Muddy sand and sandy mud on the distal Mississippi fan: Implications for lobe depositional processes

Andrea Fildani1, Julian Clark1, Jacob A. Covault2, Bruce Power3, Brian W. Romans4, and Ivano W. Aiello5

1Statoil Research Center, Austin, Texas 78730, USA
2Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, University Station, Box X, Austin, Texas 78713-8924, USA
3Clastic Stratigraphy R&D, Chevron Energy Technology Company, Houston, Texas 77002, USA
4Department of Geosciences, Virginia Tech, Blacksburg, Virginia 24061, USA
5Moss Landing Marine Laboratories, Moss Landing, California 95039-9647, USA

ABSTRACT

We used laser particle size analysis (LPSA) to quantitatively analyze grain-size characteristics from distal Mississippi submarine fan deposits (Gulf of Mexico) and relate them to established depositional models along the spectrum of sediment gravity flows. One hundred and seventy-nine (179) sediment samples from 22 beds were obtained from cores of Deep Sea Drilling Project Leg 96 Sites 614, 615, and 621. The sediment from Sites 614 and 615 was deposited in lobes ~500 km downstream from the Mississippi canyon head. Most samples were described as sand from visual inspection of cores, containing >75% volume of sand grains, with clay content <5% based on LPSA. A muddy sand definition was given to sands comprising >20% silt and finer grains, with generally higher clay content (3%-16%). However, LPSA data show that facies assignments from visual core description overestimated the proportion of sand grains: 15% of samples initially interpreted as sand contain <75% sand grains; 40% of muddy sand samples have <50% sand. Samples from lobes at Sites 614 and 615 were compared to samples from Site 621, where beds are sandier with a relatively narrow distribution of grain sizes deposited in a more proximal channel setting, <250 km from the canyon head. We interpret the large proportion of silt and finer grains in the distal lobes to reflect diminished turbulence within sediment gravity flows as they expand from confined to unconfined settings downstream of channel conduits. Entrainment of finer-grained sediment at the channel-to-lobe transition could have also contributed to larger proportions of silt and finer grains in distal lobes.

INTRODUCTION

Submarine fans contain a wealth of information about the environmental changes to upstream sediment-routing systems and depositional processes in the deep sea (Cliff and Gaedicke, 2002; Covault et al., 2011; Fildani et al., 2016). Submarine fans comprise canyon, channel, levee-overbank, and depositional-lobe architectural elements (Mutti and Normark, 1987, 1991; Normark et al., 1993; Piper and Normark, 2001) (Fig. 1). Canyons transition to U-shaped, lower-relief channels with levee-overbank deposits across the lower slope and rise. Canyon-channel systems transition to relatively unconfined depositional lobes beyond the terminal mouths of major channel-levee systems (Normark et al., 1993). Sediment transport and deposition in deep-water lobes has been related to textural and compositional variability across architectural elements, with implications for oil and gas reservoir quality in analogous settings (e.g., the Paleogene Wilcox Formation, Gulf of Mexico; Kane and Pontén, 2012; Marchand et al., 2015). The deposits of ancient deep-water lobes in outcrop and the subsurface range from turbidite sandstone to matrix-rich beds deposited by hybrid (i.e., slurry) sediment gravity flows (Lowe and Guy, 2000; Haughton et al., 2003; Hodgson, 2009). Hybrid flows are characterized by a transitional flow rheology and sediment-support mechanisms, including the fluid turbulence of turbidity currents and the cohesion of debris flows, producing deposits that reflect transitional characteristics between fully turbulent and cohesive flows (Lowe and Guy, 2000; Haughton et al., 2009; Kane and Pontén, 2012). Muddy sand deposits of hybrid sediment gravity flows form at lobe margins to fringe environments (e.g., Kane and Pontén, 2012), and recent work suggests that these deposits can form both within and adjacent to proximal, channelized depositional environments at abrupt changes in slope (Amy and Talling, 2006; Talling et al., 2007; Power et al., 2013; Patacci et al., 2014). However, a quantitative understanding of textural characteristics directly related to depositional processes (e.g., grain-size distributions) is difficult to obtain in ancient deposits because of lithification and diagenetic modifications. Moreover, ancient deposits, especially from outcropping successions, commonly lack the explicit and unambiguous information regarding position within the system (e.g., distance from canyon head) that latest Pleistocene to modern deposits provide.

We examined sediment cores from channel and lobe architectural elements of the late Pleistocene Mississippi fan (Gulf of Mexico) collected during Deep Sea Drilling Project (DSDP) Leg 96 (Sites 614, 615, and 621; Fig. 1A) and archived at the Gulf Coast Repository located at Texas A&M University in College Station, Texas. We used high-resolution grain-size analysis (laser particle size analysis (LPSA) to quantify the particle-size distributions of facies observed in the DSDP cores. We combine facies and quantitative grain-size analyses of unconsolidated samples to interpret depositional processes in deep-water lobe and channel architectural elements.
Figure 1. (A) Bathymetry of the eastern Gulf of Mexico with location of Deep Sea Drilling Project (DSDP) Leg 96 Sites 614, 615, and 621. The canyon, channel and lobe outlines (colored yellow for the canyon and orange for the lobe), and depth contours are from the National Geophysical Data Center (2001). (B) GLORIA sidescan sonar image of the Mississippi fan with locations of DSDP Sites. Images have been recolored with bright yellows indicating high backscatter and dark reds indicating low backscatter (EEZ SCAN 85 Scientific Staff, 1987). Changes in backscatter intensity primarily reflect variations in sediment properties within the upper few tens of meters of sediment and delineate channels, lobes, and mass-transport deposits. (C, D) Line drawings of architectural elements of the more proximal leveed channel system (C-C’) and for the more distal fan comprising low-relief confined channel deposits and lobes (D-D’) (modified from Bouma et al., 1986). Note the presence of channels and levee deposits in both surficial and buried stratigraphy within the distal fan. Interpretive line-drawing highlighting seafloor morphologies in the surroundings of Site 621 (E) and Sites 614 and 615 (F) (modified after Bouma et al., 1986). Brighter yellow indicates higher probability of sand accumulation; gray tones indicate higher probability of mud-silt. TWTT—two-way traveltime.
Sediment Gravity Flows and Their Deposits

Middleton and Hampton (1973) differentiated sediment gravity flows based on dominant sediment-support mechanism. Turbidity currents are at one end of the spectrum of sediment gravity flows, in which sediment is predominantly supported by the upward component of fluid turbulence (Middleton and Hampton, 1973). Debris flows are at the other end of the spectrum, and include large grains and gravel supported by a cohesive matrix of interstitial fluid and fine-grained sediment with finite yield strength (Middleton and Hampton, 1973). Classification schemes of sediment gravity flows have focused on end-member states of sediment concentration (e.g., dilute versus dense), interpreted rheology (e.g., turbulent versus laminar), and sediment-support mechanism (e.g., the upward component of fluid turbulence versus cohesion) (Lowe, 1982; Lowe and Guy, 2000; Haughton et al., 2003, 2009; Talling et al., 2012). During the past two decades, much work has been devoted to covering the spectrum of intermediate flow types, falling between turbidity currents and debris flows (e.g., Talling et al., 2004; Barker et al., 2008). Many deposits exhibit evidence of such hybrid depositional processes, including abrupt, progressive, or cyclical changes in flow behavior (e.g., turbulent versus laminar) during deposition (Lowe and Guy, 2000; Haughton et al., 2009).

