Sedimentation from Jets: A Depositional Model for Clastic Deposits of all Scales and Environments*

By

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General Statement

Sedimentary geologists typically employ depositional models in order to predict subsurface sand body morphology and distribution. One assumption of these models is that sedimentary processes are environment and scale specific (Walker and James, 1992). However, because the physics of sediment and fluid transport operate independently of environment and scale (e.g., Fischer et al., 1979; Middleton and Southard, 1978), a more logical approach may be to develop depositional models that are based on the properties of the decelerating flows responsible for most clastic deposits (Bates, 1953).

Applying a flow-based method significantly reduces the number of unique depositional models, potentially simplifying and improving sand body prediction. It also provides the context for a transition from the current qualitative depositional models to more quantitative models that are based on well-established laws of fluid and sediment transport dynamics. To be useful, these models must predict the properties of 3-D sedimentary bodies over a wide range of complexity, from simple deposits of a single flow to highly self-organized, avulsive complexes. Real progress in this field can only be made with a coordinated program of sediment transport and fluid mechanics research based on laboratory experiments, mathematical models and fieldwork. Sedimentary process models used in the forward sense can provide quantitative estimates of grain-size, layering, and connectivity at various scales over complex 3D-topography and potentially include syndepositional tectonics and changing sea level. These models can also be used in the inverse sense to investigate the strong interdependence of deposit properties, for example, grain-size distribution, relative thickness (Sadler, 1982), facies (Bouma, 1962), and erosion patterns inherited from the flow field and associated grain transport mechanism. Results from these investigations can be used to constrain predictions of micro-scale properties like grain-size distribution from some observable macro-scale property like facies or relative thickness.

Turbulent Jet Model

We propose that in all environments and at all scales there is a dominant flow type that creates most clastic deposits. Consequently these deposits, including deltas, submarine fans, crevasse splays, overwash fans, tidal bars, lower shoreface deposits and bedforms, are constructed from fundamentally similar elements. They are point-sourced, down-flow expanding deposits with well-defined horizontal and vertical distributions of thickness, grain-size, facies, erosion and bedding type. Even deposits in channels, for example braid and point bars in rivers and submarine channels, exhibit features similar both to the above listed types and to one another. Allen (1982) proposed that the dominant mechanism controlling the geometry of most clastic deposits is deceleration associated with flow separation and the growth of turbulent shear layers. We suggest that the observed commonality in the shape and property distribution results from a subset of these separated turbulent flows, those that expand and decelerate from a submerged, focused slot or orifice into a lower velocity region. These flows are commonly called turbulent jets. While traditionally applied to coarse-grained parts of deltas (Bonham-Carter and Sutherland, 1968; Syvitski et al., 1998), a jet model may also explain the delta-like properties of other clastic deposits, for example submarine fans (Beaubouef et al., I, II, 2003) and river bars (Dunn et al., 2003). Other point-source expanding flows including: pure plumes or modified jets (e.g., bi-directional oscillating jets, jets bent by a cross-current), may produce deposits with some similarities to unidirectional jet-plume pair deposits, because these flows also expand and decelerate from a submerged orifice. However, these deposits may be more heterogeneous and geometrically complex.

Fluid entrainment in turbulent jets is the most efficient mechanism for flow deceleration. Deceleration immediately downstream of a topographic discontinuity or submerged orifice requires the transfer of momentum from the moving fluid to the slower or stationary ambient fluid. In dilute Newtonian flows (<10% v/v), the major momentum transfer mechanism is turbulence (Fischer et al., 1979). If the flow boundary downstream from the orifice expands more than a few degrees the main flow and the surrounding fluid will separate causing a distinct velocity discontinuity. Strong turbulence will develop at this discontinuity due to a Kelvin-Helmholtz instability creating a shear layer, which will grow downstream as the momentum diffuses through a cascade of turbulent eddies. Viscous and gravitational forces inhibit turbulence development at the shear layer. If the viscous or gravitational forces significantly exceed the inertial force, turbulence will not develop (Allen, 1982; Turner, 1973). Consequently the rate of deceleration from an orifice is controlled by two variables: (1) Reynolds number: the ratio of inertial force to viscous force ($Re = \Delta\rho\Delta UL/\mu$); and (2) Froude number: the ratio of the inertial force to the gravity force ($Fr = \Delta U/[\Delta\rho gh]^{0.5}$). Here L and h are characteristic length and height scales, g is gravitational acceleration and μ is the dynamic viscosity. The velocity (ΔU) and density ($\Delta\rho$) gradients are calculated between the region of separated flow and the surrounding fluid environment and not necessarily integrated across the entire flow. At the orifice most natural sedimenting flows have a high Reynolds number and can be considered fully turbulent ($Re > 5000$). However, the Froude number may vary widely, producing either an inertial dominated supercritical jet ($Fr > 1$) or gravity dominated subcritical plume ($Fr < 1$) (Fischer et al., 1979). A pure, homopycnal ($\Delta\rho = 0$), completely inertial jet, similar to the high Fr jet in Figure 1a, represents an asymptotic end-member with the smallest possible expansion angle. As the Froude number decreases the jet becomes wider as gravitational collapse becomes more important.

