Sediment Instability in the Mississippi River Delta

James M. Coleman, H. Jesse Walker and Warren E. Grabau

Coastal Studies Institute
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

Department of Geography
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

U.S. Army Corps of Engineers, Retired
2 Signal Hill Lane
Vicksburg, MS 39180, U.S.A.

ABSTRACT


One of the first major studies conducted by James P. Morgan was the examination of the structure, nature and origin of mudlumps. The origin of these features, which are virtually unique to the Mississippi River delta, had been the subject of much debate since they were first reported in 1528. Morgan and his colleagues concluded that they are small diapirs that have resulted from upthrusting of plastic clays in response to overloading by distributary mouth bar sands.

These mudlump studies led to further research into sediment instability across the subaqueous delta of the Mississippi. This research, much of it conducted by Morgan’s students, was greatly enhanced as the petroleum industry began to work in deeper water. Eventually side-scan sonar and high-resolution geophysical techniques were added showing the complicated nature of the subaqueous delta front.

This paper summarizes the initial work of Morgan on sediment instability and mudlump formation and discusses the sediment instabilities that occur on the subaqueous delta front off the river mouths.

ADDITIONAL INDEX WORDS: Mudlumps, sediment instability James P. Morgan, Mississippi River Delta.

INTRODUCTION

Deltas are extremely dynamic regions, a fact that was recognized early in the geologic and geomorphic literature. Famous early geologists, such as RIDDLE (1846), LYELL (1847), CREDNER (1878), PRESTWICK (1885), and JOHNSON (1891) commented on the extremely rapid changes in river distributaries, the rapid construction and enlargement of delta plains, and the deposition of vast volumes of sediment in relatively short periods of time. However, it was not until the extensive work of R. J. RUSSELL (1936, 1940, and 1958), H. N. FISK (1944, 1952, and 1961), FISK and McFARLAN (1955), and WELDER (1959) that the truly dynamic nature of deltas was realized. Most of these studies concentrated primarily on the short-term changes in sedimentation patterns, short-term changes in channel morphology and location, and rapid progradation of river mouths. The notion that sediment instability was also a rapid, dynamic factor in the construction of deltas did not become apparent until the work of MORGAN (1951, 1952, and 1961), MORGAN et al. (1968), SHEPARD (1955), COLEMAN (1976), COLEMAN and GARRISON (1977), and COLEMAN et al. (1980). Morgan’s research concentrated on a unique component of the Mississippi River delta, the mudlumps at the mouths of the modern Mississippi River, while the research of Shepard, Coleman, and others concentrated on the subaqueous portion of the delta front.

MUDLUMPS

The Spanish explorer Alvar Nunez Cabeza de Vaca reported that while sailing along a very low, marshy coast on the northern coast of the Gulf of Mexico on 2 November 1528, he had encountered a number of very curious mud islets just offshore. He thus became the first European to be confronted with mudlumps. His description was so precise that there is no doubt that he was describing features that occur off the mouths of the Mississippi. Thus, his account is considered proof (FONTAINE, 1872) that he discovered the mouth of the Mississippi River, some 13 years before Hernando de Soto crossed it far in the interior.

Although, over the years, many attempts, especially by the Spanish and possibly also by the English, had been made to sail into the Mississippi River from the sea, it was not until March 3, 1699 that Pierre le Moyne d’Iberville, a French Canadian, was successful. The same feat was achieved a few months later by an English captain who however turned back after meeting d’Iberville’s brother, Jean Baptiste le Moyne d’Bienville, who was travelling down the river from Bayou Manchac. This is approximately 30 km south of the present-day New Orleans and is known as English Turn. There is little doubt that a major reason for the long delay in negotiating the passage into the river was due to the presence of the mudlumps (WALKER and GRABAU, 1992). Once navigation of the Passes had been demonstrated, ships began to enter the river with increasing frequency, but it remained a challenge. And of course the strange features naturally attracted the attention of the scientific world. Sir Charles Lyell wrote, after visiting the area in 1845 and 1846:

“In this region, where so rapid a conversion is going on from sea into land, a phenomenon occurs which is without parallel, so far as I am aware of, in the delta of any other river. I often heard . . . of the swelling up of the
muddy bottom of the gulf to a height of several feet . . .
and this in places where there had previously been a
depth of several fathoms (Lyell, 1889, 445)."