Slurry Flows, Hybrid Flows, Transitional Flows, and Their Deposits

Studies of subsurface data sets rich in core from the North Sea were among the first to produce interpretations of the depositional processes of hybrid sedimentation units. Lowe and Guy (2000) measured between 10%–35% detrital muddy matrix (undifferentiated clay and silt) in distinctive banding and lamination interpreted to be a result of mud-rich cohesive flow behavior at the base of sediment gravity flows from the Britannia field sandstone of the North Sea. Sylvester and Lowe (2004) interpreted fluctuations in flow rheology to be caused by increasing concentration of mud accumulating toward the base of the flow as it became less effective in grain-size segregation. This basal part of the flow reaches a threshold concentration and viscosity, which causes the sedimentation surface to jump to the top of this mud-rich, viscous layer. This process repeats multiple times as the flow decelerates, resulting in cyclic alternations of mud- and sand-rich bands. Subsequent research by Haughton et al. (2003, 2009), drawing on a wide range of North Sea depositional systems, emphasized a type of debris genetically associated with a turbidite. This turbidite-debrite couplet (i.e., linked debrite) is characterized by a sharp-based, structureless, but commonly watered, sandstone overlain by or gradationally transitioning into a matrix-supported debrite with mudstone clasts. The mudstone-clast debrite can be rich in terrestrial plant fragments and capped by thin, laminated mudstone. Talling et al. (2004) documented similar linked-debrite couplets (i.e., cogenetic beds) in outcrops of the Marnoso-Arenacea Formation in Italy and in Quaternary deposits of the Madeira abyssal plain offshore of northwest Africa. They noted that the uppermost section of a debrite does not consistently contain mudstone clasts and is better described as a muddy sandstone. Haughton et al. (2009) provided a useful synthesis of deposits and inferred processes of transitional flows, including slurry-flow deposits, linked debrites, and cogenetic beds.

STUDY AREA: THE MISSISSIPPI SUBMARINE FAN

The Mississippi submarine fan is a large-scale (>300,000 km²) accumulation of Plio-Pleistocene sediment deposited in the Gulf of Mexico by the Mississippi River of North America (Stuart and Caughey, 1976; Bouma et al., 1986; Figs. 1A, 1B). The fan was targeted by major research efforts in the 1980s: in 1983, DSDP Leg 96 recovered cores from nine sites, including channel deposits, levees, the Walker-Massingill slump, and distal depositional lobes (Bouma et al., 1986). In 1985, the seafloor of the Gulf of Mexico was surveyed by the U.S. Geological Survey using GLORIA (Geological Long Range Inclined Asdic) sidescan sonar and high-resolution seismic-reflection profiles (EEZ-SCAN 85 Scientific Staff, 1987).

Stelting et al. (1985) developed a seismic-stratigraphic interpretation of the youngest deposits of the Mississippi fan. These deposits include a long (>500 km), leveed canyon-channel system feeding at least eight depositional lobe complexes, each ~150 km long, 50 km wide, and 10–40 m thick (Twichell et al., 1991), which comprise multiple stacked lobate architectural elements fed by a network of shallow channels (see Prélat et al. (2010) for an explanation of the stratigraphic hierarchy of lobe deposits). At Site 621 (Fig. 1A), DSDP drilling penetrated a ~4-km-wide, ~35-m-deep Mississippi channel >250 km downstream of the Mississippi canyon head (Stelting et al., 1985). In the subsurface beneath the wide channel on the seafloor, Stelting et al. (1985) interpreted relatively coarse-grained channel deposits bounded by a composite valley surface (Figs. 1C and 1E). At Sites 614 and 615, the seafloor across the distal Mississippi fan includes multiple weakly confined, <1-km-wide, 10-m-relief channel deposits bounded by a composite valley surface (Stelting et al., 1985). In cross section, a continuous channel form is bounded by low-relief levee-overbank deposits (Stelting et al., 1985; Figs. 1D and 1F). In the subsurface, Stelting et al. (1985) interpreted weakly confined channel deposits and lobes interstratified with local heterolithic to fine-grained mass-transport deposits and/or debrites (Fig. 1).

DATA AND METHODS

Description and Sampling of Sites 614, 615, and 621 of DSDP Leg 96

The core sediments used in this study are from the distal Mississippi submarine fan (Sites 614 and 615 at 3310 m below sea level [mbsl] and 3268 mbsl, respectively) and the Mississippi channel (Site 621 at 2481 mbsl) (see Fig. 1A). Operational problems with drilling at Site 614 resulted in the need for a second
of 5 cm³) to investigate the distribution of grain sizes within beds. We reanalyzed a subset of these samples under different operational conditions to test repeatability of the results and address potential biases using LPSA on coarse-grained siliciclastic sediment (see Appendix for details).

Laser diffraction particle-size measurement is based on the Fraunhofer and Mie theories of light scattering whereby spherical particles of a given size disperse light at a specific angle, with the angle increasing with decreasing particle size (Singer et al., 1988). This analytical method has successfully been used on pelagic and hemipelagic sediment of mainly biogenic composition (Aiello and Ravelo, 2012).

For this study, we used a Beckman-Coulter LS 13 320 (particle size analyzer) (the instrument uses a 5 mW laser diode with a wavelength of 750 nm). We split the sediment to obtain the necessary amount of sample by the "coning and quartering method" (Popenoe et al., 2000), which was tested by repeat runs. We diluted samples in a 1.2 L aqueous module filled with deionized water equipped with a pump unit running at 100% power. Preliminary analysis of the Leg 96 samples indicated that sample treatment was unnecessary; once added to the aqueous module, the energy of the water controlled by the pump was sufficient to ensure complete disaggregation. Preliminary tests using different concentrations of sodium hexametaphosphate also showed a lack of flocculation; thus, dispersants were not used. We provide tabulated LPSA data in the Supplemental Files.

### FACIES DESCRIPTIONS AND LPSA RESULTS

We compare the facies from the core defined by visual description with the quantitative results from LPSA. Figure 3A shows the proportion of facies observed and described in cores recovered from Sites 614 and 615, and Figure 3B shows the proportion of facies sampled for LPSA. Sampling for LPSA was focused on muddy sand facies to investigate grain-size variation in sandy deposits that appeared to show subtle variations in fine-grained matrix content, which were difficult to visually determine and quantify. Although such sampling strategy does introduce a recognized bias, the finer-grained portion of these deposits was the main scope of this study. Figure 4 summarizes the relative proportions of sand, silt, and clay obtained from LPSA for each sample plotted on classification schemes of Shepard (1954) and Folk (1954, 1974). Both classification schemes are shown for completeness, but textural categories identified in the core are specifically discussed in relation to the Shepard scheme unless otherwise stated. Shepard "silty sand" and "sandy silt" categories equate to the visually defined "muddy sand".

