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Hierarchical, Self-Affine Fluvial Sand Body Shapes from Ancient and Modern Settings

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Introduction

Hydrocarbon production rates and recovery efficiencies depend on the spatial distribution of reservoir properties at scales ranging from the pore network seen in a core plug to the distribution and connectivity of bodies resolvable at seismic scales. Analog studies of modern environments and outcrops help span the range of length scales, but there is always uncertainty related to the applicability of a given analog to a subsurface data set. If there are common stratigraphic elements or bodies found in a wide range of depositional environments and over a wide range of dimensions, then reservoir models could be built of such objects without reliance on a specific analog. This paper describes the preliminary results of an on-going effort to test the hypothesis that most coarse-grained fluvial strata are composed of bodies that have strong commonalties in shape, internal structure and property distributions over a range of depositional styles and dimensions. In conjunction with work reported in other abstracts (see Van Wagoner et al., Hoyal et al., and Beaubouef et al., this volume), we hypothesize that sedimentary bodies in fluvial systems share a common shape and evolutionary pathway with bodies in other environments of deposition such as deltas, submarine fans, crevasse splays, and washover fans, among others.

We postulate that similarity in sedimentary body shape over this spectrum of environments of deposition, including fluvial strata, is a function of similar global dynamics of flow and particle deposition. We believe that these are the dynamics of nonequilibrium thermodynamics of open systems that form structures (beds, bars, lobes, fans) to dissipate excess kinetic and potential energy (see Van Wagoner et al., this volume).

Stratigraphic studies of ancient (Jurassic, Salt Wash Mbr., Morrison Fm. Green River, Utah) and modern (Red River, Randlett, Oklahoma) fluvial bar complexes delineated multiple orders of nested sand bodies which are statistically similar in shape and have consistent internal grain size and sedimentary structure distributions. Sand body shape is defined as the 3D surface bounding all genetically related sedimentary particles. In practice, the boundary is determined by using a "cut off" criterion based on thickness, grain size, or other characteristic. Where thickness information is not available, planform (mapview) outline can be used as a measure of shape. Shape planforms from the Salt Wash and modern Red River were analyzed as part of a larger effort to characterize sandstone body shape in many depositional environments.

Statistical Shape Similarity

Length-area plots of depositional fluvial planforms yielded slope exponents near two, indicating space filling (non-fractal) behavior. However, box counting of perimeters of 34 fluvial bar planforms from the Red River using high resolution aerial photos taken during a low flow stage of the Red River generated statistically self-affine dimensions (Df = 1.16) over 3.0 orders of deposit size. The calculated fractal dimension shows a small but consistent, statistically significant difference from one. Principal component analysis using shape length (central axis or "backbone") and shape width measurements at ten equally spaced locations along the backbone ("ribs") was found to be a more robust and useful characterization of sand body shape (Figure 1). A three component model including length, and two parameters which characterize width variation along the central axis (termed "lobateness" and "fatness") was able to fit 88% of body shape variability from a population of over 200 deposits from a wide range of depositional environments.

Field Areas and Methods

Field testing of a new approach to analyzing siliciclastic deposits as hierarchical structures built of similar elements required data sets from a variety of depositional environments where three-dimensional sand body morphology and internal properties could be assessed. For fluvial deposits, data types included topographic surveys, aerial photos, and ground penetrating radar (GPR) surveys for morphology and geometry assessment as well as vertical and point observations of grain size, sorting, sedimentary structures, and paleocurrent indicators. All surveying was carried out using a real time kinematic global positioning system (RTK-GPS) which allowed all observations to be located to within ±2cm.

