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Sedimentation along the Eastern Chenier Plain Coast: Down Drift Impact of a Delta Complex Shift

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ABSTRACT

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The Mississippi River Chenier Plain is a shore parallel landform (down-drift from the Atchafalaya distributary of the Mississippi River) consisting of an alternating series of transgressive sand-shell ridges and regressive, progradational mudflats. The late 1940s shift of 1/3 of the flow of the Mississippi to the newly developing Atchafalaya delta complex to the west has resulted in injection of the river waters and suspended sediment into the westward flowing currents of the coastal current system. This has reactivated the dormant processes of mud accumulation along this coast. These environmental circumstances have provided the opportunity to (1) investigate the depositional processes of the prograding, fine grained, mud flat facies of the open Chenier Plain coast and (2) to test the hypothesis that the impacts of the frequent cold front passages of fall, winter and spring exceed those of the occasional and more localized hurricane in shaping the coast and powering the dominant sedimentary processes.

We conducted field investigations with the benefit of multi-scale, time series environmental surveillance by remote sensing systems, including airborne and satellite sensors. These systems provided invaluable new information on areal geomorphic patterns and the behavior of the coastal waters. This is a classic case of weather systems impacting inner shelf waters and sediments and causing the development of a new landform. It is clear that mud flats of the eastern chenier plain are prograding seaward, as well as progressively growing in a westerly direction.

ADDITIONAL INDEX WORDS: *Remote sensing, satellite images, sediment transport, storm surge, cold front, hurricanes, coastal geomorphology, coastal sedimentation, coastal erosion.*

INTRODUCTION

Because of its 300 km shorter route to the Gulf, the Atchafalaya Distributary would have captured the entire Mississippi discharge in the 1940's but for the Old River Control Structure, built and maintained by the U.S. Army Corps of Engineers. This structure allows the Red River and one-third of the Mississippi to flow down the Atchafalaya distributary. The increased influx of suspended sediment into the westward flowing coastal current has now re-initiated accumulation of the mud facies of the Chenier Plain sedimentation.

The Delta Complex Shift

The Holocene delta plain of the Mississippi River evolved in a series of major delta-building events. On the larger scale, it is a cyclic process of stream capture, where the steepest gradient to the sea captures an existing prograding delta complex or lobe creating a flood of sediment and water in a new pathway. At smaller scales, the cycle basically involves a breaching of natural levees and spillage of water and sediment into the shallow, adjacent bays to create a sub-delta or crevasse-splay. Progressively the bay fills, the crevasse is closed, and gradually compactional subsidence creates a new bay, and the cycle repeats. COLEMAN and GAGLIANO (1964) were the first to recognize that there is an orderly repetition of sub-delta and crevasse-splay deposition within a major delta. They defined the cyclic depositional development of delta lobes and their smaller scale sub-delta components. As outlined recently by ROBERTS (1997) the hierarchical structure of the cyclically evolving delta components may be enumerated as follows:

> "Holocene deltaic deposits of the Mississippi River are (1) delta plain (1st order), (2) delta complex (2nd order), (3) delta lobe (3rd order), sub-delta (4th order), and crevasse-splay or over-bank splay (5th order). This series of "deltas within deltas" results from cyclic deposition that occurs on different temporal and spatial scales."

The most recent change is the trend toward the abandonment of the Balize Delta complex (modern birdfoot delta) and a switch to the Atchafalaya Delta complex (Figure 1). Because of the damaging consequences for the regional economy the switch is being controlled by the U.S. Army Corps of Engineers, allowing only one-third of the Mississippi River discharge down the Atchafalaya channel. The fine sands and muds have filled in the lakes within the Atchafalaya basin (a regional topographic low) and are now spilling into the Atchafalaya Bay. Here they are building the bayhead Atchafa-

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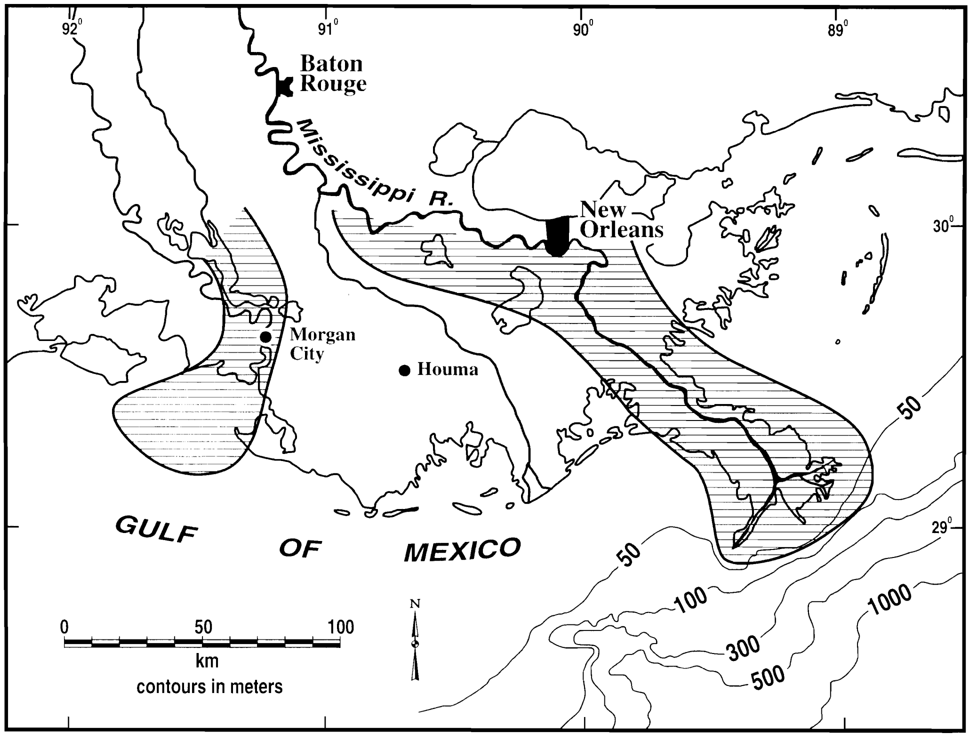