The LPSA data show that the majority (84.9%) of the samples we visually described as sand correspond with Shepard’s (1954) definition of sand (>75% volume of sand grains). The clay content in the sand facies is <5%.

The muddy sand facies defined by visual core description comprises >20% fine grains (silt and clay). Clay content in this facies, measured by LPSA, is generally higher (3%–16%) than in the sand facies but still less than the >20% assigned visually. Collectively, the sand and muddy sand facies show a continuum of grain-size composition from 100% sand to sandy silt with up to 16% clay content when plotted with Shepard’s classification scheme (Fig. 4A).

Figure 5 shows a cross plot of standard deviation (sorting) versus mean grain size (in phi units), with facies defined by visual description indicated by color. Mean and standard deviation were calculated using the geometric method of moments. Sand and muddy sand facies generally plot in different fields with some overlap in the very-fine-sand range. Four samples from the Mississippi channel at Site 621 (Fig. 1A) are generally coarser-grained sand with a narrower distribution of grain size compared to the samples from Sites 614 and 615 (Fig. 5).
Figure 2. Description of core from Site 614 (A) and Site 615 (B), showing sediment type, grain size, and location of laser particle size analysis (LPSA) samples. Grain-size abbreviations: ms—medium sand; fs—fine sand; vfs—very fine sand. See stratigraphic placement of Figures 6, 7, 8, and 9. mbsl—meters below sea level. Detailed core descriptions are available in the Supplemental Files (footnote 1 in the main text).
The LPSA data show that facies assignments based on visual core description overestimated the proportion of sand grains. Fifteen percent (15%) of samples visually described as sand are shown by LPSA to have <75% sand grains, and 40% of samples visually described as muddy sand have <50% sand grains and should therefore be classified as sandy silt according to the Shepard (1954) classification scheme (Fig. 4A). Using the Folk (1954, 1974) classification scheme (Fig. 4B), only 7% of the samples collected from Sites 614 and 615 are clean, well-sorted sand beds (i.e., >90% sand grains). In contrast, Site 621 sand beds from a more proximal channel setting contain <5% silt and finer grains.

**EVENT-BED TYPES**

Event beds, or sedimentation units, are interpreted to represent deposition from a single sediment gravity flow (e.g., a turbidity current, debris flow, or hybrid flow) based on visual description (Hickson and Lowe, 2002). We interpret most event beds sampled in cores from Sites 614, 615, and 621 to be turbidites and hybrid-event beds, with fewer debrites. We highlight three end-member event beds below: a turbidite, a hybrid-event bed, and a debrite (see the Supplemental Files [footnote 1] for all LPSA data and visual core descriptions). The entire set of digitized core images for Leg 96 are available at http://deepseadrilling.org/cores/leg096/.

Beds that are ungraded to normally graded with clean (relatively well sorted) sand are interpreted to be turbidites. Figure 6 shows a turbidite bed from a channel deposit in the shallow subsurface at Site 615 (~16 m below seafloor; Stelting et al., 1985) (Fig. 1). The LPSA samples show subtle normal grading and a consistent presence of finer-grained sediment. Figure 7 shows a turbidite sampled in either a proximal lobe or a channel deposit much deeper...
in the subsurface (~134–135 m below seafloor; Stelting et al., 1985). The bed is ~1.9 m thick and is interpreted to represent deposition from a single gravity-flow event. The grain-size distribution tends to be unimodal, with a wider distribution (poorer sorting) near the base of the bed. The modal grain size is finer and with a relatively narrow distribution (well sorted) toward the top of the bed. This bed is representative of other relatively well-sorted sand beds at Sites 614, 615, and 621, which we interpret to have been deposited by concentrated, non-cohesive flows commonly with suppressed near-bed turbulence and particle support (Fig. 7) (e.g., Cantero et al., 2012). The upward fining of grain size reflects settling of initially coarser-grained sediment, followed by progressively finer-grained sediment, out of turbulent suspension (Bouma, 1962). The wider distribution of grain sizes at the base of the bed might reflect suppressed near-bed turbulence, which inhibited suspension and sorting of some of the sediment within the flow (e.g., Lowe, 1982). Mud clasts at the base of the deposit might have been ripped up from the unconsolidated, muddy seafloor upstream of the depositional site and partially entrained in the flow before deposition (e.g., Ito, 2008).

Sand beds that are ungraded or weakly normally graded and rich in fine-grained (clay and silt) matrix are interpreted to be hybrid-event beds. These beds contain medium to coarse sand, but have significantly larger proportions of silt and finer grains compared to turbidites. Figure 8 shows two amalgamated poorly sorted, matrix-rich hybrid-event beds from Site 614. We interpret an amalgamation surface between samples D and C, where the grain-size distribution becomes wider and bimodal, including a coarser-grained mode, in sediment overlying sample C (Fig. 8). This interpretation is mainly guided by LPSA results; although subtle, this surface could be otherwise interpreted as an interface of banding (sensu Lowe and Guy, 2000). The bases of both beds include wide and bimodal distributions, with coarse grains but also very fine-grained sand and silt, suggesting some entrainment at the flow base. The beds grade upward into finer-grained sediment with silt to clay tails (Fig. 8). Both beds are enriched in matrix (silt and finer grains) near their tops. Relatively poor sorting throughout the beds suggests that turbulence was not as effective when compared to the deposits displayed in Figure 7 (deposited by fully turbulent flows at the time of deposition). We interpret that these beds were related to more mixed turbulent-laminar flows with transitional, or hybrid, depositional behavior that fluctuated between fully turbulent and cohesive sediment-support mechanisms (e.g., Lowe and Guy, 2000; Haughton et al., 2009).

Debrites are present but rare in cores from Sites 614 and 615. They are composed of predominantly mudstone matrix containing some intra-clasts of mud and/or sand. The most common type of debrite includes gray to dark gray layers with high proportions of mud and some fine-grained sand to coarse-grained silt. Although present in the described core, these deposits were only sampled as a representative end member (Fig. 9). The lower sample (G) of Figure 9 is from a matrix-supported, mud clast–rich debrite recovered from Site 615. It shows poor sorting, with a grain-size distribution from very fine-grained sand to clay (Fig. 9). Sample F is from a sandier section, showing a grain-size distribution from fine-grained sand to clay. Samples E–A show very poor sorting of predominantly silt and clay and the presence of pseudo-nodules and mud clasts throughout. LPSA suggests that this section includes portions of two event beds: a lower bed (sample G) showing a bimodal distribution and skewness toward fine grains of a muddy matrix and mud clasts, and an upper bed (samples A–F) comprising a debrite with asymmetric distributions skewed toward fine grains and weakly developed normal grading; the overall interpretation samples A–F could also be the typical expression of a distal hybrid-event bed (HEB, sensu Haughton et al., 2009). The poorly sorted, mud-matrix deposits reflect deposition en masse by cohesive freezing of a debrite (e.g., Middleton and Hampton, 1973).