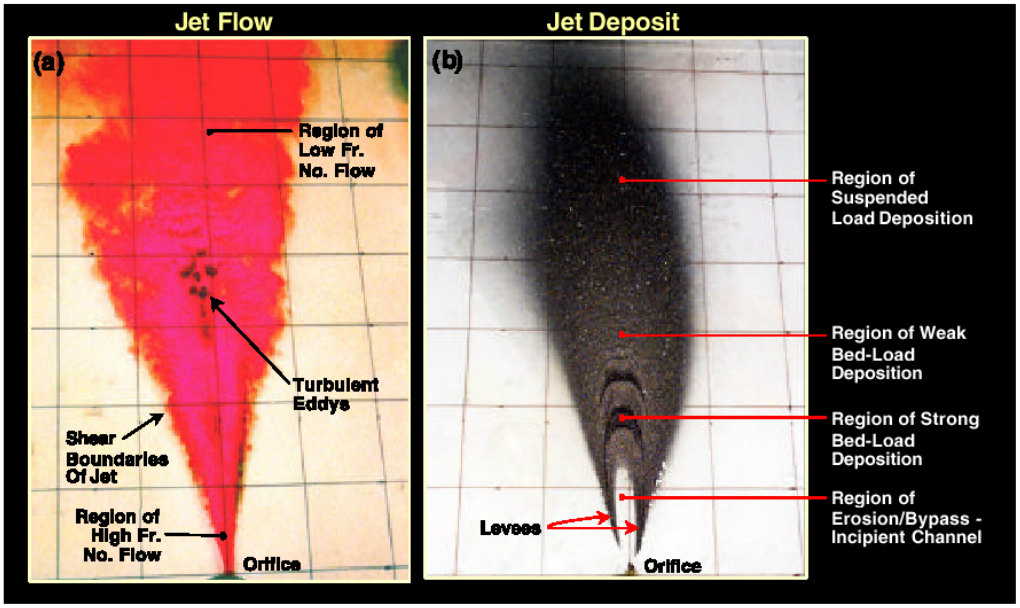

Figure 1. Wall jet-plume pair flow and deposit.

Flow separation in natural flows is commonly focused at a 3-D point-source orifice or a 2-D line-source orifice. For a channel exiting from a canyon, expansion is in 3D from a point-source. In flow over 2-D bedforms, expansion is in 2-D from a half orifice (step) producing a half jet (Jopling, 1965). In the classic literature this type of separation has been called both a jet (Jopling, 1965) and a wake (Raudkivi, 1963). Wakes and jets are geometrically equivalent as they are both products of relative fluid motion and differ only in the coordinate systems that define them (Allen, 1982). Therefore, the jet is not a single flow but a distinctive family of flows belonging to the larger class of separated flows that includes wakes (Allen, 1982). A wake behind a flow-blocking object creates two shear layers, which can also be considered as half jets expanding into the separated/blocked flow region. Flow between two objects creates two shear layers; this is often called a jet but can also be considered as two half wakes, one behind each object. In essence all jets need a region of slower moving fluid, or separated flow blocked behind some obstruction.

