Energy Dissipation and the Fundamental Shape of Siliciclastic Sedimentary Bodies*

By

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NOTE: This is the first of six presentations on the general subject of the shapes of siliciclastic sedimentary bodies presented by this group of ExxonMobil researchers under the leadership of John C. Van Wagoner.

General Statement

After years of systematic application and validation, sequence stratigraphy remains, in our opinion, the fundamental framework for the characterization and prediction of siliciclastic reservoirs. Recent advances and modifications to the sequence stratigraphic model have resulted as our stratigraphic resolution has increased through the careful integration of high-quality 3-D seismic surveys with well logs, cores, and outcrops. One outcome of the analysis of these data is that sedimentary bodies appear to have similar shapes regardless of environments of deposition and scale. For example, deltas resemble submarine fans (Beaubouef et al, 2003); the shapes of fluvial bars are related to the shapes of cross beds. An analysis of these similarities was conducted using fluid-dynamics simulation, laboratory experiments, ultra-high resolution 3-D seismic data, numerical simulation, and outcrop and modern studies. Based on this research we propose a new physics and hydrodynamics-based sedimentology that provides a unifying context for the analysis and interpretation of clastic sedimentary systems, largely independent of depositional environment and scale. We hypothesize that this new physics involves energy dissipation predicted by nonequilibrium thermodynamics.

Siliciclastic strata are arranged in bundles of nested, hierarchical bodies or deposits. Shape is an attribute of these sedimentary bodies. It is defined as a body's 3-D outline or external surface. If a sedimentary body could be shrink-wrapped with an infinitely thin sheet of material, the shape of the body is the shrink-wrapped form or surface that separates all the connected grains in the body from unrelated or unconnected grains outside the body. Figure 1 shows the 2-D shapes of sedimentary bodies from a range of scales and environments of deposition. From the shape alone it is impossible to determine the size or depositional environment of these bodies. Thus, shape is independent of scale and place of deposition.

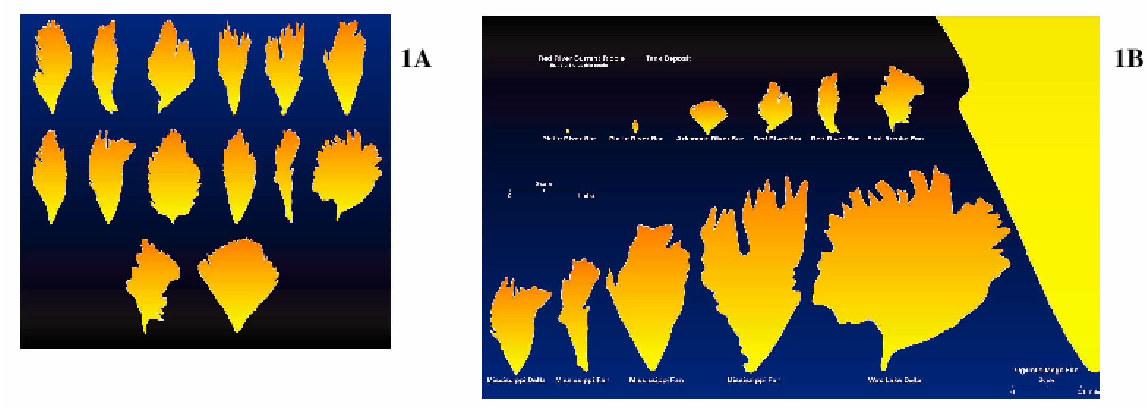


Figure 1 A. Shapes of sedimentary bodies. From shape alone it is impossible to determine size or environment of deposition. Figure 1 B: Shapes of sedimentary bodies displayed at true scales, labeled with environment of deposition. The environments include fluvial, deltaic, submarine fan, and alluvial mega fan.

Research Project: Workflow and Results

To test the similarity of sedimentary-body shape, 482 siliciclastic shapes were collected from a variety of depositional environments including braided and meandering rivers, tidal bars and shoals, deltas, crevasse splays, bay-head deltas, washover fans, tidal deltas, slope channels, submarine fans, and experimental deposits. We restricted the study to deposits of turbulent flows but excluded bodies from aeolian and foreshore environments. The bodies studied range in length scale from 1000 km to <10 cm and span 14 orders of magnitude of area. Perimeter/arithmetic length cross plots (Figure 2) and box counts of shape perimeters for a subset of high-resolution shapes show that they are self-affine. Area/geometric length cross plots (Figure 3) and principal component analyses show that these shapes are statistically similar.