A sandbar complex in the Red River valley near Taylor Oklahoma had the following features which made it attractive for study: (1) composite nature of the bar complex permits analysis of group as well as individual properties of sand bars, (2) typical low flow conditions leave most of the bar complex subaerially exposed, (3) bar complex is only moderately vegetated and slightly eroded or modified by fluvial and eolian processes, (4) aerial photo coverage was available from 1943 – 2000, and (5) USGS stream gauge, in operation from 1960 – present is located 30 km up river at Burkburnett, Texas with no intervening major tributaries. Key elements of the Red River data acquisition program are shown in Figure 2 and consist of: (1) GPR surveys at 250 ft spacing and denser infill (100, 250 and 500 MHz), (2) 67 vibracore sites (5- 20 ft penetration), (3) detailed bar complex topography using RTK-GPS (over 200,000 pts.) All GPR data was acquired using Sensors and Software Inc. equipment and processed with Win Ekko software. Processing steps included: removal of low frequencies (dewow), trace decimation or interpolation to a constant spacing, synthetic aperture migration, and topographic correction. Trace spacing was sufficiently dense (5, 10, 25cm for the 500, 250, and 100 MHz systems respectively) so as to minimize spatial aliasing. Cores were described, photographed and sampled at 2-10 cm intervals for laser particle size analysis (LPSA). Grain size curves and other core observations were tied to the GPR using a two-layer velocity model (vadose and phreatic zones). Figure 3 shows examples of the data types. Note the downstream expanding, digitate topography of the bar complex.

A unique outcrop of the fluvial Salt Wash member of the Jurassic Morrison formation 15 miles south of Green River, Utah was selected for study by virtue of its extensive map view exposure of coeval fluvial bar complexes. The data acquisition program was similar to that of the Red River except that visual grain size and sorting estimates of the outcrop surface were made instead of coring and LPSA. Data acquisition consisted of (Figure 4): (1) GPR surveys shot parallel to and across paleoflow (100, 250 and 500 MHz), (2) 150 visual estimates of grain size and sorting, (3) detailed bar complex topography using RTK-GPS (> 200,000 pts.), (4) over 500 paleocurrent measurements.

Orthorectified aerial photos and the digital elevation model show a Salt Wash bar complex that forms an east-west trending high with a distinct left-hand (northward) bend (Figure 4, paleoflow from left to right). The limits of the channel which must have once enclosed the sandbars is not visible as all finer grained material which formed the coeval floodplain has been removed by recent erosion. Erosion of the well lithofied sandbars themselves is considered to be minor on the basis of: (1) their preserved depositional morphologies, (2) their similarity to sand bodies exposed in cross sections in adjacent canyons where the fine grained facies are preserved, and (3) the lack of evidence for significant erosion in high resolution GPR sections.

The composite nature of the Salt Wash bar complex can be seen in the aerial photo where elements ranging in size from crossbed sets, bars and bar complex appear as light areas against the dark, vegetated background (Figures 4 and 5). The terminology used to describe the elements of the complex is arbitrary in the sense that there is a continuous spectrum of body sizes. Allowing for a gentle regional structural dip to the NE, bar complex topography shows the overall down flow expanding, digitate morphology of the bar complex (Figure 4). The exhumed depositional topography shows bar and bar complex apices are narrow highs that have steep upstream (western) margins. These steep exhumed slopes are interpreted to result from filled scours in the proximal bar as well as positive depositional relief of the bar crest. The medial bar forms a downstream expanding platform with low relief "grooves" oriented parallel to paleoflow. Distal bar and bar complex relief is subdued, forming a broad region of relatively flat sandstone.

GPR surveys of 100, 250 and 500 MHz image the internal geometries of the bar complexes, bars and crossbed sets respectively. As imaged in the 100 and 250 MHz GPR surveys, bar complexes form down flow expanding lobate bodies resting on a composite basal surface that is erosional beneath the proximal bar complex and becomes conformable or downlapping in the distal bar complex. When viewed transverse to paleoflow, the basal composite surface forms a

U-shaped proximal profile that gradually broadens down flow beneath the wide, tabular distal bar complex. The surface is composite in that it is formed by lower bounding surfaces of multiple bars. Where bars overlie one another they show dominantly lateral, compensational stacking. Bars that make up the proximal bar complex are thicker and narrower than the bars in the distal complex.