Examination of the Froude number equation shows that jet flow is favored when one or more of the factors dominates: (1) velocity of the flow is significantly higher that the surrounding flow (high ΔU = large inertial force) (2) the density contrast between the flow and its surroundings is weak (small $\Delta\rho$ = small gravity force), or (3) if the flow is very thin (small h= small gravity force). Consequently, all turbulent sediment-laden flows are either jets themselves or, if they are plumes, they will contain separated flow regions that are jets (Allen, 1982). Because stratigraphically significant sedimentation is associated with high velocity flows (e.g., floods, storms, or slope failures), many flows are jets at the primary orifice. In other highly gravitationally dominated flows, for example, rivers and turbidity currents in channels, or in the plume region of an expanding turbidity current; flow separation will occur; and jets will form when $\Delta\rho$ (separated vs ambient flow) is small. Apart from topography, separation may also be the result of intrinsic turbulent flow structure. A separated jet associated with a stable turbulence structure (soft jet) will evolve into a separated topographic jet (hard jet) as sedimentation proceeds (Sidorchuk, 1996). Jets associated with channel terminations at the periphery of a complex sedimentary body (e.g., submarine fan or delta) are the dominant sites of deceleration, and hence sedimentation. It is proposed in an accompanying paper (Van Wagoner et al., 2003) that energy dissipation controls the location and evolution of these jets and jet deposits.

As a point-source jet expands from the orifice, velocity decreases downstream, and the density (gravity force) of the flow begins to dominate the inertia (motion force). Since all sediment-laden flows have a different density than the surrounding fluid, they will transition at a submerged hydraulic jump, into a gravity-dominated plume that expands through gravitational collapse. We call this fundamental decelerating depositing flow the jet-plume pair. In an expanding jet-plume pair flowing over a horizontal or downward sloping surface the submerged hydraulic jump is usually weak and diffuse; so deposition is predominantly in the jet. Submerged hydraulic jump deposits may become important if the flow is one-dimensional or if the topography slopes upstream. The coarsest sediment is deposited in the jet region, producing better hydrocarbon reservoir deposits than the plume deposit. An experimental wall-bounded jet-plume pair is presented in Figure 1a. Jet-plume pair properties include: (1) characteristic spreading angle controlled by vertical confinement, bottom friction and Froude number, (2) strongly turbulent in the jet region, (3) maximum turbulence intensity occurring some distance downstream from orifice [8 orifice diameters for a free jet (Fischer et al., 1979)], and (4) power law downstream and gaussian across-stream velocity distributions (Fischer et al., 1979).

Although boundary and stratification conditions vary between jets in different depositional environments, the functional form of the velocity decay and dependence on controlling variables is the same due to the universality of the jet deceleration mechanism. Consequently, the only effect of environment specific controls like variations in gravity force (density), friction, and entrainment, is to alter the ratio of across-stream and downstream velocity magnitude, or expansion angle. The simplest point-source, turbulent jet flow pattern is that of an axisymmetric free jet issuing into a semi-infinite body of fluid and expanding in all directions with a well defined expansion angle (Albertson et al., 1950; Fischer et al., 1979). Variables that affect this expansion angle include: (1) magnitude of the density contrast, (2) geometric constraints on the shear boundary expansion due to the proximity of the bed or water surface, (3) roughness of the bottom, and (4) lifting or blockage of the flow due to sedimentation. The net effect of the latter 3 controls is that expansion angle is reduced by shoaling (reduced turbulent entrainment) but increased by friction (Wright, 1977) and lifting of the flow due to deposition (increased gravity force). In the near-orifice region where the deposit builds up, all jets become wall-attached regardless of the sign and magnitude of the density contrast ($\Delta\rho$).

Features of Jet-Plume Pair Deposits

All of the features of the deposit of a point-source jet-plume pair can be explained by convolving the sediment flux process at the bed (erosion → bypass → suspension deposition) with the spatially decaying velocity field. The jet flow field is more systematic and predictable than a plume because jet behavior is largely independent of slope and hence topography (Imran et al., 2002), while a plume is very slope sensitive. Consequently jet deposits have very characteristic bed patterns and vertical successions. These characteristics, illustrated in Figure 1b, include: (1) point-source planform expanding outwards at characteristic expansion angle controlled by the jet velocity field and grain-size, (3) near orifice erosion / incipient channel formation surrounded by levees (Imran et al., 2002), (4) progression of facies with decreasing velocity: erosion region → bedform region → pure suspension deposition region, and (5) thickness decreasing exponential-linear downstream and gaussian-like across-stream. In a larger scale deposit with paleo-flow indicators, vectors will be spreading from point-source orifice.