By the time of the Civil War, the dual problems posed by
the mudlumps (which are markedly concentrated around the
mouths of the passes (Figure 3) and the shallow bars at the
seaward ends of the passes, had developed into a serious
impedance to the sea-borne commerce of the entire Mississippi
Valley, and concerted efforts were made to solve the problem
by dredging. It was soon discovered that not even the dredges
were immune to the ubiquitous mudlumps; in August of 1876
a US Corps of Engineers dredge in Pass a Loutre was forced
to suspend operations because the mudlumps grew faster
than they could be removed (Walker and Grabauf, 1992).
About this time, a noted St. Louis engineer, James B. Eads,
proposed to both deepen the channel through the bar at the
mouth of one of the passes and to remove the mudlumps as
well, both by the expedient of constructing artificial jetties to
“train” the current. The Corps of Engineers, in the person of
Chief of Engineers Brig. Gen. A.A. Humphreys, opposed the
plan as impractical, and an epic contest of wills and public
relations ensued (Corthell, 1880). Eads’ final—and successful—plan
was to offer to build jetties at Southwest Pass at his own expense, and Congress need pay for them only if
they were successful. Congress accepted, but with the proviso
that they be built at South Pass, a stipulation inserted at the
insistence of Humphreys and intended to insure failure. To
Humphrey’s astonishment, the Eads jetties worked as advertised, and as a consequence New Orleans became one of the
world’s greatest seaports.

An unsurprising spin-off was the fact that the controversy
stirred scientific interest in the mudlumps, whose origin
seemed so mysterious. The mystery persisted for a long time.
Modern investigations began with R.J. Russell, who carefully
described their general nature and location in 1936 (Russell,
1936), but detailed field research intended to solve the
problem of their structure, nature, and origin did not begin
until the late 1940s (Morgan, 1951).

The mudlumps are features unique to the Mississippi River
delta. In their subaerial expression, they range from pinnacles
to elongated, often S-shaped, islands as large as 8 hectares
in area (Figure 4). Prior to their emergence above the
sea, they are readily detectable as individual mounds and
pinnacles projecting above the general level of the sea floor.
As long as they remain as subaqueous features, they are not
seriously affected by waves, currents, and tides, but once they
emerge as islands they erode rapidly. Some are destroyed
within days, but others may last for years. Some are de­­
stroyed by waves, only to re-emerge a new incarnation as
additional material is forced upward from below. Their be­to­ha­vior is conditioned by their areal extent, composition, loca­tion with respect to wave action, the protection offered by
other mudlumps or other relief forms, and the rate of reju­ve­na­tion, among others (Morgan, 1961).

Their surfaces are usually highly irregular, and the mass
exhibits both bedding planes (mostly dipping seaward away
from the axis of the islet) and local faulting. Most mudlumps
also incorporate vents up to 50 cm in diameter which emit
either methane or low-viscosity mud. The vents generally oc­
cur along fault lines. The gas vents are filled with water, through which bubbles the inflammable gas. The mud vents build mud cones that tend to be circular and broad, because the mud has such a low viscosity. Because they occur along lines of weakness, individual vents tend to form, last for a relatively short time, and then expire, only to be replaced by other vents emerging along the same fault line.

MORGAN et al. (1963) mapped the distribution of mudlumps at the mouth of South Pass for one time period 1867 to 1961 (Figure 5). Some 104 distinct mudlump islands have been recorded at the mouth of South Pass during the ninety-four year period, so that an average of slightly more than one new mudlump appeared per year at the river mouth. As the mouth of South Pass extended seaward, the zone of active mudlump islands also shifted seaward. However, MORGAN et al. (1963) found that the rates of emergence were by no means constant. Instead, there were “mudlump periods” followed by periods of relative quiescence.

Many theories to explain the origin of mudlumps have been proposed, including that favorite of the 19th century, gas pressure. Others invoked the beating of waves against river sediment in suspension, deposition by waves and tides, the result of subterranean water courses (RUSSELL, 1936), and the processes that raised the Alps and Andes. The currently accepted explanation is that they are a special form of diapir, formed in a manner closely related to that which

Figure 3. Areas of mudlump development at the mouths of major distributaries, Mississippi River delta, (from Morgan et al., 1963).