Figure 1. The Mississippi River Deltaic Plain with the two most recently developed delta complexes: The Balize (birdfoot) delta complex to the east with a life span of 1000 yrs BP to the present and a surface area of 9,930 km², and the Atchafalaya Bay head delta complex to the west, with a life span of 400 yrs BP up to the present and an area of 2,800 km².

laya and Wax Lake outlet deltas with the sand fraction and the down-drift Chenier Plain with the clays and silts.

Chenier Plain

The Chenier Plain of the Mississippi River is a down-drift coastal erosion and deposition zone directly influenced by the delta complex or lobe shifts. The Chenier Plain stretches some 200 km from southwest Louisiana to Texas. It ranges in width between 20 and 30 km and exhibits elevations of upward of 2 m (PENLAND and SUTER, 1989). It is a shore-parallel zone of sediments regionally "sorted" into alternating transgressive clastic ridges separated by prograding, regressive mudflats.

The Chenier Plain evolved during Holocene time. These coastal sediments were deposited as a sequence of prograding mudflats with coarse fraction intermittently reworked into sandy or shelly ridges (HOYT, 1969). Episodes of mud flat progradation are tied to pulses of sediment transported westward along the inner continental shelf. This occurs during periods when a major distributary of the Mississippi River is located in the western portion of the delta plain. The geomorphology of the Chenier Plain coast includes mudflats, and beach ridges, with scattered mud washover flats, marsh platforms, sandy washover flats, and sandy terraces. Activation of the Atchafalaya-Wax Lake Outlet distributaries has re-initiated deposition of fine-grained sediments along the eastern Chenier Plain, a zone of rapid seaward progradation that is growing westward as well (see Figure 2). The name chenier comes from the Cajun-French term "chene" for oak, the dominant tree species found only on the crests of the shell ridges.

Preliminary studies have indicated that wind forcing plays a major role in sediment resuspension processes in and seaward of the Atchafalaya Bay and in sediment resuspension processes on the continental shelf (ROBERTS, *et al.,* 1987, HUH *et al.,* 1991; WALKER and ROUSE, 1993; WALKER, 1996; WALKER and HAMMACK, 1999). The purpose of this paper is to report on the atmospherically induced suspended sediment transport, the coastal sedimentation processes, and the resulting coastal geomorphology.

The Cold Front Model and Coastal Processes

Some 30–40 cold fronts pass over the Louisiana coastal region each year primarily between the months of October and April. The cold fronts display a spatially and temporally ordered system of changes in surface wind speed, wind direction, barometric pressure, temperature and humidity (ROBERTS *et al.,* 1987). Figure 3 depicts idealized model of the surface wind fields associated with a cold front as it advances from NW to SE. The cold front approaching the coast consists of three phases: (1) the pre-frontal phase in which southerly winds strengthen, and warm humid atmospheric conditions develop with falling barometric pressure; (2) the frontal passage phase, with strong and variable winds and a characteristic sharp shift of wind direction from a southerly to a west-