Figure 4 shows some of the shapes used in this study from a variety of depositional environments. These shapes are similar in that they all have an orifice or point source, expand down flow, and typically exhibit lineations indicating that the depositing flows expanded away from the orifice.

These empirical and statistical similarities in shapes indicate that these bodies were deposited by a common physics. The physics at the local, instantaneous scale are the well-established laws of fluid and sediment dynamics However, these dynamics do not explain the cause of the global organization of the bodies observed in nature. A deeper, more encompassing explanation is required. We believe that the explanation can be found in nonequilibrium thermodynamics and energy dissipation.

The Second Law of Thermodynamics states that the entropy of the Universe is increasing; systems are always evolving toward states of increasing disorder. Yet, it is common knowledge that sedimentary systems from bed forms to submarine fans and deltas evolve toward states of increasing order, at least as long as these systems are open. This apparent paradox is explained by nonequilibrium or far-from-equilibrium thermodynamics (Glansdroff and Prigogine, 1971; Nicolis and Prigogine, 1989; Prigogine, 1997; Chaisson, 2001). Nonequilibrium thermodynamics describes how open, far-from-equilibrium systems behave; it applies to all irreversible, open systems, for example: Galaxies, life, economics, culture, clouds, snowflakes, crystal growth, and flow systems such as bed forms and deltas (Chaisson, 2001; Nicolis and Prigogine, 1989). All open systems (i.e., systems through which energy and matter are transmitted) evolve toward increasing complexity with time (Prigogine, 1996; Schneider and Kay, 1995) as these systems form dissipative structures to minimize gradients (Glansdorff and Prigogine, 1971). Such evolution has been described as the arrow of time (Chaisson, 2001). The archetypal arrow of time is: cosmic evolution→particles→galaxies →stars→planets→chemical elements→life→culture. "Regardless of its shape or orientation, such an arrow represents an intellectual guide to the sequence of events that have changed systems from simplicity to complexity" (Chaisson, 2001). An arrow of time, or evolutionary succession, can be defined for all nonequilibrium systems including "things whether galactic clouds, slimy invertebrates, luxury automobiles, or the whole universe itself" (Chaisson, 2001). The sedimentary arrow of time, also called by us the energy dissipation pathway, is: flow→turbulence→jets→jet deposits→"leaf" deposits or bars→flow splitting→channel formation→avulsion→lobes and lobe complexes→"tree" or submarine fans or deltas→landscapes (or submarine seascapes).

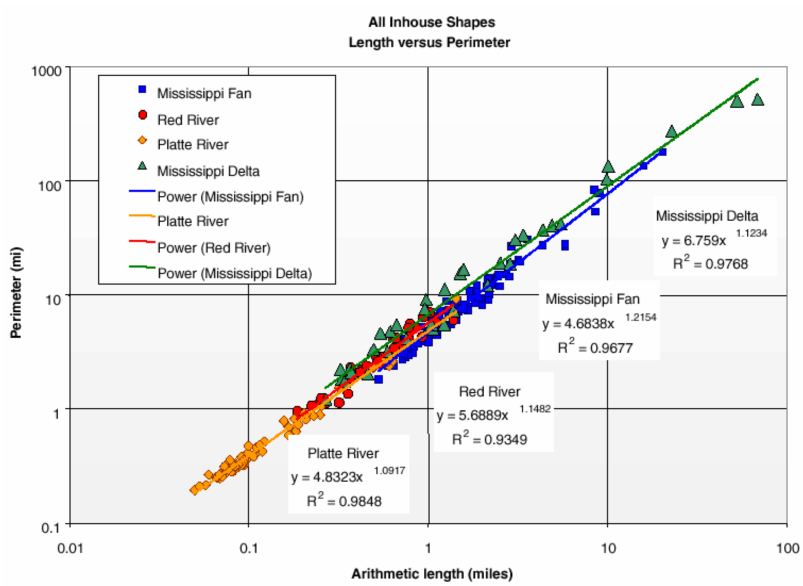


Figure 2. Perimeter/arithmetic length for Mississippi Fan, Red River, Platte River, and Mississippi delta sand-body shapes. The highly correlated fractal exponents indicate that these data are fractal.