Figure 4. Photo of mudlumps off South Pass. The mudlump at the lower left is an example of elongated types.
formed the famous salt-domes of the Gulf Coast. As proposed by Morgan et al. (1963) in the detailed study of the South Pass mudlumps, the specific mechanism involves the rapid deposition of relatively dense (and therefore massive) sands in the bar at the distributary mouth. The deposition of the sands slowly extends the bar seaward over the relatively plastic and under-consolidated prodelta and marine clays that cover the seafloor seaward of the face of the advancing bar. The specific gravity differential (i.e., a dense layer overlying a less-dense stratum), coupled with uneven loading results in seaward plastic and block flow of the underlying clay, rather like pastry dough in front of the chef’s roller. The process culminates in diapiric folding and finally upward thrusting of the clay mass through the overlying bar sands. This interpretation is based in part on the observation that sediments found at depths of 107 m were being exposed on the surface of emerged mudlumps. The subsidence of the distributary-mouth bar that results from the compaction and plastic flow of the marine clay stratum is promptly compensated for by the deposition of fresh material on the surface, so that the surface of the bar remains at the same depth while simultaneously the sand stratum comprising the bar increases in thickness.

The origin and development of mudlumps are shown diagrammatically in Figure 6. The general subsurface stratification, as determined by borings, is shown to a depth of 190 m, at which point a Late Quaternary dense sand is encountered. The advancing sand-rich distributary-mouth bar grading over weaker underlying prodelta and marine clays is illustrated in Figure 6-A. Differential weighting by river mouth sands causes initial compaction and seaward flowage of the immediately underlying weaker prodelta clays, and the
The continued loading and progradation of the bar causes consequent subsidence of the overlying bar sands. Subsidence rates of the bar sands often exceed 0.5 m/yr.

The inception of diapiric thrusting is shown in Figure 6-B. Note that the bar sands have increased in thickness as a result of the subsidence associated with the evacuation of the prodelta clays, coupled with continued deposition of sand supplied by the river. During this time the bar continues to prograde seaward, generally at a faster rate than the flowage of the underlying clays. As a result, a zone of upward diapiric intrusion is localized, thus becoming the site of the mudlump formation.

The continued loading and progradation of the bar causes continued upward thrusting of the weaker clays (Figure 6-C). As shown, this movement often incorporates deeper-seated marine clays. Meanwhile the bar front has advanced well seaward of the growing diapir. The resulting compression of the weak clay seaward of the diapiric fold results in a landward flow of the clay into the diapir, and the result of this conflict of forces within the diapiric fold is the creation of a low angle thrust fault through the axis. By this time, the diapiric spine of the mudlump has become a definable subaqueous feature.

The continued progradation of the river mouth bypasses the site of the subaqueous mudlump and because of continued accumulation of bar sands seaward of the newly formed mud-

Figure 6. Diagrammatic representation of South Pass mudlump origin and development. (modified from Morgan et al., 1963).
lump, another site of loading becomes dominant and a new mudlump begins to form seaward of the previous mudlump (Figure 6-D). As the initial mudlump continues to grow, it eventually breaks the surface of the sea and becomes a subaerial mudlump. As long as the distributary-mouth bar continues to advance seaward, sites of new mudlumps are formed as a result of the continued sedimentary loading.

The cycles of activity reported by Morgan et al. (1963) are probably the result of variations in the rate of sediment loading on the distributary-mouth bar as the result of periods of higher-than-normal flood discharges.

DELTA SUBAQUEOUS SEDIMENT INSTABILITY

The initial research on sediment instability in the Mississippi River delta concentrated primarily on the mud diapirs or mudlumps (Morgan, 1951). The subaqueous portion of the delta was considered an area of “quiet suspension sedimentation,” with the materials provided by the fresh water effluent plume of the Mississippi. Even the pre-electronic “lead-and-line” surveys had long since revealed that depositional slopes are extremely low, generally less than 0.5° even on the relatively steep front of the river mouth bar. On the delta front and in the prodelta regions, slopes are generally less than 0.2°. It was widely assumed that sediment instabilities were impossible on such low slopes, and therefore the combination of high sediment rates (often up to 0.5 m/yr) and low slope angles would result in surfaces that were relatively featureless.