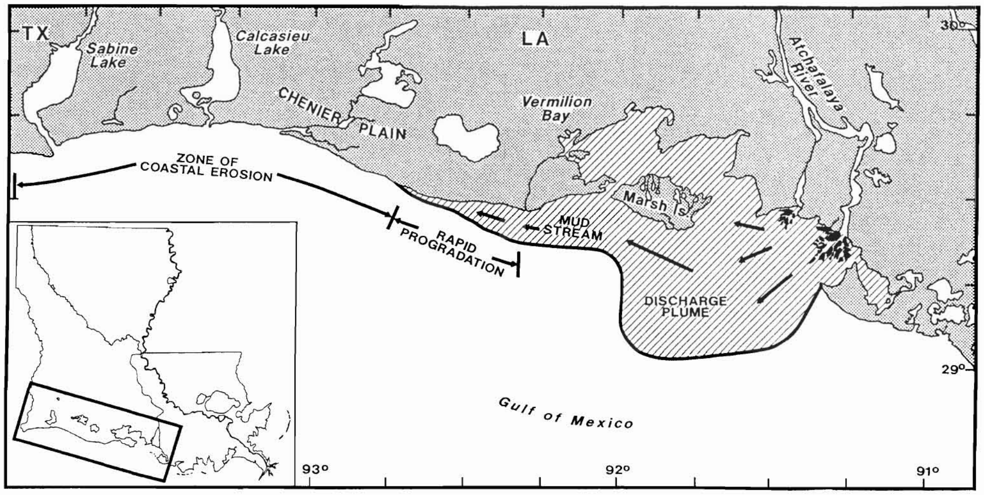

Figure 2. The Atchafalaya-Chenier Plain sedimentary system with river discharge that provides sediment for accretion in the eastern-most portion of the Chenier Plain coast.

erly component; and, (3) the post-frontal or cold air outbreak phase (behind the front) in which winds become northerly, and air temperature and humidity decrease significantly with rising barometric pressure. Cold front systems exhibit considerable variability in their behavior. Some pass through rapidly, while others may stall for several days, and still others may back-up to form a warm front.

Individual cold fronts vary significantly in "style" of forcing. The natural variability of cold fronts through the season includes their orientation, direction of propagation (west to east or north to south), strength (pressure gradient, wind field, temperature and humidity characteristics), and speed of propagation. Stalling of a front just landward of the coast is a most effective mechanism for altering the coastal environment. It operates by prolonging the attack by the long fetched seas, sustaining storm surge, inducing rise of sea level, and by initiating intense precipitation, and local run-off. Precipitation associated with cold fronts in general is torrential and violent but of short duration (<20 min.). Drainage is slow and inefficient due to the low relief (0.5–1.5m) and dense wetlands grasses and shrubs. The result is local flooding and backup in main channels.

The response of the coast to cold front forcing includes (1) rising sea level caused by wind setup and the inverse barometer effect with intrusion of inner shelf waters against the coast and into bays and estuaries; (2) increasing effects of waves set up by long-fetched southerly winds; (3) wind shift to northerly direction after cold front passage, which sets sea level down and initially reduces, then reverses inshore wave action. Dropping water levels induce marsh drainage and discharge of sediment-laden bay waters onto the inner continental shelf. Wave attack is observed to erode sandy coasts and accumulate sediment along muddy coasts. A cold front may extend geographically for 2000 km in length.

The Hurricane Model and Its Impact on the Coast

Hurricanes are the most powerful geological agents, providing very severe winds, rainfall, waves and storm surge. They are, however, small in spatial scale so that their impact is geographically limited. Hurricane Andrew (Aug. 1992), for example, was a Category 4 hurricane, and one of the costliest disasters in modern time. When it crossed south Florida it impacted a 168 km swath of the state. By way of contrast, cold fronts can extend for thousands of kilometers. Figure 4 illustrates the plan view of a hurricane and the quadrant of maximum surface winds. Hurricanes are infrequent compared to cold front passages. For example, for the 92 years between 1900 and 1992 the Louisiana coast was hit by 38 hurricanes of which only 8 were class 4 or greater. The trajectory of these storms is often erratic and quite unpredictable, even by the sophisticated National Hurricane Center models. Storm overwash and backwash create massive changes with the most severe attack occurring in the leading right-hand quadrant where forward motion of the storm is added to the surface winds of the strong cyclonic circulation. There is a sediment type influence on the effect of storm impact. Sand dominated coasts are badly eroded, with storms dispersing coastal sands both seaward and landward. Muddy coasts build from the landward surge of fluid mud and coastal water (a mixture of brackish and fresh water), and the coastal water backwash flows back into the Gulf, stranding the fluid mud.

METHODS

The experiment plan included the following observations and measurements.

1) Observational traverses were made along the coast immediately after cold front passages, via small boats along the inland canals and offshore waters, surveying along the shell