## DISCUSSION

In this manuscript, we used LPSA data to quantitatively analyze grain-size characteristics from distal Mississippi submarine fan deposits and relate them to established depositional models of the spectrum of sediment gravity flows. The LPSA data show that visual core descriptions and facies assignments tend to overestimate the sand fraction of deposits. Fifteen percent (15%) of sand samples from visual recognition turned out to contain >25% silt and finer grains; 40% of muddy sand samples from visual recognition contained >50% silt and finer grains. Much of the fine-grained fraction in these sand samples is silt (Fig. 5). Clay is common only in debrites and muddy thin beds that we interpret to have settled from fine-grained, dilute turbidity currents. Only ~7% of the samples collected from the deposits in cores from Sites 614 and 615 are clean, well-sorted sand containing <10% silt and finer grains and interpreted to be turbidites. In contrast, all four samples from Site 621 each comprise predominantly well-sorted sand grains and <5% silt and finer grains. Core samples from Site 621 are from a more proximal setting, and we interpret them to have been deposited by turbidity currents in a channelized environment (Fig. 1).
Samples from Sites 614 and 615 are from the relatively distal depositional lobes of Bouma et al. (1986), and we interpret them to have been predominantly deposited by turbidity currents and hybrid (more cohesive) flows in less-confined environments (Fig. 1). The high proportion of silt and finer grains in apparently sandy deposits of distal lobes is likely the result of two processes: flow expansion and depletion across distal lobe environments related to loss of confinement (e.g., Kneller and Branney, 1995) and the entrainment of mud into overriding sediment gravity flows at the channel-to-lobe transition (e.g., Mutti and Normark, 1987; Ito, 2008; Haughton et al., 2009).

The effect of grain sorting on lobe depositional processes in distal parts of submarine fans has been the subject of many experimental and field studies, since the earliest studies of turbidity currents and their deposits (e.g., Kuenen and Migliorini, 1950; Kuenen, 1951). In general, we propose that flows will result in grain segregation during transport and deposit coarser grains upstream, in more proximal channelized environments (e.g., Lowe, 1982). The progressive segregation of silt and clay in turbidites deposited hundreds of kilometers from the turbidity current source has been known for a relatively long time (see Piper, 1978).

Furthermore, higher-resolution seafloor mapping (O’Connell et al., 1985, 1991) demonstrates that the deposits sampled at Sites 614 and 615 are in an area where channels are poorly expressed, suggesting the possibility of being close to or at the channel-lobe transition zone (sensu Mutti and Normark, 1987; also see recent discussion in Carvajal et al. [2017]). At the channel-to-lobe transition, flows generally pass from a relatively higher-gradient and channelized setting to a flatter and smoother setting, which can result in a hydraulic jump (Komar, 1971; Mutti and Normark, 1987; Garcia and Parker, 1989; Carvajal et al., 2017; Fig. 10). Hydraulic jumps in turbidity currents result in dissipation of energy through increased internal turbulence and, consequently, increased erosion of the seafloor and entrainment of sediment into the overriding current (Mutti and Normark, 1987). Beyond the channel-to-lobe transition, flows continue to lose momentum and transition to lower-energy flows, where silt and finer grains remain in suspension (e.g., Mutti and Ricci Lucchi, 1972; Piper, 1978; Lowe, 1982). Flow expansion at loss of confinement, such as at the terminus of a channel (as in Fig. 10), causes a momentum reduction (i.e., flow depletion; Kneller and Branney, 1995), potentially favors flow stratification, and could promote the deposition of muddy, hybrid-event beds.

In the experiments of Baas et al. (2004), depletive sediment gravity flows of varying density, velocity, and grain size produced scours and depositional lobes downstream of the confined entry point to a wide basin. Like in our hypothetical model above, deposition and erosion are interpreted to be controlled by the location of hydraulic jumps: erosion occurs and scours are produced as a flow enters the wide basin and passes through a jump; high fallout rates of suspended sediment load cause deposition of massive sand beyond the scours in the proximal lobe. Finer-grained sediment bypasses the proximal lobe to the distal lobe. Thus, the depletive experimental flows produced a radial decrease in mean grain size in the depositional lobes (see Baas et al. [2004] and references therein for additional examples), like in our LPSA results.

**Figure 6.** Laser particle size analysis (LPSA) results and core photographs from sand deposits collected between 15.75 and 16.50 m below seafloor at Site 615. The three samples are from one turbidite event bed. The LPSA results reflect the mean grain-size grading, but the sand is relatively poorly sorted with a “tail” of fine-grained sediment. Grain-size abbreviations: vfs—very fine sand; fs—fine sand; ms—medium sand; cs—coarse sand; vcs—very coarse sand.
Figure 7. Laser particle size analysis (LPSA) results and core photographs from sand deposits collected between 133.77 and 135.48 m below seafloor at Site 615. The six samples are interpreted to be from one turbidite event bed. The LPSA results reflect the mean grain-size grading, and show the sand to be well sorted compared to that of the intervals shown in Figures 8 and 9. Grain-size abbreviations: vfs—very fine sand; fs—fine sand; ms—medium sand; cs—coarse sand; vcs—very coarse sand.
Figure 8. Laser particle size analysis results and core photographs from muddy sand deposits collected between 45.38 and 46.42 m below seafloor at Site 614. The eight samples are interpreted to be from the deposit of one hybrid flow event. The base of the bed is at 46.95 m below seafloor and shows some disturbance either due to loading or coring. For this reason, we avoided sampling the very base. All samples show poorer sorting compared to turbidites in Figures 6 and 7. Samples H–D show a general upward decrease in mean grain size, but this trend is interrupted by an increase in sand for the uppermost three samples A–C. These three samples could represent an amalgamated deposit of a second flow event, or related flow surge. Grain-size abbreviations: vfs—very fine sand; fs—fine sand; ms—medium sand; cs—coarse sand; vcs—very coarse sand.
Figure 9. Laser particle size analysis results and core photographs from clayey silt and muddy sandy deposits collected between 153.06 and 153.85 m below seafloor at Site 615. The seven samples were interpreted to be from debris-flow deposits of either two or three events. The data show all samples to be poorly sorted compared to turbidites in Figures 6 and 7. Grain-size abbreviations: vfs—very fine sand; fs—fine sand; ms—medium sand; cs—coarse sand; vcs—very coarse sand.
Figure 10: Conceptualized sketch diagram for generic planform and cross-sectional geometry of channel and lobe deposits of the Mississippi fan (cf. Stelting et al., 1985; Bouma et al., 1986). We interpret that channel and related lobe deposits avulse, prograde, and eventually back-step to build up the stratigraphy of this sector of the Mississippi fan. Consequently, vertical penetrations at Sites 614 and 615 likely encounter deposits from both confined (channelized) and unconfined (lobe) parts of this depositional model. The variability in grain size across the Mississippi fan is a result of flow expansion and depletion across distal lobe environments related to loss of confinement and the entrainment of finer material (silt and clay) into overriding sediment gravity flows at the channel-to-lobe transition. Samples from Sites 621 and 615 show the progressive enrichment in finer material: sample 1855610 is from up-dip channel fill; sample 1855581 is from a low-relief channel on a proximal lobe; the distal deposit (in an interpreted less-confined environment) is represented by sample 1855603. Grain-size abbreviations: vfs—very fine sand; fs—fine sand; ms—medium sand; cs—coarse sand; vcs—very coarse sand.