Strong turbulence in the jet region has great potential for eroding the substrate creating a flute-like erosional scour. A jet experiment that illustrates a high velocity scour, with fill from a lower velocity flow is presented in Figure 2. The jet erosion scour widens and deepens with distance downstream to the region of maximum turbulence, (~4-8 orifice diameters) where it shallows, widens and then merges with the depositional surface. Allen (1982) suggested that flutes are developed from separated flows behind an obstacle or bed defect (i.e., wakes). We suggest that many flutes, including the largest, may be related to flow separation from jets emanating from a hard or soft orifice. Scour and fill patterns such as these can be found throughout the sedimentary geology literature and may often have been interpreted as channels and channel fills.

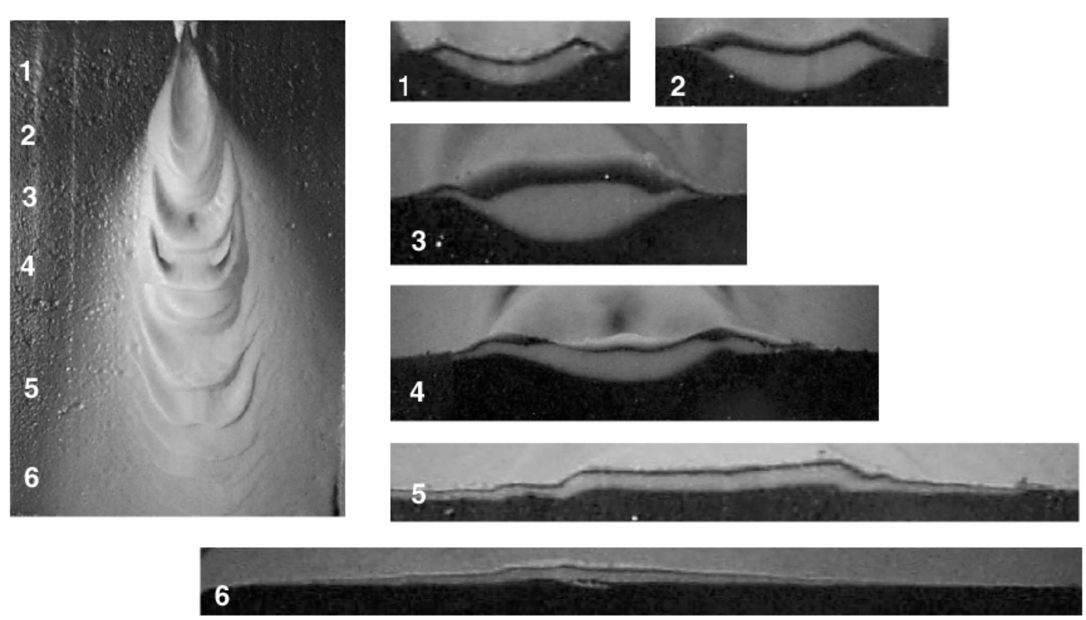

Figure 2. Jet scour and across-stream deposit shape.

Grain-size decay in a jet-plume pair deposit is also highly systematic, reflecting systematic velocity and concentration decay. The results of an experimental high Froude number flow (Fr = 14.6) with over 300 grain-size samples collected on a grid is presented in Figure 3. Although downstream velocity decay in the jet region follows a power law, the grain-size decay is exponential-linear in the downstream direction due to convolution of the jet velocity field and depositional flux process (Figure 3c). In the cross-stream direction, convolution of a gaussian transverse velocity decay and deposition flux gives a peaked gaussian-like distribution (Figure 3c). Because the thickness and grain-size distributions are both ultimately controlled by the flow field, there is remarkable similarity in the shape of thickness and grain-size contours (Figure 3b), creating a strong correlation between statistics of the grain-size distribution and thickness as observed in Figure 3d. The exact form or the correlation depends on the position in the deposit, suspension, bypass or bedload region. As discussed earlier, for a particular boundary configuration, the planform of the jet-plume pair flow and hence that of the deposit are a function of Froude number. In Figure 4 we present experimental deposit shapes and axial grain-size decay for multiple experiments on a flat horizontal plate with different Froude numbers. The orientations of bedform crests illustrated in Figure 4a generally mimic the deposit thickness contours which vary in shape from elongate for a jet to almost circular for the low Froude number (plume-like) case (Figure 4b). A cross-plot of plan shape against Froude number is presented in Figure 4c where the plan shape is calculated as the ratio of maximum length to maximum width of a specific thickness contour (0.5 relative thickness). This plot (Figure 4c) shows that at high Froude numbers (>5) the deposit approaches an elongate shape about 4 times longer than wide, a feature which seems reasonable, because as discussed earlier, the pure jet flow field is the narrowest and asymptotic in all properties. This relationship between body shape and Froude number could be used to estimate the Froude number of the flows that deposited natural sand bodies, such as the turbidite piston core data of Pilkey et al. (1980). However, the effect of slope on down-flow and across-flow gravity components must be taken into account to properly distinguish plume deposits from jet deposits.