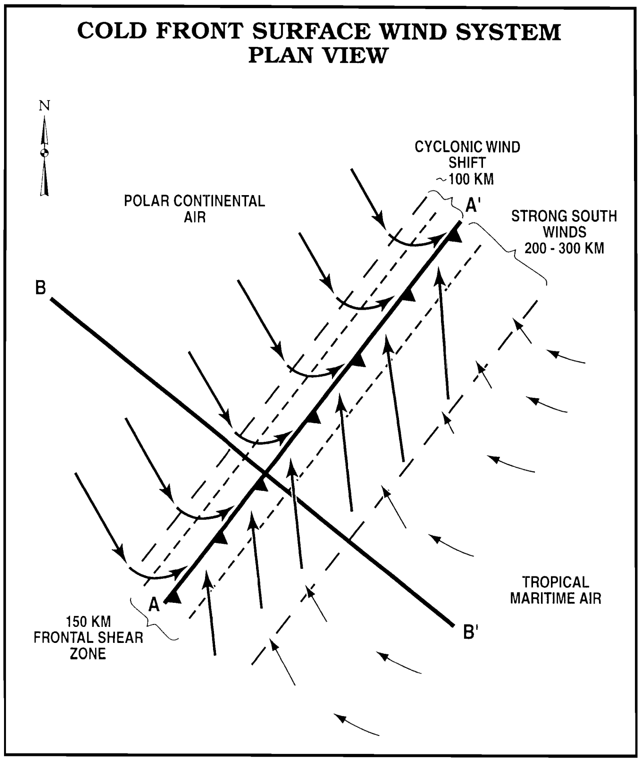

Figure 3. Schematic diagram of a cold front weather system and an idealized model of the surface wind conditions, converging from northwest and southeast on the low pressure trough with a squall line along the shear zone. The fronts burst out over the Gulf of Mexico, inducing major changes in the inner shelf circulation, temperature, storm surge and wave action. Modified from Huh, et al., 1991.

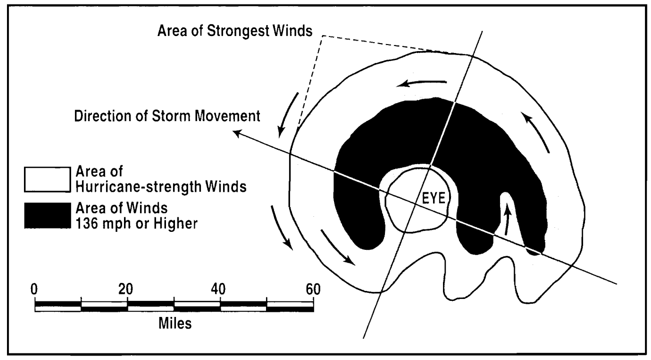

Figure 4. Schematic diagram of a hurricane, showing an example of its dimensions and the distribution of winds around the eye. Modified from Henry, et al., 1961.

ridges, and airboat traverses over the very shallow water areas and mudflats. These field observations provided information on sedimentary structures and the temporal evolution of newly deposited mud sheets. This provided the physical characteristics of both new and older coastal sediment deposits, which are largely mud with small quantities of quartz sand and shell hash granules.

2) High and low altitude aircraft overflights were conducted by NASA two or three times a year since 1994, with data acquisitions including scanning multispectral radiometers and color aerial photography. Aerial photography provided very high-resolution imagery of the sedimentary environments and was particularly useful in making measurements of distances and dimensions of sedimentary features. Land building processes and their progress were monitored by repeated aircraft overflights to acquire high resolution imagery of the evolving coastal geomorphology.

(3) This study has exploited the digital imagery acquired by the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA series environmental satellites. These data have been available in real-time, several times daily and archived since June 1988 by the Earth Scan Laboratory of the Coastal Studies Institute. With these data it was possible to observe the distribution and movement of the turbid river discharge waters. The AVHRR provides imagery from five parts of the spectrum: two in the reflected solar visible/near IR range (useful for calculating estimates of suspended sediment concentrations) and three in the thermal infrared range (for computing sea surface temperatures and mapping the SST field). These data have a spatial resolution of 1.1 km at nadir and a swath width of 2800 km (HUH, 1991). The reflected solar radiation channels of the AVHRR, when corrected for atmospheric contamination can provide important information on the surface suspended sediment transport and distribution. Atmospheric correction includes processing to remove the effects of changes in downwelling irradiance, aerosols, Rayleigh scattering and sun glint. The visible and near infrared channels are used in this procedure (STUMPF, 1992). In this study, the calibration algorithm developed by collecting surface water samples off the Balize (bird-foot, Figures 5a and 5b) delta region by helicopter, simultaneously with satellite overpasses in April 1992 (WALKER and ROUSE, 1993; WALKER, 1996).

Using these image data it is possible to map the surface temperatures and turbidities and their patterns using the multichannel sea surface temperature algorithm (MCCLAIN, *et al.,* 1985, not shown) and an aerosol corrected reflectance (STUMPF, 1992) calibrated to suspended sediment concentrations. Hourly wind measurements were obtained from the town of Burrwood, Louisiana, to monitor wind speed and direction changes along the coast. In addition, daily estimates of Atchafalaya River discharge, obtained from the Army Corps of Engineers, were used to interpret the satellite data.