Other experimental results on unconfined sediment gravity flows and their deposits show some similarities to the experiments of Baas et al. (2004), and agree with models of downstream-diminishing grain size and the deposition of Bouma $T_n$, $T_m$, and $T_{mn}$ turbidite divisions with increasing distance (e.g., Bouma, 1962; Lowe, 1982); however, sorting is also observed to improve downstream in these experiments (e.g., Lüthi, 1981). This is at odds with our LPSA results from the distal lobes of the Mississippi fan, as well as recent results from the distal reaches of other submarine fans (see Haughton et al., 2009, and references therein), which contain poorly sorted, muddy sand or sandy mud hybrid-event beds. For example, sediment piston cores from depositional lobes of the distal Congo submarine fan (offshore western Africa), >800 km from the shelf, contain mostly muddy sand; clean sand is restricted to the feeder channels and distributary channels of the proximal portions of lobes, which represent only 13% of the planform of the entire lobe complex (Dennielou et al., 2017). The enrichment of mud in lobe deposits might also account for the frond-like planform shape recognized in distal submarine fans (e.g., Nelson et al., 1992; Twichell et al., 1992). For example, depositional lobes fed by a secondary “feeder” channel of the main Mississippi canyon-channel system exhibit a very irregular, frond-like planform shape, which suggests deposition from cohesive debris flows and/or hybrid flows characterized by transitional rheology and sediment-support mechanisms (Talling et al., 2010).
Haughton et al. (2009) stressed the importance of entrainment of mud clasts as a key step in the generation of hybrid flows. In general, such a process is enhanced by erosion where there is a loss of confinement at the channel-to-lobe transition (Mutti and Normark, 1987; Terlaky and Arnott, 2014; Kane et al., 2017; Carvajal et al., 2017). Entrainment of sediment is common in turbidity currents as evidenced by the erosional surfaces in deep-water channels observed in outcrop and on the seafloor (Elliott, 2000; Eggenshuisen et al., 2011; Fildani et al., 2013; Hubbard et al., 2014; Traer et al., 2015). Entrained mud clasts are detached from the seafloor, segregated in the flow, and commonly progressively disaggregated by internal shearing (Sylvester and Lowe, 2004; Fonesu et al., 2016). The disaggregated mud in the flow could dampen turbulence (Lowe and Guy, 2000; Haughton et al., 2009); the development of a high-concentration, muddy lower boundary layer inhibits transfer of turbulent kinetic energy into the upper parts of the flow (Lowe and Guy, 2000; Sylvester and Lowe, 2004; Eggenshuisen et al., 2017; Kane et al., 2017) and causes flow stratification. Our finding suggests that silt plays an important role as entrained finer material in the distal reaches of deep-sea fans and has been probably overlooked.

Deposition of hybrid-event beds is likely common in unconfined environments such as Mississippi fan Sites 614 and 615, as well as in interpreted avulsion splays at the base of leveed channels (e.g., Power et al., 2013). These settings are characterized by entrainment of near surface sediment and depletion associated with confined-to-unconfined sediment gravity flow transitions, which decrease momentum and turbulence, enhance stratification in overriding flows, and increase the proportions of mud in hybrid-event beds.

CONCLUSIONS

Deposits of the Mississippi submarine fan were evaluated with LPSA to quantitatively explore grain-size distributions within sand beds recognized from visual inspection of cores. We report that sand samples from the depositional lobes of the distal fan have large proportions of silt and finer grains, reflecting poor sorting related to diminished turbulence of waning flows caused by loss of confinement. Erosion and entrainment of the substrate at the channel-to-lobe transition might have contributed to larger proportions of silt and finer grains in the depositional lobes. These results are compared with samples collected in channelized settings where sand samples are well sorted and normally graded. Muddy sand and sandy mud might be common in the distal reaches of submarine fans because of the common processes of entrainment and flow depletion. We expect these processes to impact the reservoir quality (i.e., proportion of silt and finer grains) of oil and gas reservoirs in deposits analogous to those of the distal Mississippi fan, such as the Paleogene Wilcox Formation in the Gulf of Mexico.

ACKNOWLEDGMENTS

We thank Chevron Energy Technology Company (ETC) for permission to publish this study. AF, JC, JAC, BP, and BWR were members of the Clastic Stratigraphy Team at Chevron ETC in San Ramon, California, when this project was conceived and executed. We would like to thank Will Schwelller, Tim McHargue, Bill Corea, Angela Hessler, Morgan Sullivan, and the late Bryan Bracken for constructive discussions and the creative environment they fostered at the San Ramon “Lab.” We thank the many scientists serving on Leg 96 of the Deep Sea Drilling Project, Bill Normark being one of them. Phil Rumford, Chad Broyles, and the staff of the International Ocean Discover Program’s Gulf Coast Repository, Texas A&M University, were instrumental throughout the data collection. JAC acknowledges support of the Quantitative Clastics Lab sponsors. Constructive reviews from Guest Associate Editor David Pipier and reviewers Peter Haughton and Luke Pettinga largely improved this manuscript.

APPENDIX

Laser Particle Size Analysis

To investigate the distribution of grain sizes within beds, 179 samples (~1 g samples) were analyzed using laser particle size analyses (LPSA). A subset of these samples (24) was reanalyzed under different operational conditions to test repeatability of the results and address potential biases using LPSA on coarse-grained siliciclastic sediment (see below).

Laser diffraction particle-size measurement is based on the principle that particles of a given size diffract light at a specific angle, with the angle increasing with decreasing particle size (Singer et al., 1988). This analytical method has successfully been used on pelagic and hemipelagic sediment of mainly biogenic composition, while LPSA of coarse-grained siliciclastic sediment is less common (Aiello and Ravelo, 2012). A typical LPSA system is composed of an infrared (IR) source, an aqueous module in which the sample is circulated (we used deionized water) and that has windows that to allow the IR light to interact with the sediment particles, a Fourier lens to rectify the light backscattered by the particles, and a number of light detectors prearranged to capture different angles of backscattering. The system is connected to a computer, which uses an optical model to convert the information from light to size relative to volume using the Fraunhofer and Mie principles of light scattering.