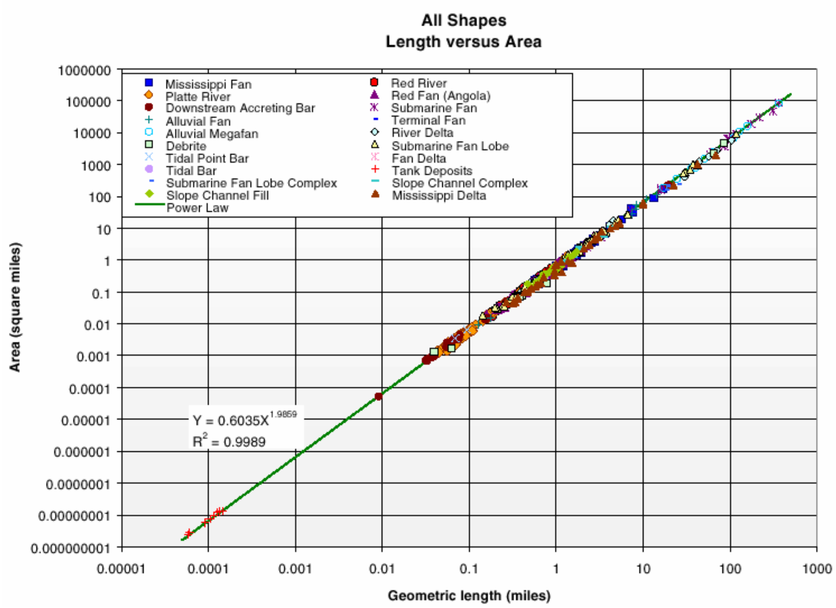
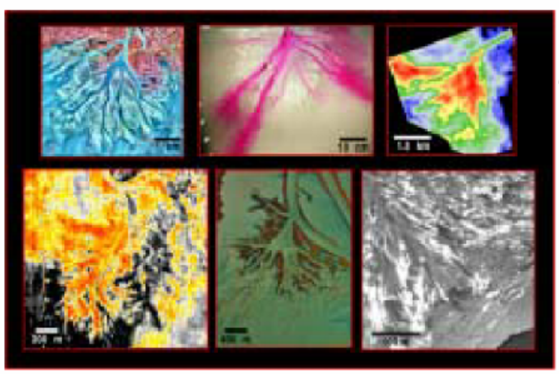


Figure 3. Area/length plot for 482 sedimentary body shapes.



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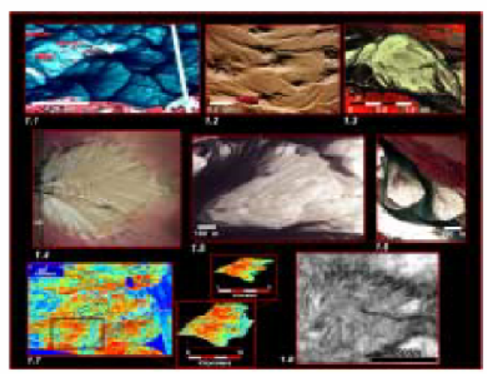

4B

Figure 4. A) Shapes of sedimentary bodies formed in fluvial, deltaic, and submarine fan environments. Clockwise from upper left these images are: Wax Lake bay-head delta, LA.; ExxonMobil Upstream Research Company (URC) tank experiment; Submarine fan; Bar complex or "delta", Red River, OK; Delta; Mississippi Delta Complex; Submarine fan lobe, East Breaks, offshore Gulf of Mexico. B) 1.1, Bar, Platte River, NB; 1.2, Current ripple, Red River, OK; 1.3, Bar, Red River, OK; 1.4, ExxonMobil, URC tank deposit; 1.5, Bar, Arkansas River, OK;1.6, Bars, Arkansas River, OK; 1.7, Side-scan sonar from Mississippi Fan; 1.8, Bar from East Breaks submarine fan.

Global rules govern evolution toward increasing complexity in open systems : 1) Open systems attempt to return to equilibrium, a state in which gradients are minimized. 2) Open systems create dissipative structures to dissipate energy in an effort to minimize gradients. 3) Energy dissipation must be optimized. 4) Energy dissipation transforms energy from one form to another, generally from kinetic energy to heat. In the process of dissipation, entropy is created. Entropy must be transferred from the open system into the surrounding environment in order for the system to grow in complexity and continue to perform optimally (Prigogine, 1997; Chaisson, 2001). 5) Entropy transfer must also be optimized. By optimally transferring entropy to the global environment the system can increase in complexity, the entropy of the global environment increases, and the Second Law is honored. The dissipative structure must do two things: optimally dissipate energy and transfer the entropy created by dissipation to the surrounding environment.

In the world, a single shape optimizes these constraints: the shape of a tree or leaf (Bejan, 2000). Tree structures are all around us: brains, circulatory systems, trees, root systems, clouds, heat sinks, deltas, channel drainage systems, and turbulence (Bejan, 2000) to name a few. All tree structures share common characteristics: 1) they have low-resistance pathways to optimally transport energy to dissipation sites. 2) Dissipation sites are located at the periphery of the structure because that is the optimal location to transfer entropy into the surrounding environment. 3) Low-resistance pathways branch so that the optimal area or volume is utilized for dissipation and the optimally maximum number of dissipation sites at the periphery of the system can be connected to the orifice or energy input site. Many small dissipation sites are more optimal than a single, large site.