TRANSPORT, DEPOSITION AND STABILIZATION OF FINE-GRAINED SEDIMENTS

Analysis of clear-sky NOAA satellite imagery from 1989 through 1994 has revealed that the classical idea of Atchafalaya River sediments flowing west along the coast within the Atchafalaya mud stream (ROBERTS, *et al.,* 1987) occurs primarily under the influence of southeasterly and northeasterly winds, when a westward-flowing coastal current prevails. Easterly winds (southeasterly through northeasterly) predominate during all seasons except summer when relatively weak southwest winds are most frequent (WALKER and

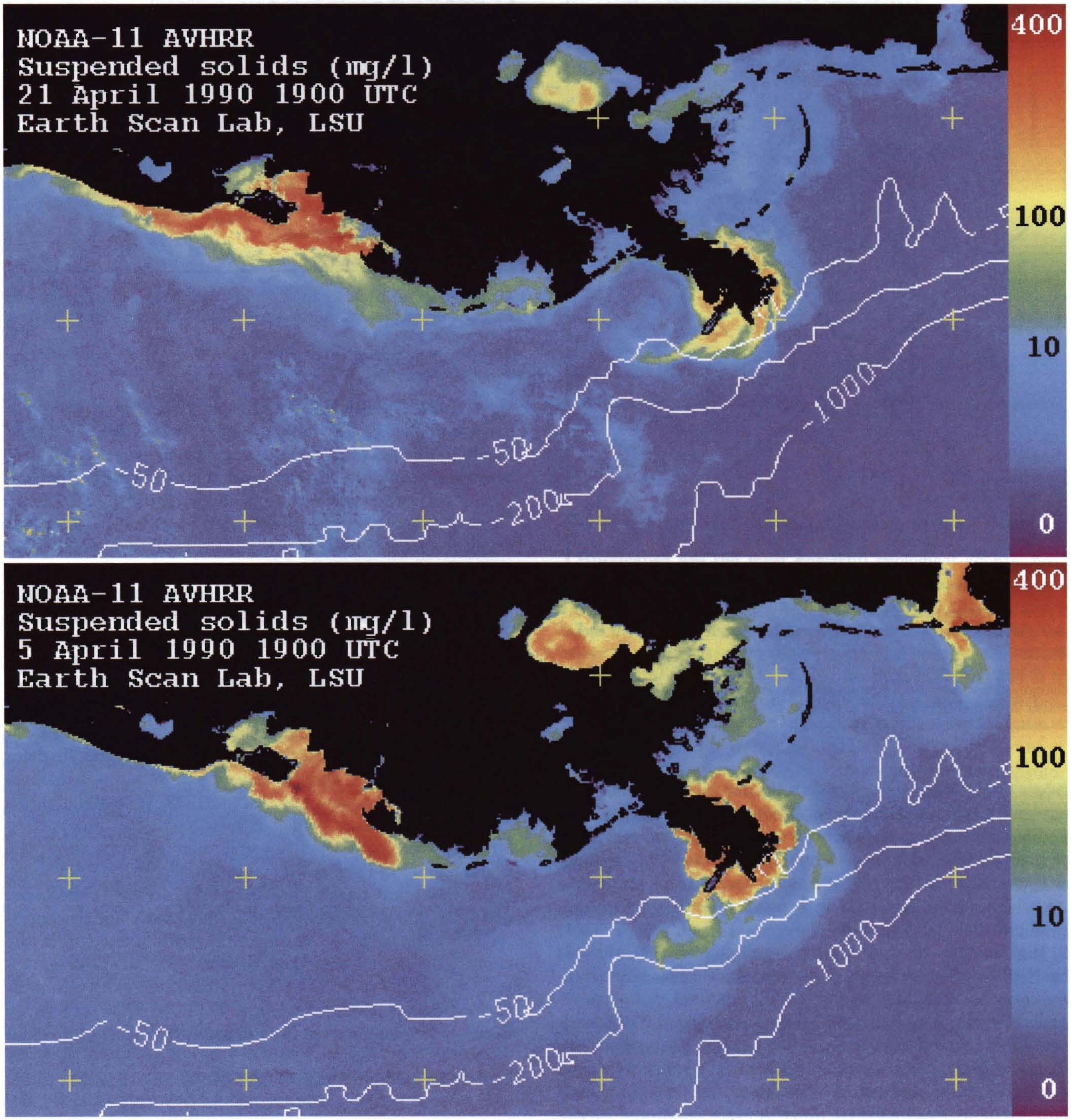

Figure 5a. NOAA satellite AVHRR reflected solar radiation, calibrated to suspended sediment content, April 21, 1990 (1900Z), illustrating the transport of suspended sediment westward from the Atchafalaya River mouth to the Chenier Plain, the "normal" coastal current. Figure 5b. NOAA satellite AVHRR satellite image, April 5, 1990 reflected solar radiation, calibrated to suspended sediment. This change in plume pattern is cause by wind shift from SE to SW prior to a cold front passage and resulted from 12 hours of weak to moderate SW winds (< 10 kts.).

HAMMACK, 1999). The NOAA satellite image of April 21, 1990 (1900Z) reveals, as expected, that the Balize and the Atchafalaya deltas have the highest suspended sediment concentrations along the Louisiana coast (Figure 5a). This image was acquired during the spring flood of the Mississippi River after 3 days of continuous southeasterly wind forcing of 8 to 15 knots (4–8 m/s). The highest suspended sediment concentrations (>100 mg/l) were observed in Atchafalaya Bay, bays immediately to the west, and in a 10 km-wide zone extending westward along the Chenier Plain coast (Figures 5a and b).