Some of the advantages of using LPSA include the small sample size required for the analysis. When using an aqueous module, the samples do not need to be dried and sample disaggregation is created by the energy of the pump itself. A disadvantage of using LPSA is the limit on the maximum measurable grain size (2000 µm). Moreover, studies that have compared various particle-size measurement techniques and instrumentation have shown that the analysis of the distribution of the fine-grained fraction (clay and fine silt) is less accurate in LPSA compared to settling methods (e.g., Konert and Vandenberghhe, 1997). The platy shape of clay affects the light scattering such that the instrument returns a larger size, potentially resulting in an underestimation of the clay fraction. However, McCave et al. (2006) demonstrated that differences in estimates of the mean and relative percentage of the silt and finer grain-size fraction from LPSA versus settling methods are evident but negligible.

For this study, we used a Beckman-Coulter LS 13 320 laser diffraction particle size analyzer (the instrument uses a 5 mW laser diode with a wavelength of 750 nm). This instrument analyzes small (~0.5–2.0 µm) masses of unconsolidated sediment and combines conventional laser beam diffraction with polarized intensity differential scattering, allowing high resolution of grain size (126 logarithmically spaced channels between 0.04 µm to 2.00 mm). We split the sediment to obtain the necessary amount of sample by the quartering method, which was tested by repeated runs (see methods details in Poppe et al. [2000]). We diluted samples in a 1:2 L aqueous module filled with deionized water equipped with a pump unit running at 100% power. Samples tend to have log-normal grain-size distributions in the 0.04 µm to 2 mm spectrum (Beckman Coulter Inc., 2003). Geometric statistics were applied to the values obtained by the logarithmically spaced size channels of the particle analyzer using the method of moments. Preliminary analysis of the Leg 96 samples indicated that sample treatment was not necessary either before or during LPSA: once the sample was added to the aqueous module, the energy of the water controlled by the pump was sufficient to ensure complete disaggregation, and sonication was not necessary. Preliminary tests also showed a lack of flocculation, hence further use of dispersants was not necessary.

LPSA Obscuration Experiments

The first set of analyses was done with the LS 13 320 under standard obscuration conditions. Obscuration is the amount of IR light absorbed in the sample cell that, in turn, is proportional to the volume of sediment added and is affected by the optical characteristics of the sediment. Obscura-
Figure A1. Results of the experiments carried out to test whether concentrations of sediments above standard obscuration conditions (automatically determined by the Beckman Coulter LS 13 320 laser diffraction particle size analyzer and generally between 4% and 6%) determine different results of the grain-size analyses and specifically a bias toward lower grain sizes. Panels A and B show the relationship between Δ Obsc. (obscuration conditions of the test minus standard obscuration) and the difference between mean size (or standard deviation, S.D.) measured during the test and the mean size (S.D.) measured under standard obscuration conditions for all samples analyzed (n = 26). Panels C and D show the same relationships as in panel A and panel B but only for the subset of samples with Δ Obsc. < 10 (about twice the standard value of obscuration). Dashed lines are R² (fitted) regression lines. While mean size does not correlate with Δ Obsc., the plot in panel D shows that the S.D. increases with Δ Obsc., thus, suggesting that a broader range of particles is measured when obscuration conditions are about twice the standard obscuration values. The obscuration reported is the percentage of light scattered out of the beam by the particles. The detector on the opposite side of the cell from the light source measures the intensity of the unscattered light to determine the amount of obscuration.

REFERENCES CITED
Aiello, I.W., and Ravelo, A.C., 2012, Evolution of marine sedimentation in the Bering Sea since the Pliocene: Geosphere, v. 8, p. 1231–1253, https://doi.org/10.1130/GES00710.1.
Amy, L.A., and Talling, P.J., 2006, Anatomy of turbidite and debrite sandstones based on long distance (120 × 36 km) bed correlation, Marnoso Arenacea Formation, Northern Apennines, Italy: Sedimentology, v. 53, p. 161–212, https://doi.org/10.1111/j.1365-3091.2005.00756.x.
Baas, J.H., Van Kesteren, W., and Postma, G., 2004, Deposition of depletive high-density turbidity currents: A flume analogue of bed geometry, structure and texture: Sedimentology, v. 51, p. 1053–1088, https://doi.org/10.1111/j.1365-3091.2004.00660.x.

Further tests were carried out to assess the effects of obscuration on the reproducibility of LPSA and specifically to test whether the finer-grained samples were biased toward overrepresenting the finer particles. We reanalyzed a subset of 26 samples representative of different grain sizes at ~2× and 4× the standard obscuration. The main statistical parameters do not change significantly between runs under different obscuration conditions: the coefficient of variation (ratio of the standard deviation to the mean) is <0.3 for ~90% of the samples. The difference between the obscuration used during each test run and the standard value of obscuration for the sample (Δ Obsc.) is compared to mean and standard deviation (S.D.) in Appendix Figure A1 to test whether there is a correlation between these parameters. Figure A1A shows that there is no increase in mean grain size with increasing Δ Obsc. (a similar plot is produced by using Δ median); thus, the grain-size statistics are not biased toward smaller sizes with increasing obscuration conditions. However, Figures A1B and A1C show that there is a relationship between increase in obscuration and increase in S.D. (expressed as Δ S.D.). This relationship is weak for all of the samples (~37%), but it becomes highly significant (~40%) for obscuration values up to about twice the standard value (Δ Obsc. ≤ 10; Fig. A1C). In other words, with increasing obscuration conditions beyond the standard value indicated by the instrument, a larger range of particles is measured. The optimal Δ Obsc. value seems to be approximately twice the standard value (Fig. A1D). The experiment suggests that in sand samples mixed with clay and silt, standard obscuration conditions might not capture the full extent of the particle size distribution. However, the experiments also demonstrate that the mean grain size does not change significantly using different values for obscuration. Thus, our first set of measurements done under standard obscuration conditions was used for the sedimentological interpretations presented in this study.
Barker, S.P., Haughton, P.D.W., McCall, W.D., Archer, G.G., and Hakes, B., 2008, Development of rheological heterogeneity in clay-rich high-density turbidity currents: Apatian Britannia Sandstone Member, U.K. continental shelf: Journal of Sedimentary Research, v. 78, p. 46–68, https://doi.org/10.2110/jsr.2008.014.

Bedrock Couter, Inc., 2003, LS 13 320 particle size analyzer manual PN 7222061A: Miami, Florida, Beckman Coulter, Inc.

Bouma, A.H., 1962, Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies Interpretation: Amsterdam, Elsevier, 188 p.

Bouma, A.H., Coleman, J.M., and Meyer, A.W., 1986, Introduction, objectives, and principal results of Deep Sea Drilling Project Leg 96, in Bouma, A.H., Coleman, J.M., Meyer, A.W., et al., Initial Reports of the Deep Sea Drilling Project, Volume 96: Washington, D.C., U.S. Government Printing Office, p. 15–36, https://doi.org/10.2303/jgs.proc.96.102.1986.

