quartz grains helps identify Holocene samples; intermediate values (10–19.9%) of stained quartz in samples of reworked, but unspecified, age and origin; and >20% stained quartz helps identify Pleistocene core samples. Note field of modern Rio Grande channel samples (9 of 11 samples) and 2 isolated samples (see arrows), collected on deltaic plain, that comprise mostly intermediate proportions of stained particles. Explanation in text.

This RG silt-rich intermediate lithofacies, not reported in other deltas, actually comprises the majority (62%) of core samples we examined. It is defined by intermediate values (10 to 19.9%) of partially plus fully stained quartz and highly variable proportions of sand (Figure 6). Some RG core samples, recovered along the Brownsville Ship Channel and Arroyo Colorado and comprising an intermediate to high content of iron-coated grains, are attributed to 'spoil' material, *i.e.* artificial mixes of dredged Holocene and Pleistocene sediment released near frequently maintained (widened, deepened) navigation channels and post-dredging shoal material. However, not all subsurface samples of this 'intermediate' category are necessarily of such dredge-mix, older reworked nor of post-dredging shoal origin. By their presence at shallow depths in cores and associated radiocarbon dates obtained by us [870±40 (Beta-145127) and 2740±40 (Beta-145128) uncalibrated radiocarbon years before present, respectively 3.1 and 3.4 m from the top of cores BI95-117 and BS89-41; AMS dated using plant material], we recognize that a number of such samples with intermediate to large proportions of stained quartz are of late Holocene age and deposited by natural deltaic processes.

PROVENANCE OF STAINED-QUARTZ GRAINS

The overall relationship among iron-stained quartz and sand content in surficial sediment and RG depositional environment is weak. This is illustrated by a diagram (Figure 7) on which have been plotted the relative percentages of coated-quartz grains versus sand for all 164 samples collected in the 10 deltaic environments. Nonetheless, some interpretations can be made on the basis of plotted data in Figure 7:

- Of the ten modern deltaic environments, only the surficial RG channel (VI) samples (9 of 11) occupy a relatively dis-

tinct sand and iron-stained grain field (delineated in Figures 4 and 7); Rio Grande channel sediment appears to best retain its original fluvial transport imprint, *i.e.* naturally reworked sediment that comprises intermediate to high proportions of iron-stained quartz (Table 3) dispersed prior to emplacement of dams from RG drainage basin source areas (references in CHURCH, 2000; PEREZ-ARLUCEAN *et al.*, 2000) downvalley to the delta.

- Samples (n = 16) of Gulf coast beach (I) and dune (II) are distinctly grouped by grain size (almost entirely very well sorted sand), and those of the delta plain proper (V, n = 36) also form a general grouping by sand content, albeit much less well defined. However, in contrast with group VI, samples from I, II and V record a broader range of stained-grain values. Sediment from these latter three environments, comprising intermediate to high proportions of stained quartz, likely records transport of reworked material from other and/or earlier depositional settings along the delta margin.

- As a group, samples (n = 45) from wind-tidal flat (III), Laguna Madre (VII) and Arroyo Colorado (X) facies on Figure 6 indicate a less distinct distribution of stained-grain and sand values. A generally positive relation between these two parameters is recorded, although data points occupy irregular fields on the diagram. These facies patterns, while retaining a sediment transport imprint, also suggest subsequent modification by unspecified (natural or anthropogenic or both) reworking processes.

- The 3 remaining environments [mud dunes (IV), resacas (VIII), other wetlands (IX)], comprising about one-third of all examined samples (n = 56), are unlike the other 7 depositional settings in that stained quartz-sand data points are randomly distributed. For these 3 facies that show no coherent relation among petrologic factors and depositional environments, we postulate several episodes of reworking of older deposits by recent natural transport processes, and perhaps also by human activity.

To obtain additional information on the origin of the RG delta's surficial cover, three stained-grain fields are superposed on the plotted sample data in Figure 6. On the basis of comparison with subsurface core data plotted in Figure 6 and RG up-valley channel data listed in Table 3, surficial deltaic samples (n = 31) with highest proportions (>20%) of iron-coated grains are attributed primarily to a derivation from Pleistocene and/or older source materials. In contrast, nearly 2/5 of surficial samples (n = 64) are characterized by low proportions (<10%) of stained grains; these are assigned a Holocene origin on the basis of comparison with Holocene field exposures and core data plotted in Figure 6.

The third surficial sediment category, the one that comprises intermediate proportions of stained grains (10 to 19.9%), is of special interest here. In fact, this sediment type, also characterized by highly variable sand content, constitutes a majority (42%) of all examined deltaic surface samples (n = 69). Such RG delta samples are not clearly attributable to either Holocene or Pleistocene sources, but appear to record a mix of recent and older sediment at the delta surface.

DISPERSAL OF REWORKED COATED GRAINS TO THE DELTA

Several processes account for the natural, syndepositional introduction of Pleistocene and older material with substantial stained quartz content in Holocene to modern sediment of the RG deltaic cover. The highest proportions of iron-stained particles occur in modern Gulf Coast beaches and dunes, suggesting the importance of reworking in a landward direction of pre-Holocene sand-size material. This process has involved active erosion of older material from the Gulf shelf, and its displacement to the coast by nearshore processes (LOHSE, 1952; CURRAY, 1960; VAN ANDEL, 1960; GARNER, 1967; WATSON, 1971; WITHERS and MAZZULLO, 1983). Northerly oriented wave-driven shelf and coastal currents are sufficiently strong to winnow and disperse older relict material from the shelf and also from wave-cut shorelines, including those located to the south of the present delta coastal margin.