Cold front passages subject the coastal zone to episodes of a progressively rotational wind field. Wind direction generally shifts from southeast to southwest prior to frontal passage, from southwest to northwest with frontal passage, and from northwest to northeast with intrusion of the high pressure system in the lee of the cold front. The April 5, 1990 image (Figure 5b) illustrates surface suspended sediment distribution along the coast after 12 hours of weak-to-moderate southwesterly wind forcing (<5 m/s). The wind shift appeared to have reversed the prevailing westward flow of sediment to the Chenier Plain as the sediment plume was oriented towards the southeast.

Repeated satellite observations showed that the less turbid portions of the Atchafalaya plume (10–100 mg/l) were observed to extend 30 to 40 km seaward. This wider zone of turbid water most probably resulted from resuspension of unconsolidated sediments seaward of the bay by wind-waves. WALKER *et al.* (1992) showed that under moderate-to-high wind conditions (>9 m/s) much of the Atchafalaya sediment plume observed in satellite data results from resuspension of bottom sediment caused by wind-waves rather that from newly discharged water.

Fine-grained sediments and river water are transported from the mouth of Atchafalaya Bay westward, forming the mud stream that converges along the coast (Figure 5a). This westward flow of turbid cold waters is evident from observations with the daily NOAA satellite imagery of sea surface turbidity and temperature patterns. It is also evidenced by the masses of freshwater hyacinth that are discharged only by the Atchafalaya River Basin in the fall and end up strewn along the Chenier Plain coast. Literally tons of decaying organic matter are heaped along the newly built land. Shore face deposition involves formation of a mud bar (Figure 6a) or a wide mud flat (Figure 6b).

The highly turbid water and fluid muds shown in Figure 6a–d are heaved up over the strand and penetrate landward as storm surge driven overwashes. We have observed small wavelets (3–10 cm) runup loaded with sediment, in suspension until the forward motion stops. Then the sediment load of silty mud is instantaneously dropped and crystal clear water runs back into the Gulf. Figure 6c shows a boat track a few hours old, partially covered by a thin (several cm thick) layer of mud. Figure 6d shows the rheological pattern of the mud slowly flowing seaward, "slumping seaward" down a very low slope.

With the offshore return of the storm surge, the water outruns the fluid mud, leaving it stranded, de-watering, changing from a "heavy cream" consistency to a "jello" or "yogurt-like" consistency (see Figure 7a). The newly deposited mud undergoes a series of changes that stabilize it, forming new land. Behind each cold front are strong winds bringing cold, dry air. Seaward gravitational draining, wind-driven evaporation, plus solar evaporation desiccate the mud, generating contractional mud-cracks (see Figure 7 b, c and d).

The processes that operate to stabilize these new sediment accumulations include:

(1) The presence of fluid mud underlying the surface waters of the inner shelf, dampens the wind wave attack and converts wind waves to a train of solitary wave crests (see Figure 6a). These waves cause great runup and overwash, but little longshore transport.
(2) The conversion of fine-grained sediment in fluid sheets to sturdy cobbles of dried clay (figure 6a–d) that are hard to erode and now armor the coast from current and wave attack.
(3) Organic binding of the fine-grained sediment. The profusion of Panicum sp. cane, with its network of interlocking root systems, plus algal "mats" bind the newly deposited mud into a fertile soil protected from wave attack.
(4) In the fall of the year, water hyacinth breaks loose from the fresh water swamp environments of the Atchafalaya Basin in prodigious quantities. It is discharged with fresh water and sediment, transported westward and strewn along Chenier Plain coast. It further protects the coast from wave erosion, at least temporarily.

At this stage, an increment of coastal progradation has been established and the eastern Chenier Plain regressive facies has prograded a step further into the Gulf of Mexico. Figure 8 shows the results of a decade of sediment accumulation in the eastern Chenier Plain coast, which may be seen in the color aerial photographic record of these environments between January 27, 1987 to April 4th, 1998.

DISCUSSION

Approximately 25% of the coastline of the Americas (DOLAN *et al.*, 1972) consists of muddy, sedimentary environments. Critical differences occur between the coastal accumulation of fine-grained sediment (clays and silts) and sand-sized sediment. The sands of the dune, beaches and barrier island complexes are dispersed landward and seaward by extreme wave, storm surge, and current activity. These environments are rebuilt, and advance landward under the calmer prevailing conditions. In contrast, the fine-grained sediments once discharged into the ocean flocculate because of sea water salinity and evolve into a slurry, or dense fluid of "heavy cream" or "yogurt-like" consistency, which settles out beneath the surface waters. This fine-grained sediment accumulation continues to evolve and have an important effect on inshore and coastal conditions. It dampens incoming, wind driven gravity waves, absorbing energy through bottom shear, and transforming them into a "parade" of solitary waves, with linear crests impinging on the coast. Individual waves have been observed to leave a thin sheet of semi-fluid mud stranded on the shore face. On a large scale, storm surges transport the fluid mud and seawater as a two-layer sheet, penetrating many meters landward into the coastal marshes.