Cantero, M.I., Cantelli, A., Pirmez, C., Balachandar, S., Hickson, T.A., Ye, T.H., Naun, H., and Parker, G., 2012, Emplacement of massive turbidites linked to extinction of turbulence in turbidity currents: Nature Geoscience, v. 5, p. 42–46, https://doi.org/10.1038/ngeo1320.

Caravajal, C., Pauli, C.K., D.W. Fildani, A., D.L. McGann, M., Gwiazda, R., and Herguera, J.C., 2017, Unraveling the channel-lobate transition zone with high-resolution AUV bathymetry: Navy Fan, offshore Baja California, Mexico: Journal of Sedimentary Research, v. 87, p. 1049–1059, https://doi.org/10.2110/jsr.2017.258.

Cilt, P., and Giardini, C., 2002, Accelerated mass flux to the Arabian Sea during the middle to late Miocene: Geology, v. 30, p. 207–210, https://doi.org/10.1130/0191-6312(2002)030<0207:AMFTAA>2.0.CO;2.

Covault, J.A., Romans, B.W., Graham, S.A., Fildani, A., and Hilley, G.E., 2011, Terrestrial source to sedimentary Research, v. 86, p. 929–943, https://doi.org/10.2110/jsr.2016.58.

Clift, P., Haughton, P.D.W., McCaffrey, W.D., Archer, S.G., and Hakes, B., 2008, Development of Deep-Sea Mangroves, the Arabian Sea: Sea-level driven mass flux and deposition: Journal of Sedimentary Research, v. 78, p. 668–682, https://doi.org/10.2110/jsr.2008.076.

Cowe, W.G., 1969, Classification, origin and significance: Marine and Petroleum Geology, v. 26, p. 1900–1918, https://doi.org/10.1016/S0025-3203(97)00027-8.

Eggenhuisen, J.T., Cartigny, M.J.B., de Leeuw, J., 2017, Physical theory for near-bed turbulent particle suspensions and their sedimentary capacity: Earth Surface Dynamics, v. 5, p. 269–281, https://doi.org/10.5194/esurf-5-269-2017.

Elliot, T., 2000, Megafault erosive surfaces and the initiation of turbidite channels: Geology, v. 28, p. 119–122, https://doi.org/10.1130/0191-6312(2000)028<0119:MESESAT>2.0.CO;2.

Fildani, A., Hubbard, S.M., Fildani, J.A., Zuffa, G.G., and Rowland, J.C., 2015, Sources and processes of submarine fans: Marine and Petroleum Geology, v. 64, p. 1236–1273, https://doi.org/10.1016/j.marpetgeo.2015.10.005.

Fildani, A., Siebert, B., and Rowland, J.C., 2016, Submarine channel and channel-lobate deposits on the Arabian Shelf: Turbidity current deposits and associated processes: Amsterdam, Elsevier, 168 p.

Fildani, A., Rickenbacher, M., and Rowland, J.C., 2018, Morphology, structure, composition and build-up processes of submarine fans in the active Congo channel-mouth lobe complex with input from remotely operated underwater vehicle (ROV) multibeam and video surveys: Deep-Sea Research, Part II: Topical Studies in Oceanography, v. 142, p. 25–49, https://doi.org/10.1016/j.dsr2.2017.03.010.

Fildani, A., Hubbard, S.M., Fildani, J.A., Zuffa, G.G., and Rowland, J.C., 2013, Erosion at inception of deep-sea channels: Marine and Petroleum Geology, v. 41, p. 49–61, https://doi.org/10.1016/j.marpetgeo.2012.03.006.

Fildani, A., Mayka, M.P., Stockil, D., Clark, J., Dykstra, M.L., Stockil, L., and Hessler, A.M., 2016, The ancestral Mississippi drainage: Journal of Paleontology, v. 90, p. 479–482, https://doi.org/10.1016/j.jpalnele.2017.06.007.

Folk, R.L., 1954, The distinction between grain size and mineral composition in sedimentary-rock classification, origin and significance: Marine and Petroleum Geology, v. 26, p. 1900–1918, https://doi.org/10.1016/0191-6312(89)90010-4.

Folk, R.L., and Ward, W.C., 1957, Organic, origin and significance: Marine and Petroleum Geology, v. 10, p. 384–399, https://doi.org/10.1016/0191-6312(71)90027-9.

Folk, R.L., and Ward, W.C., 1957, Organic, origin and significance: Marine and Petroleum Geology, v. 10, p. 384–399, https://doi.org/10.1016/0191-6312(71)90027-9.

Folin, E., and Normark, W.R., 1987, Comparing examples of modern and ancient turbidite systems: Problems and concepts, in Leggett, J.K., and Zuffa, G.G., eds., Marine Clastic Sedimentology: Concepts and Case Studies: London, Graham and Trotman, p. 1–38, https://doi.org/10.1007/978-1-4684-2876-8_4.

Folin, E., and Ricci Luchetti, F., 1972, Le torbiditi dell’Appennino settentrionale: Introduzione all’analisi di facies: Memorie della Societa Geologica Italiana, v. 11, p. 161–199.

Folk, R.L., and Ward, W.C., 1957, Organic, origin and significance: Marine and Petroleum Geology, v. 10, p. 384–399, https://doi.org/10.1016/0191-6312(71)90027-9.

Garcia, M., and Parker, G., 1989, Experiments on hydraulic jumps in turbidity currents near a canyon fan transition: Science, v. 245, p. 393–396, https://doi.org/10.1126/science.245.4916.393.

Haughton, P.D.W., Barker, S.P., and McCall, W.D., 2003, ‘Linked’ debris in sand-rich turbidite systems: Origin and significance: Sedimentology, v. 50, p. 459–482, https://doi.org/10.1046/j.1365-3091.2003.00560.x.

Hubbard, S.M., Haughton, P.D.W., Davies, C.E., and McCaffrey, W.D., 2009, Hybrid sediment gravity flow deposits: Classification, origin and significance: Marine and Petroleum Geology, v. 26, p. 1900–1918, https://doi.org/10.1016/0191-6312(89)90010-4.
Mississippi fan: Geology, v. 20, p. 693–696, https://doi.org/10.1130/0091-7613(1992)020<0693: UPTSB>A2.3.CO;2.

National Geophysical Data Center, 2001, U.S. Coastal Relief Model—Central Gulf of Mexico: National Geophysical Data Center, NOAA, https://doi.org/10.7289/V64Q7RW0 (accessed November 2017).

Normark, W.R., Posamentier, H., and Mutti, E., 1993, Turbidite systems: State of the art and future directions: Reviews of Geophysics, v. 31, p. 91–116, https://doi.org/10.1029/93RG02832.