Intermediate resolution 250 MHz and high-resolution 500 MHz GPR data provide the best imaging of the stratal geometries at the bar scale. The basal surfaces of most bars form the same down flow expanding and shallowing U-shape profile observed in the bar complex. There is a range of vertical successions seen in the GPR sections, but the basic motif seen in most cases permits a two-fold subdivision. The lower bar is dominated by parallel to very low angle trough cross stratification which are nearly conformable to the basal surface, but commonly onlap the proximal scour surface and downlap in the distal bar region. Where exposed at the surface, the lower bar facies exhibit flat or broadly mounded topography. The upper bar is composed of trough crossbed sets that onlap and downlap on to local scours that broaden and diminish in relief in a down flow direction. Upper bar facies form rough surfaces where exposed with paleoflow parallel groves formed at the lateral boundaries of the crossbed sets. The upper bar facies may not be present over the entire bar area. Upper bar deposits are thickest in the proximal bar and taper gradually or abruptly and downlap in the medial or distal bar region. Paleoflow directions taken from cross bedding show more variation (lateral divergence away from the bar core) in the upper bar facies than in the lower bar (dominantly parallel to general paleoflow).

Spatial Variations in Grain-Size

Grain-size analysis of the Red River cores is ongoing. With 11 core sites analyzed to date in two flow down flow transects, the core average grain size trends show distinct downstream fining trend punctuated by coarsening trends in a saw-tooth fashion (yellow line, Figure 2 inset). Two of the core locations (red triangles) were taken in a separate bar complex which was deposited when the main channel was on the north side of the valley. Future work clarify these trends. The addition of deep penetrating 100 MHz GPR should help correlation among core sites, particularly in the proximal bar complex where amalgamation and erosion are important.

Spatial grain-size distributions within the Salt Wash bar complex were assessed using visual estimates of point locations on the outcrop surface. Coring or hand-sampling was not permitted by the BLM in this area and, as a result, vertical grain-size variations could not be assessed. Figure 5 shows grain-size variation with distance along two transects originating from the upstream apex of the bar complex. Note the overall decay in grain size from proximal to distal bar complex. Downstream fining of fluvial deposits is not a new observation. The matter of real interest in these two transects is the composite nature of the grain-size decay. The plot of the northern transect shows a power law fit through the coarse end-members of each bar as well as individual visual fits through the coarsest samples in each bar. Much of the scatter seen in these data for the component bar elements can be attributed to grain size variation in the most proximal areas where winnowing has produced poorly sorted lags.

Fluvial Sandbar Complex Development

The geometric observations of the proximal, medial, distal bar regions, and the vertical facies succession are consistent with deposition from expanding, decelerating, flows. Bar nucleation is initiated immediately down stream of a zone of scour. As the bar builds the scour is commonly filled and the deposit begins to interact more with the flow. Bedload features (trough crossbedding) dominate the upper bar. Flow over the bar top is forced to diverge away from the crest resulting in formation of crossbed sets that diverge obliquely away from the bar axis. With progressive shoaling, grooves form on the bar top as flow begins to develop enhanced pathways to the margins of the bar complex. Finally, the complex is abandoned after avulsion moves the channel to a new location. This process of scour formation and bar growth is interpreted to form in response to jets in the flow, jet deposits, and subsequent evolution of the jet deposit into a "leaf-like" deposit (Hoyal et al. and Van Wagoner et al., this volume).