Figure 6a. Oblique aerial photograph showing a portion of the Chenier Plain coast, a mud bar, solitary waves (crests only) and mud dampening of all wave action just seaward of the mud bar. Figure 6b. Photograph of the "tidal" mud flat, low slope shore face with scattered Panicum sp. colonies developing at the shoreface. Figure 6c. Photograph of "intertidal" mud flat with boat trail exposed in the mid-ground, covered by water in the foreground, and by a newly deposited sheet of mud in the background. Figure 6d. Rheological patterns in the fluid mud as it flows back toward the Gulf just after deposition.

In the return flow to the Gulf, the water, outruns the more viscous fluid mud that becomes stranded. As noted above, the fine-grained sediment after deposition changes rapidly into cobbles and becomes stabilized, colonized, and part of a new shore face.

Fine grained sediment is now being deposited on and is accumulating along the eastern Chenier Plain coast. The width of the newly accumulated mud banks varies along the length of the affected coast, reaching a maximum of 0.7 km over 11 years at the "Triple Canal" site. The newly discharged Atchafalaya sediment is blanketing the zone of rapid progradation, see Figure 2. At the periphery of the Mississippi River delta and delta plain, a regional sediment sorting process is at work. Sandy beaches occur on a deteriorating, a broken chain of, eroding barrier islands. Sandy beaches also occur at the distributary mouths or headlands to the east of the Chenier plain. Fine-grained sediment accumulations occur at the open coast, downdrift from the active distributaries and in the sheltered bays. Ultimately, it is the river channel shifts that distribute the sediment and initiate delta lobe developments in the delta plain. It is the meteorology, the energetic weather systems and associated coastal currents, that redistribute the sediment and reshape the coastal geomorphology.

Hurricanes, by far the most powerful geological agents, are, fortunately, very localized in time and space. They rarely affect a coastal area of greater than 200 km and occur at time intervals of two to three years. Cold fronts, in contrast, extend geographically as far as thousands of kilometers and occur in one-to-two week time intervals through fall, winter and spring of each year.

CONCLUSIONS

Presently, the Mississippi Birdfoot delta has built out over the continental shelf to the edge of the continental slope. Fine-grained sediment, entering the coastal ocean is transported to the continental slope and the adjacent Mississippi

Figure 7a. Profile of a fresh sheet of fluid mud converted to a "tofu-like" consistency. The earliest stage of consolidation after deposition as a fluid mud. The partially consolidated mud is easily breakable by hand. Figure 7b. Freshly deposited mud (several days) with mud cracks developed and sheet of mud penetrating the coastal shrubbery. Figure 7c. A desiccation-cracked mud deposit consolidated into hardened cobbles, firm clay polygons. Figure 7d. A "cobble" beach, desiccated mud-cracked sediment sheets broken up into wave rounded cobbles. A mud-cracked, intact sheet of cobbles preserved to the left.

Canyon. That sediment is discharged seaward, settling in the nearby deep water and thus lost to coastal land building processes. In the Atchafalaya complex, fine-grained sediment is a commodity, rapidly building land. This is possible because of the broad shelf (circa 200 km wide) and very shallow inshore areas. The transition of the eastern Chenier Plain from a transgressive, shell-sand ridge phase to a mud-rich regressive (prograding) mud flat phase is now progressing steadily. This portion of the Chenier Plain is building seaward at an average rate of approximately 50 m/yr.

Storm surge and wave action are observed to "heave" the fluid mud onto the shore face and then be outrun by water back to the Gulf and remain stranded. Single mud sheets, deposited on the coast from waves and storm surges, are observed to range in thickness from 1–2 cm to 16 cm in thickness and are deposited during a solitary wave or a single storm surge at a time scale of a few seconds to a few hours. Wave runup has been observed to carry sediment load, run out of momentum, drop its sediment load, then drain back into the Gulf as crystal clear water. The sedimentary buildup of the Chenier Plain is progressively extending westward, closing up Gulf access channels and building a consolidated mud sheet that extends both seaward and westward. It is quickly colonized by Panicum sp. Cane after deposition. This cane grows to 3 m high, forms a dense cover, and binds sediment with its complex interlocking root system.