It therefore came as something of a shock in the early 1950s when newly-acquired detailed bathymetry of the Mississippi River delta enabled Shepard (1955) to map a series of radial gullies that creased the delta-front in the immediate vicinity of river mouths. Furthermore, the topography immediately in front of the advancing river mouth was highly irregular. Shepard concluded that the old conceptions must be wrong, and that the “irregular topography and gully features” must be the result of massive subaqueous landslides. However, he was at that time unable to explain how such massive slumping of sediments could occur on such low slope angles.

Further research by Coleman et al. (1964) indicated that the patterns of subaqueous topography of the bar front were not random, but displayed definite patterns and characteristics. Fathometer profiles (Figure 7) obtained off the mouth of South Pass revealed that the delta front consisted of an extremely intricate series of seaward-facing “stairsteps.” Some of the scarp were quite traceable for several kilometers. Very often the surface of the sea-floor immediately below the scarps appeared to be gently tilted landward, a condition very similar to the topography displayed by subaerial block slumps. It thus became clear that there were subaqueous sediment instabilities that were closely analogous to those in subaerial contexts, but occurring on astonishingly low slopes.
At about this time (early 1960s), side scan sonar became a common tool used to map subaqueous features, and the results of sonar surveys indicated beyond any further doubt that a large number of subaqueous slides had produced the irregular topography observed by Shepard. Further investigation, using high resolution seismic data, revealed that the shear planes display a concave-upward geometry in profile, and that the head-scars are curvilinear in plan view (Figure 8). The shear planes tend to merge into bedding planes with depth, and the subaqueous surface of the slump block is normally hummocky and irregular.

Once discovered, the explanation of the slumping hinged on the temporal and spatial patterns of sedimentation that occur at river mouths. The highest rates of sediment accumulation occur near the river mouth in an environment referred to as the distributary-mouth bar. Repeated surveys have shown that accumulation rates in this area can be as high as 1.5 m/yr. Further offshore, beyond the bar and out to water depths of 20 to 60 m, accumulation rates are much less, generally in the range of a few cm/yr. Further out in this prodelta region the sedimentation rates decline, so that in water depths greater than 100 m, accumulation rates are generally only a few mm/yr. The difference in rates is to some degree due to grain size differentials (coarse materials settle more rapidly, and so accumulate near shore), but primarily because of the spreading of the effluent plume. As a result of these differential accumulation rates in an offshore direction, the progradation rate is greater at or near the bar crest.

The consequences of the differentials in sedimentation rate and progradational rates are illustrated in Figure 9. At time T-1, the bar front would have an average slope of generally less than 0.4°. With several years of sediment accumulation and bar progradation, the bar front assumes the configuration shown at time T-2. As the process continues, the face of the bar will develop slopes approaching 0.5° to 0.7° (Time T-3). These under-consolidated sediments are not stable on such slopes and, as a result, a series of block slumps occur, which remove sediment from high on the bar and deposit the slump debris lower on the slope. The effect is to reduce the overall slope of the bar front (Time T-4). Studies have indicated that slumping episodes at South Pass generally occur in time periods of 5 to 10 years.

By the early 1970s, the offshore petroleum industry had begun to emplace bottom-fixed drilling platforms in water depths of 100 to 150 m. Following hurricane Camille in 1969, several platforms in water depths of 110 m were severely damaged or lost. Post-hurricane analysis indicated that hurricane-driven wind, wave, or current forces were not responsible for the damage, but that it had instead been caused by massive slides of the sea-floor material on a slope of less than 0.3° (BEA, 1971). Interestingly enough, this failure mode had been discussed in the classic paper by SHEPARD (1955) some 15 years earlier. Unfortunately, little attention had been paid at the time, because the state-of-the-art of soil mechanics had led to the conviction that massive sediment failure just could not occur on such low angle slopes. About 20 years passed before the development of marine remote-sensing tools (side-scan sonar and high resolution seismic equipment), in-situ testing instruments, and vastly improved soil mechanics models demonstrated that Shepard had been correct in his assessment of the cause of the features he had observed in the offshore Mississippi River delta.