The exponential coefficient of the down-axis grain-size decay (P[50]) is also a function of Froude number but varies inversely to grain-size (Figure 4c). Spatial grain-size decay is faster for low orifice Froude number flows and asymptotically reaches a slower decay at high Froude numbers. This high Froude number limit may represent the uniform suspension deposition rate of Martin and Nokes (1988), and faster deposition rates at lower Froude numbers may result from collapse of the concentration profile or flow thinning. Because both body shape and proximal grain-size decay demonstrate strong correlations with Froude number, they show a significant correlation when cross-plotted (Figure 4d).

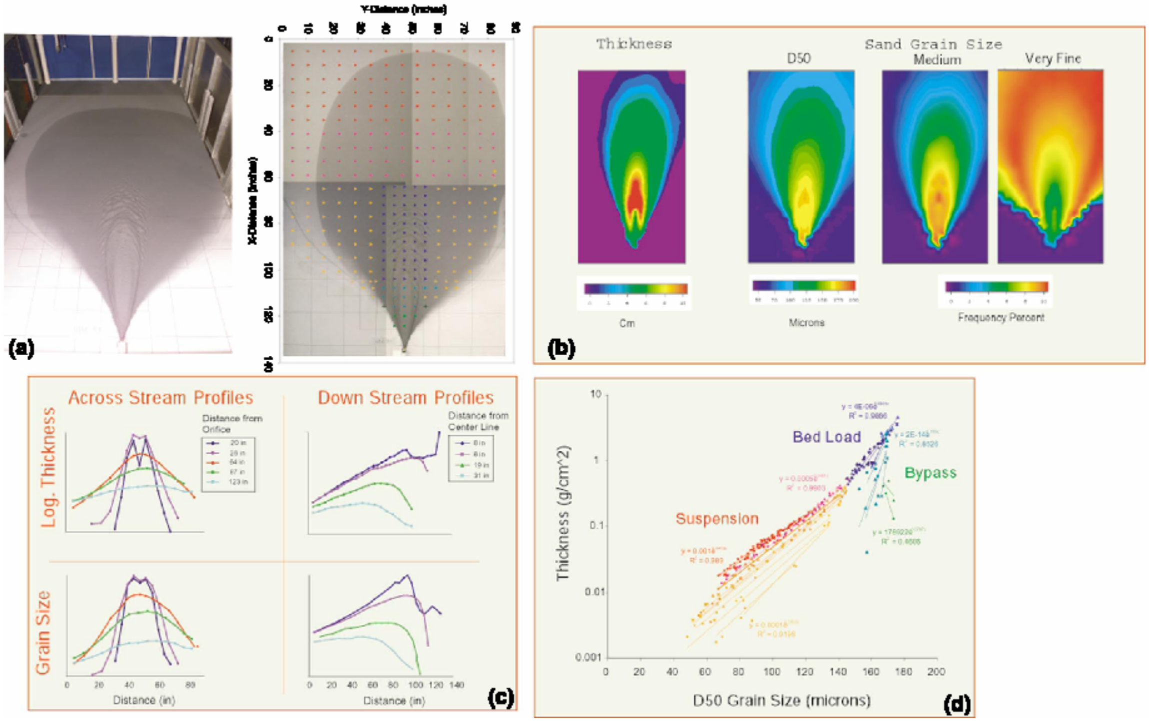

Figure 3. Grain size and thickness distribution in a jet-plume pair deposit (Fr=14.6).