Preliminary Conclusions

Initial research on modern and ancient fluvial deposits indicates that there are strong similarities in sand body shape over a wide range of length scales. However, more work is necessary to prove the volumetric significance and preservation potential of these fundamental elements and the effects of container (channel) geometry on sand body shape. The relationship between deposit morphology and internal properties also requires further assessment. At this point we make the following conclusions about the fluvial deposits studied so far:

1. There are statistical similarities among fluvial sand body shape over a range of length scales.
2. The basic building blocks of fluvial sand deposits are lobate or teardrop shaped bodies which are narrow and thick at the upstream apex and broaden and thin towards their down flow edges. These elements resemble lobes in distributive environments such as deltas and fans even though they were deposited in confined settings.
3. Scour is concentrated in the proximal zones of each element in the fluvial sand body hierarchy.
4. Grain size diminishes away from the upstream apex and away from the medial axis of all elements with more noise in the trend of downstream grain size decay in proximal areas (winnowing, lags, dominance of bedload) and at smaller length scales.
5. Spatial variation in grain size and other flow related parameters appear to be consistent within depositional complexes that issue from a single apex or "orifice".

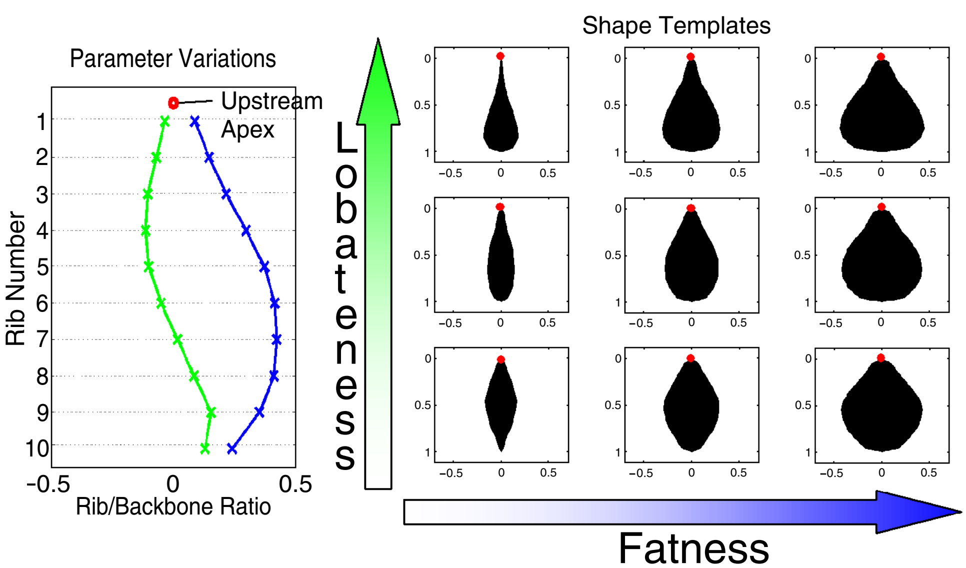


Figure 1. Principal component analysis of sand body planforms.

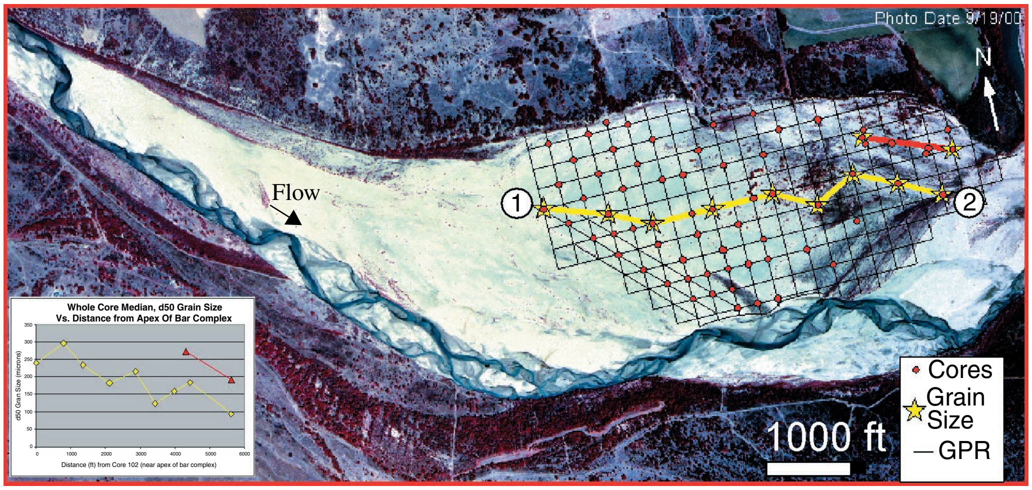


Figure 2. Red River field program and preliminary grain size trends (inset).