Stabilization of the newly deposited mud occurs through five observable processes:

(1) free drainage from the gravitational compaction of the newly deposited mud layer;
(2) drying from evaporation by the strong, cold, dry winds that follow a cold front passage;
(3) daytime solar desiccation "baking" of the mud cracked polygons;
(4) conversion of the muddy, fine-grained shore face to a "cobble beach";

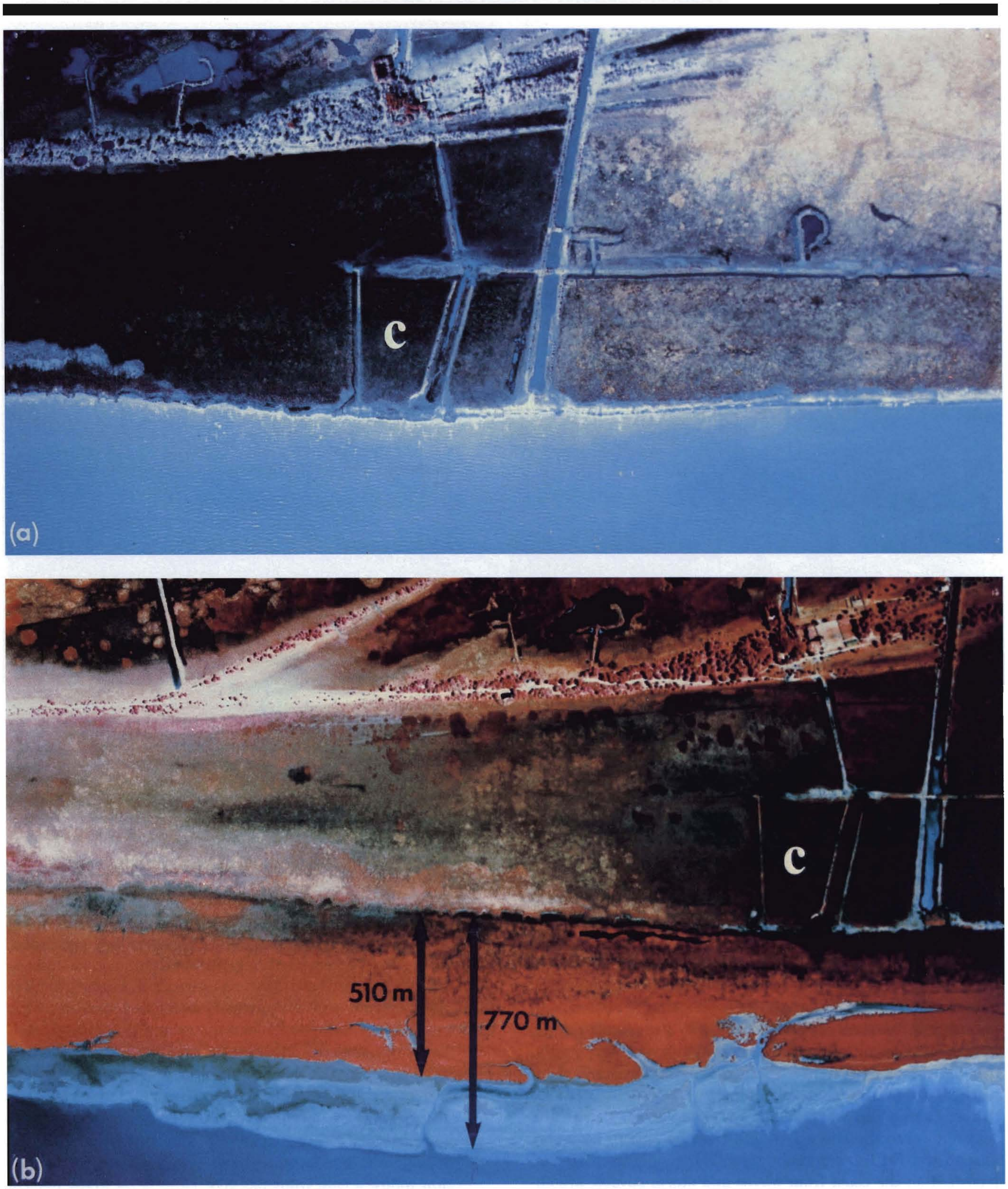

Figure 8. The triple canal site near the eastern margin of the Chenier Plain Coast, the depositional maximum. (a) January 27, 1987, pipeline canals sealed seaward by shell beach. Coast is still a site of erosion. (b) April 4, 1998, Fine-grained sediment deposited as a 510 m-wide zone of plant-colonized mud, plus 260 m of plant-free mud on the shoreface.

(5) colonization by dense growths of Panicum sp., a tall cane with an interlocking root structure;

Repeated NOAA satellite AVHRR imagery have shown that mud deposition is occurring at the location where the coast mud stream converges against the coastline, as revealed by turbidity maps from the atmospherically corrected, reflected visible radiation. Imagery has also revealed that the mud stream flows westward except during perturbations of the prevailing easterly wind field by the passage of weather systems (particularly cold front passages).

Storm surge by a hurricane is much more rare (once every 2–3 years) then those from cold fronts. Hurricanes are few in number and of much more limited regional extent than the near weekly cold fronts of the fall, winter and spring.

These muddy coastal environments are poorly known and difficult to access. In this Atchafalaya Chenier Plain muddy coast, approach from the land is obstructed by the nearly impenetrable Panicum sp. marsh. Approach from the sea is obstructed by tens of meters wide zone of engine clogging gelatinous mud. Air boats provide the best access to these depositional environments.

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