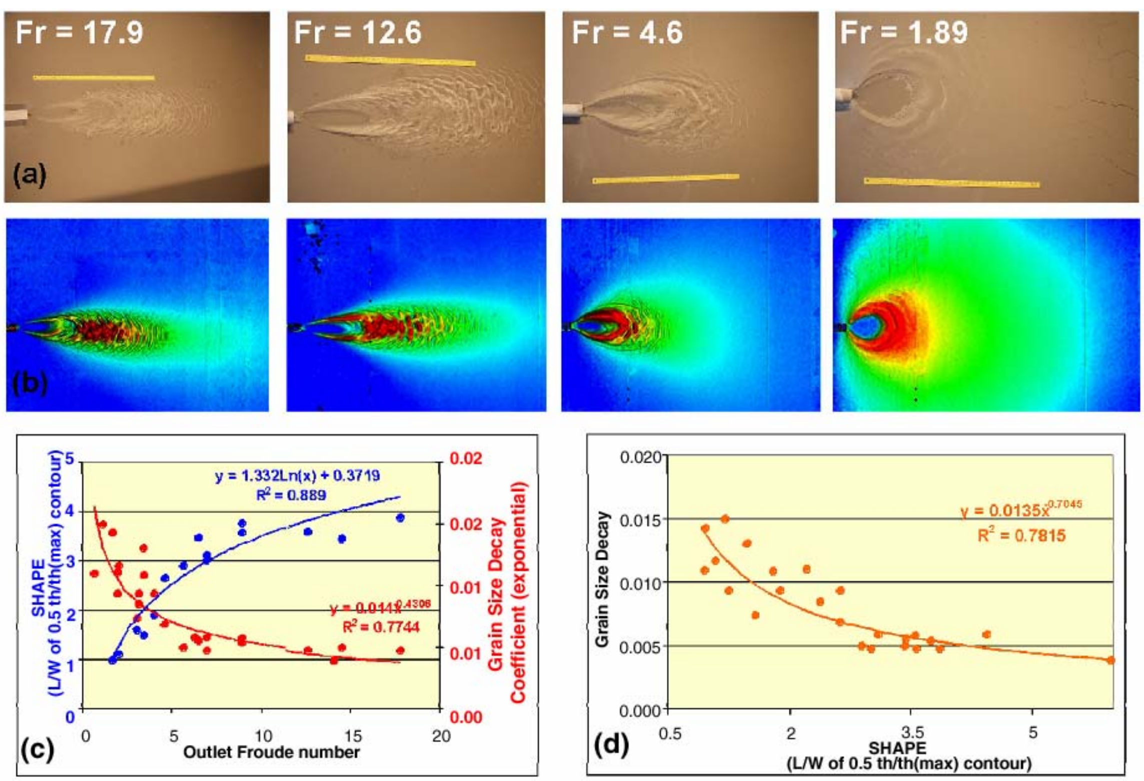

Figure 4. Controls on shape and grain size decay over a wide range of Froude number.

Sedimentary Bodies

So far the discussion has been restricted implicitly to steady flows. However, all sedimentary flows are fundamentally unsteady due to interaction of the flow with the accreting deposits and variation in water and sediment discharge at the orifice. Real deposits can be considered as a composite or sandwich of steady deposits or layers, laid down sequentially in small time steps. Each layer of the sandwich has a certain properties that are spatially correlated through the flow velocity and concentration fields at every x, y position. These properties include relative thickness, grain-size, and facies. Consequently a complex body will inherit its properties from the steady jet-plume element and its stacking defined by the spatial distribution of orifices (orifice distribution function). Smooth translation in orifice location results from continual interaction between the flow and deposit. Abrupt dislocations in layering are due to avulsion. Under steady flow, layers will translate smoothly away from the orifice (progradation) as the deposit grows from a simple jet deposit into a jet (para?)-sequence with the same orifice. This is the leaf deposit pattern of Van Wagoner et al. (this volume). If flows are unsteady and waning, the deposit will prograde and coarsen up over multiple flows, but in a single flow it will translate smoothly backwards and shrink forming a fining up, expanding, waning-flow facies sequence or turbidite (Bouma, 1962). Because complex deposits are built from simple elements, experiments on complex avulsive deltas (Figure 5) also demonstrate a remarkably strong relationship between grain-size distribution and body thickness at every x, y location, similar to the correlations for individual jet-plume pair deposits presented in Figure 3. When we compare the experimental delta from Figure 5 to a similar plot for Wax Lake Delta in Louisianas Atchafalaya Bay, we discover a trend with a similar correlation and functional form suggesting that such trends are fundamental to composite clastic sedimentary bodies. Similar relationships have been observed repeatedly in experimental, field (Sadler, 1982), and numerical deposits over a range of deposit complexity from simple to extremely complex.