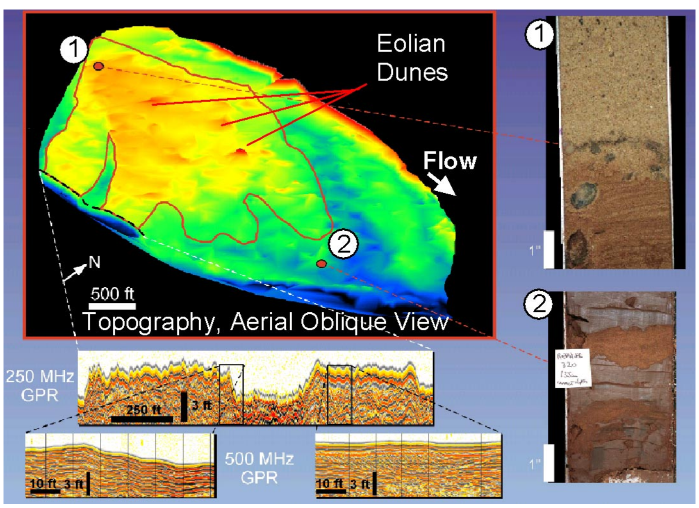
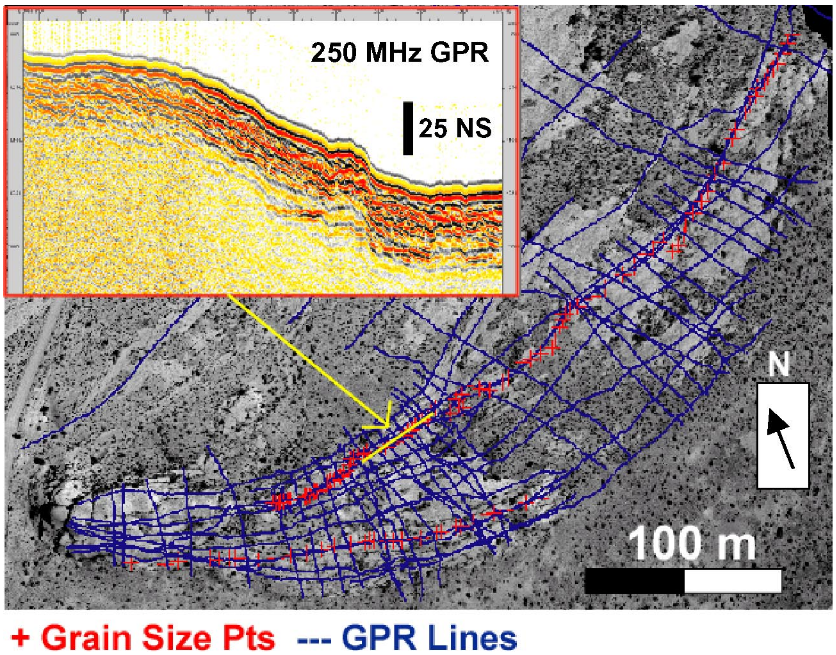


Figure 3. Red River bar complex topography, GPR sections and examples of core facies. See Figure 2 for locations of cores Note dominance of medium - coarse sand and pebbles in core #1 in contrast to fine sand, silt and mud in core #2. GPR sections are transverse to flow and show two depositional lobes (topographic highs).