O’Connell, S., Stelting, C.E., Bouma, A.H., Coleman, J.M., Cree, M., Droz, L., Meyer, A.W., Normark, W.R., Pickering, K.T., Stow, D.A.V., and DSDP Leg 96 Shipboard Scientists, 1985, Drilling results on the lower Mississippi Fan, in Bouma, A.H., Normark, W.R., and Barnes, N.E., eds., Submarine Fans and Related Turbidite Systems: New York, Springer-Verlag, p. 291–298.

O’Connell, S., Ryan, W.B.F., and Normark, W.R., 1991, Evolution of a fan channel on the surface of the outer Mississippi Fan: Evidence from side-looking sonar, in Weimer, P., and Link, M.H., eds., Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems: New York, Springer-Verlag, p. 365–381, https://doi.org/10.1007/978-1-4684-8276-8_20.

Patacci, M., Haughton, P.D.W., and McCaffrey, W.D., 2014, Rheological complexity in sediment gravity flows forced to decelerate against a confining slope, Braux, SE France: Journal of Sedimentary Research, v. 84, p. 263–277, https://doi.org/10.2110/jsr.2014.26.

Piper, D.J.W., 1978, Turbidite muds and silt on deep-sea fans and abyssal plains, in Stanley, D.J., and Kelling, G., eds., Sedimentation in Submarine Canyons, Fans and Trenches: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, p. 163–176.

Piper, D.J.W., and Normark, W.R., 2001, Sandy fans: From Amazon to Hueneme and beyond: American Association of Petroleum Geologists Bulletin, v. 85, p. 1407–1438, https://doi.org/10.1306/1365-3091.851407.

Poppe, L.J., Eliason, A.H., Fredericks, J.J., Rendigs, R.K., Blackwood, D., and Polloni, C.F., 2000, Grain-size analysis of marine sediments: Methodology and data processing, in USGS East-Coast sediment analysis: Procedures, database, and georeferenced displays: U.S. Geological Survey Open-File Report 00-358, http://pubs.usgs.gov/of/2000/of00-358.

Power, B., Covault, J., Fildani, A., Sullivan, M., Clark, J., Carson, B., Zarra, L., and Romans, B., 2013, Facies analysis and interpretation of argillaceous sandstone beds in the Paleogene Wilcox Formation, deep-water Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 63, p. 575–578, https://doi.org/10.2110/jsr.2013.06313.

Prelat, A., Covault, J.A., Hodgson, D.M., Fildani, A., and Flint, S.S., 2010, Intrinsic controls on the range of volumes, morphologies, and dimensions of submarine lobes: Sedimentary Geology, v. 232, p. 66–76, https://doi.org/10.1016/j.sedgeo.2010.09.010.

Shepard, F.T., 1954, Nomenclature based on sand-silt-clay ratios: Journal of Sedimentary Petrology, v. 24, p. 151–158.

Shipboard Scientific Party, 1986, Deep Sea Drilling Project Leg 96, Mississippi Fan, Gulf of Mexico, Deep Sea Drilling Project, Program Preliminary Report, Site 621, https://doi.org/10.2973/dsp.proc.96.104.1986.

Singer, J.K., Anderson, J.B., Ledbetter, M.T., McCave, I.N., Jones, K.P.N., and Wright, R., 1988, An assessment of analytical techniques for the size analysis of fine-grained sediments: Journal of Sedimentary Research, v. 58, p. 534–543, https://doi.org/10.1002/12.9897-8648000102C1865D.

Stelting, C.E., and DSDP Leg 96 Shipboard Scientists, 1985, Migratory characteristics of mid-fan meander belt, Mississippi Fan, in Bouma, A.H., Normark, W.R., and Barnes, N.E., eds., Submarine Fans and Related Turbidite Systems: New York, Springer-Verlag, p. 283–290.

Stuart, C.J., and Cauchoy, C.A., 1976, Form and composition of the Mississippi Fan: Gulf Coast Association of Geological Societies Transactions, v. 26, p. 333–343.

Sylvester, Z., and Lowe, D.R., 2004, Textural trends in turbidites and slurry beds from the Oligocene flysch of the East Carpathians, Romania: Sedimentology, v. 51, p. 945–972, https://doi.org/10.1111/j.1365-3091.2004.00653.x.

Talling, P.J., Amy, L.A., Wynn, R.B., Peakall, J., and Robinson, M., 2004, Beds comprising debrisc sideniched within co-genetic turbidite: Origin and widespread occurrence in distal depositional environments: Sedimentology, v. 51, p. 163–194, https://doi.org/10.1111/j.1365-3091.2004.00812.x.

Talling, P.J., Wynn, R.B., Masson, D.G., Frenz, M., Cronin, B.T., Schiebel, R., Akhmetzhanov, A.M., Dalmeier-Tiessen, S., Benetti, S., Weaver, P.P., Georgioupolou, A., Zühlsdorff, C., and Amy, L.A., 2007, Onset of submarine debris flow deposition far from original giant landslide: Nature, v. 450, p. 541–544, https://doi.org/10.1038/nature06313.

Talling, P.J., Wynn, R.B., Schmidtm, D.N., Rixon, S., Emery, A., and Amy, L., 2010, How did thin submarine debris flows carry boulder-sized intraclasts for remarkable distances across low gradients to the far reaches of the Mississippi Fan?: Journal of Sedimentary Research, v. 80, p. 829–851, https://doi.org/10.2110/jsr.2010.076.

Talling, P.J., Masson, D.G., Summer, E.J., and Malgesini, G., 2012, Subaqueous sediment density flows: Depositional processes and deposit types: Sedimentology, v. 59, p. 1597–2003, https://doi.org/10.1111/j.1365-3091.2012.01353.x.

Terlaky, V., and Arnott, R.W.C., 2014, Matrix-rich and associated matrix-poor sandstones: Avulsion splays in slope and basin-floor strata: Sedimentology, v. 61, p. 1175–1193, https://doi.org/10.1111/sed.12096.

Traer, M.M., Fildani, A., McHargue, T., and Hilley, G.E., 2015, Simulating depth-averaged, one-dimensional turbidity current dynamics using natural topographies: Journal of Geophysical Research: Earth Surface, v. 120, p. 1495–1500, https://doi.org/10.1002/2015JF003038.

Twichell, D.C., Kenyon, N.H., Parson, L.M., and McGregor, B.A., 1981, Depositional patterns of the Mississippi fan surface: Evidence from GLORIA II and high-resolution seismic profiles, in Weimer, P., and Link, M.H., eds., Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems: New York, Springer-Verlag, p. 349–363, https://doi.org/10.1007/978-1-4684-8276-8_19.

Twichell, D.C., Schwab, W.C., Nelson, C.H., Kenyon, N.H., and Lee, H.J., 1992, Characteristics of a sandy depositional lobe on the outer Mississippi fan from SeaMARC IA sidescan sonar images: Geology, v. 20, p. 689–692, https://doi.org/10.1130/0091-7613(1992)020<0689:CO SDSL>2.3.CO;2.