Summary

We suggest that environment of deposition and scale may not be first-order controls on the properties of clastic sand bodies because the physics of turbulent flow deceleration and sediment transport transcend many clastic depositional environments and scales. There are a limited number of ways to decelerate a flow; of these spatial expansion is the most common. Expansion in turbulent flows creates flow separation, shear layers, and turbulent jets. Consequently, turbulent jet deposits may be the most fundamental and ubiquitous identifiable bodies in the clastic sedimentary record. Apart from expansion angle, jet-plume pair deposits exhibit a large degree of similarity in all environments where jets dominate over ambient flow and where re-working by other processes has not obscured them. The properties of these jet-plume pair deposits are strongly correlated to their shape through the turbulent flow field and depositional process. Physics-based jet-plume pair depositional models can be used to understand the link between 3D-sediment body shape and the grain-size distribution which appears to be so fundamental to the turbulent deposition process.

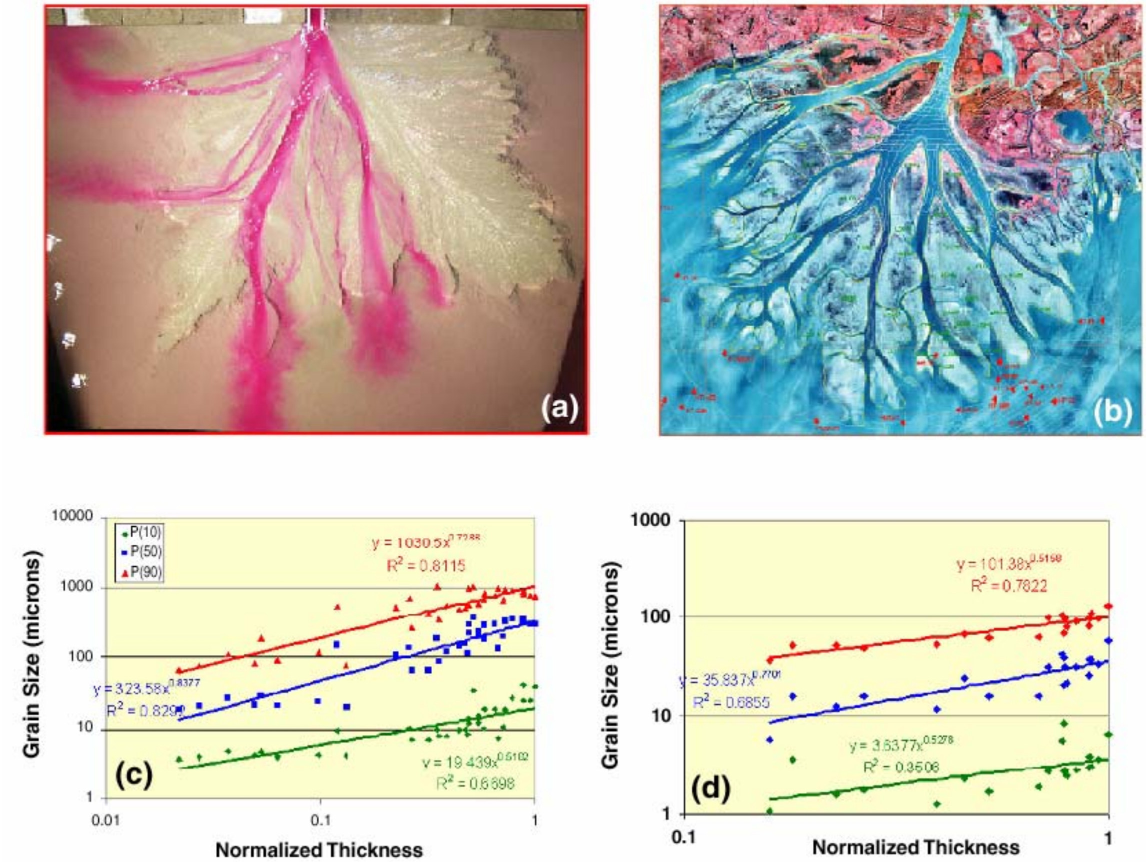

Figure 5. Comparing experimental and Wax Lake Delta thickness and grain size trends.

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