The even larger deltaic surface area covered by surficial sediment with intermediate to large amounts of stained-grains, associated with highly variable amounts of sand content in the 8 mud-rich environments, strongly suggests the importance of down-valley transport of reworked material to the RG delta. Until recently, Pleistocene and older materials with high proportions of stained, coarser-grained particles (Table 3) were introduced into the somewhat finer-grained Holocene sediment cover of the modern deltaic plain. Of the natural processes, pre-dam flooding by the RG river was of primary importance when particles of Pleistocene and older exposures in up-river sectors were eroded and displaced in high quantity by fluvial processes to the delta and Gulf. Support for this postulate is provided by three separate sample data sets that help identify sources of intermediate to high amounts of partially and fully stained quartz: (1) most samples collected in modern RG channel sites on the deltaic plain proper (designated fields in Figure 7); (2) the 8 modern RG channel samples (Table 3) collected in southern New Mexico, with proportions of partially plus fully stained-grain values ranging from ~11 to ~33% (i.e. 2 intermediate and 6 highly stained types); and (3) many surficial samples collected in the least artificially disturbed areas of the deltaic plain, including Laguna Atascosa National Wildlife Refuge and several other isolated areas (Figure 5). Surficial sample data record the pre-dam transport of intermediate to relatively high proportions of iron-stained quartz to these now-protected (3) localities. It is of special note that proportions of partially plus fully stained values measured in all 3 data sets cited above are comparable with those recorded for surficial RG deltaic plain samples.

Some Quaternary climate fluctuations recorded in the up-valley region (ALLEN and ANDERSON, 2000) likely favored conditions leading to the iron-coating of grains, but the timing and specific processes of iron-film development and quartz coating in the RG drainage basin as yet remain undefined. Possible in situ iron coating by soil formation and ground-water geochemical processes in the delta proper during the Holocene is not precluded. Moreover, activity of both plant and soil biota are capable of reworking vertically the older, underlying soil horizons. It appears that interaction of multiple natural processes is responsible for the introduction of most stained-quartz grain material at the modern RG delta surface.

Human activity, in addition to natural processes, has likely introduced and dispersed a significant amount of older material (Holocene, but perhaps also some Pleistocene) over much of the delta surface, especially during the past century. Most of the deltaic region has been subject to massive clearing of trees (especially mesquite) and other vegetation, deep tilling and leveling of fields, and emplacement of a dense network of closely-spaced irrigation, water reservoir and navigation structures. In addition, levees and roads criss-cross and artificially mold the entire delta surface in the Texas sector (U.S. GEOLOGICAL SURVEY, 1992). Maps showing human useage and environmental change published by BROWN et al. (1980), and also descriptions in tight-grid archaeological and salvage survey reports (DAY et al., 1981; BOUSMAN and BAILEY, 1990; GUSTAVSON and COLLINS, 1998) document the nature of the extensively modified delta surface. These recent changes would account for probable widespread displacement across much of the present deltaic plain of substantial volumes of subsurface (largely mid- and late Holocene) material as spoil and artificially reworked sediment. We anticipate that, as a result of increasing human activity in this region, the supply of iron-coated quartz grains derived from exposure of formerly buried, pre-modern sediment will continue to be introduced locally at the delta surface.

CONCLUSIONS

The stained quartz record in the RG delta does not show a pattern of low proportions of iron-coated quartz particles in the Holocene deltaic section and modern plain surface versus considerably higher proportions of such grains in the underlying Pleistocene strata, as recorded in some other deltas. Rather, the RG delta serves as an example of a depocenter that has received a large proportion of stained quartz by natural reworking processes during the Holocene, possibly supplemented by in situ formation of coated grains. The present deltaic sediment cover is interpreted as a 'palimpsest' comprising a mix of reworked modern and relict material.

Anthropogenic activity, however, has been effective in almost completely altering natural hydrological and sedimentation patterns across most of the RG delta in considerably less time than in more populated deltas such as the Nile, Ganges-Brahmaputra and Yangtze. This is all the more noteworthy when it is recalled that human settlements have occupied these other deltas for hundreds to thousands of years, while the RG depocenter for much of its history, and even to the early 18th century, was occupied seasonally by only small groups of Native American hunters and gatherers and then permanently by relatively few settlers (DAY et al., 1981; BOUSMAN and BAILEY, 1990; GUSTAVSON and COLLINS, 1998). In a remarkably short timespan, primarily the past ~100 years, the RG system has further evolved to what is now a mostly destructional phase delta (cf. STANLEY and WARNE, 1998) as a result of interaction of the diminished role of natural processes but much increased human pressure.

This study shows, however, that rather than a simple mixing of Pleistocene sediment into Holocene deposits by recent human activity, the relatively high proportions of stained quartz grains in Holocene deltaic sections are largely a function of natural pre-dam stained-grain provenance and dispersal to the delta.

Our field observations, coupled with examination of recent maps and aerial photographs that show extensive modification of most of the deltaic plain, indicate that anthropogenic activity has now replaced natural processes as the primary means of introducing older, for the most-part Holocene, material into younger RG surficial sediment sections. In view of the rapid evolution of the depocenter, there is an obvious need to more accurately measure the nature and rate of change affecting the lower valley and delta region. For this, we envision a combined petrological-geochemical research effort to evaluate present effects of this much-increased human activity on the RG delta surface and determine their potential impact on human health and deltaic ecosystem sustainability.

ACKNOWLEDGEMENTS

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