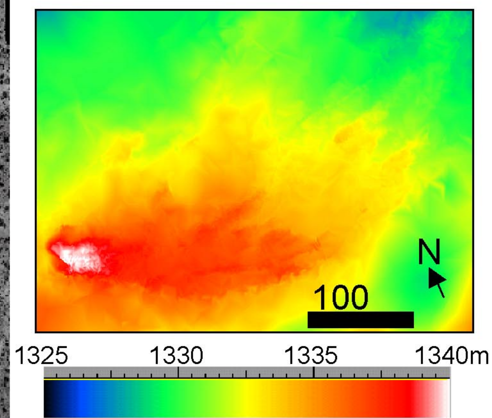
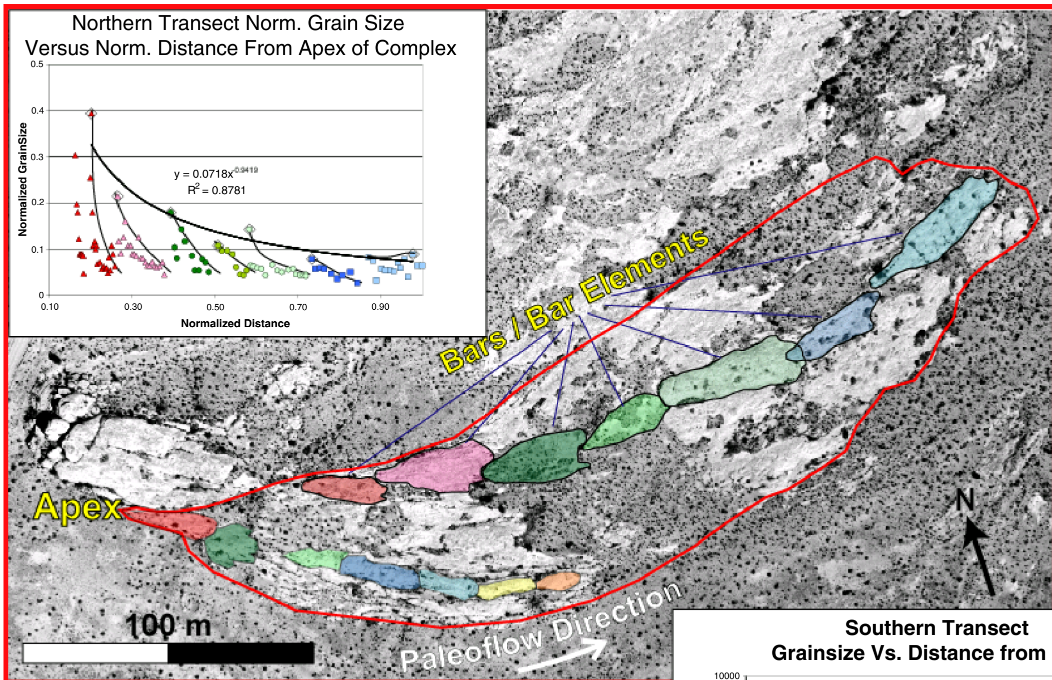


Figure 4. Salt Wash Member fluvial bar complex field program and topography (right).



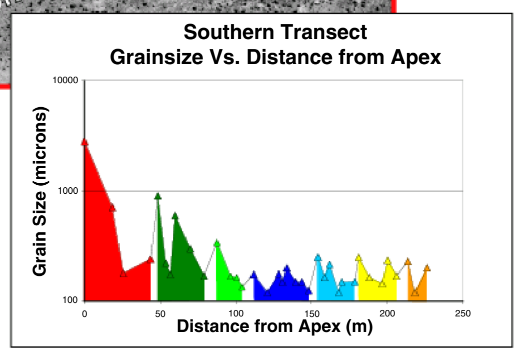


Figure 5. Salt Wash grain size from visual estimates of outcrop surface. Northern transect is plotted as normalized grain size (grain size/max. grain size) versus normalized distance from apex (downstream terminus = 1). Southern transect is shown with log scale for grain size (microns) and distance from apex (m)