The early investigations helped to explain many of the topographic characteristics observed by Shepard, but they shed little light on the radial “gully” features he had observed SHEPARD (1955). Recent research using high-resolution seismic techniques and drill hole information has indicated that they are elongate retrogressive slides (PRIOR and COLEMAN, 1978) (also commonly known as mudflow gullies), and that they are one of the most common types of sediment instabilities found in the Mississippi River subaqueous delta platform. Each gully begins as a cup-shaped depression within
an area of hummocky terrain clearly identified as being the surface of a slump block high on the delta front. The gullies continue downslope at essentially right angles to the contour lines as a long, often sinuous, narrow chute 3 to 20 m deep that links the depressed, hummocky source area on the up-slope end to composite overlapping depositional lobes (Figure 10). Some of the features extend for 7 to 10 km. The channels are highly variable in both plan and cross-section, but the most common forms display highly sinuous sections alternating with narrow constrictions and wide, bulbous sections along their length (Figure 11). Many of them branch near the up-slope end into crudely-dendritic forms, and some channels merge downstream to form crudely-anastomosing forms before broadening and merging with the massive debris lobes (Figure 12) which they have created. Most of the delta has now been surveyed by side-scan sonar and high-resolution geophysical techniques, and virtually the entire delta-front is scarred by features representing this type of mass-movement process (COLEMAN et al., 1980). A map of a section of the delta-front area seaward of Southwest Pass is given in Figure 9, illustrating the distribution of elongate retrogressive slides.

It is estimated that as much as 40% of the sediment that is annually deposited on the shallow part of the delta-front is transported downslope by short-term mass movement processes, and thus constitutes a primary example of the extremely dynamic nature of subaqueous delta environments. Yet until the development of high-resolution remote sensing systems, early investigators had no way of knowing that the subaqueous part of the delta is at least as dynamic as the subaerial delta.

More recent geological investigations on the subaqueous
Figure 12. Distribution of mudflow gullies in the vicinity of South Pass, Mississippi River delta.

parts of the continental shelves and upper continental slopes seaward of many river deltas all over the world, especially those with high depositional rates and large quantities of fine-grained sediment, have revealed that recurrent subaqueous gravity-induced mass movements which transport large quantities of sediment from shallow offshore waters to deeper marine waters along well-defined transport paths and in a variety of modes are an integral component of the normal deltaic processes involving offshore sediment transport (Coleman et al., 1974; Coleman and Garrison, 1977; Prior and Coleman, 1978a, Coleman and Prior, 1980; Roberts et al., 1976, 1980). The major factors that influence the stability of the bottom sediments on very low slope angles (generally less than 2°) and at depths from 5 to 200 m are as follows:

(1) Rapid sedimentation at the river mouths results in widespread loading of the upper delta-front slopes.

(2) Coarse-grained sands and silts, which comprise the distributary mouth bars, differentially load the underlying prodelta clays (Morgan, 1961).

(3) Fine-grained delta deposits are generally under-consolidated, with large excess pore fluid pressures causing low shear and compression strengths.

(4) Rapid biochemical degradation of incorporated organic material leads to the formation of large volumes of methane, which accumulates as bubbles and thus contributes to the generation of excess pore pressures (Whelan et al., 1975).

(5) Hurricanes and other storms cause cyclic loading on the sea floor, thus contributing to the generation of increased pore water pressure, as well as imposing direct downslope stresses on the sea-floor sediments.

**SUMMARY**

The main types of subaqueous slope instabilities that can be recognized in water depths of 5 to 200 m are illustrated schematically in Figure 10. This figure shows the instabilities
around a single distributary and part of an inter-distributary bay. Similar features can be found at each of the main distributaries within the Mississippi River delta (COLEMAN et al., 1980). In the immediate vicinity of the river mouths, differential weighting caused by dense distributary bar mouth sands causes the formation of clay diapirs (mudlumps). In the adjacent shallow-water inter-distributary bays, a variety of small-scale features such as collapse depressions and bottleneck slides occur (COLEMAN and PRIOR, 1980; PRIOR and COLEMAN, 1978a). On the seaward face of the distributary mouth bar are found a wide variety of slump-block slides, and, commencing in water depths of 10 m or less, are large number of elongate retrogressive slides (mudflow gullies and depositional lobes). Near the shelf edge, extremely large sediment instabilities, such as contemporaneous faults, submarine canyons, and shelf-edge slumps are common (COLEMAN et al., 1983).

**LITERATURE CITED**