We believe that these constraints are the global dynamics that govern the formation and evolution of most clastic sedimentary systems from bedforms to complex bodies such as submarine fans and deltas. It is for this reason that clastic sedimentary bodies have similar shapes: they organize into the shape of a tree or leaf at all scales, and in all environments of deposition, to optimally dissipate energy and transfer entropy. The fundamental dissipative structure in fluid flow is the jet (Vischer, 1995). The jet, also referred to by us as the jet/plume pair (see Hoyal et al, 2003), is a branching tree structure (Baddour and Dance, 1983; Bejan, 2000) defined as an inertially driven flow from an orifice or region of flow constriction that expands and decelerates through turbulent fluid entrainment into a body of same or similar fluid (Jirka, 1981; List, 1982). Energy cascades or dissipates from the largest eddy to the smallest eddies where kinetic energy is converted to heat and passed to the surrounding environment. Froude number, for a given boundary geometry, controls the shape of the jet and thus exerts a primary control on the shape of the deposit (Hoyal et al, 2003). Jets produce sedimentary bodies, including current ripples, trough and planar cross beds (Jopling, 1965; Allen, 1982). They play a major role in forming bars in rivers, delta mouths, and deepwater fans (Bates, 1953; Wright, 1985, Sidorchuk, 1996). Jet deposits, from the scale of the bed up to the bar, exhibit one or more of the following properties: 1) Their thickness and grain size decay approximately exponentially in the direction of flow and have a gaussian distribution across the body. 2) They typically have a region of erosion and bypass bounded by levees near the orifice. 3) There is a proximal region of bed-form deposition and a distal region of suspended-load deposition. 4) The distribution of bedding types changes with radial distance from the orifice and is predictable (for additional discussion of jets and jet deposits see Hoyal et al, 2003).

With time, jet deposits evolve into more complex sedimentary bodies. At these larger scales, sedimentary bodies organize to locate the jets most efficiently, at the periphery of the bodies. Again, the optimal energy transport network is a tree structure. The branches of the tree become channels with hard boundaries. Channels also fulfill another important optimization function. They constantly query the evolving topography to locate the optimal pathway to the periphery. When a more optimal pathway is located because of height differences within the system due to deposition, the flow shifts into this more optimal channel and a new dissipation site is created. This is the fundamental process driving avulsion, and is discussed in more detail below. This pathway, from jets→jet deposits→channelized bodies, is the general description of the sedimentary arrow of time. It is a scale-invariant pathway and describes the evolution of sedimentary bodies as small as current ripples and as large as submarine fans, although these two examples develop at different ends of this pathway. Deltas in mud puddles look like bay-head deltas or river-mouth deltas because they follow the same energy dissipation pathway.

In the following paragraphs we present a more detailed description of the energy dissipation pathway or sedimentary arrow of time with reference to observations from an experiment in the ExxonMobil Upstream Research Tank Facility (Figure 5). In general, we believe that sedimentary bodies pass through three evolutionary phases: phase 1-the jet and jet deposit; phase 2-the "leaf" deposit; phase 3-the "tree" deposit.

The energy dissipation pathway describing sedimentary-body evolution begins with phase 1-a jet and its deposit (Figure 5A). As kinetic energy is dissipated by the jet, a characteristic waning velocity field develops controlling: a proximal updip erosion and bypass region with a typical downflow-shallowing erosional pattern, a region of bed-form deposition, and a distal region of suspended-load deposition, assuming the flow cotains the required finer grains. This first, most elemental sedimentary body is called a current ripple or cross bed, depending upon scale. Many of the properties of the jet are "inherited" by the later, more complex bodies. These include: 1) An incipient channel region that will control proximal channel evolution, 2) branching pathways of preferred flow that will control flow splitting and downdip channel location, 3) the location of maximum regions of deposition that will control locations of avulsion, 4) a characteristic distribution of erosion at the base of the jet and jet deposit that will control subsequent erosional patterns. Kinetic energy continues to be dissipated, velocity decays, and the sandbody begins to grow and interact with the flow. Figure 5B illustrates this interaction in the proximal bed-form field. The pink dye shows flow expansion inherited from the jet (Figure 5A) and the incipient development of many small jets at the periphery of the body as sediment chokes the region of initial jet formation forcing the flow outward. Figure 5B illustrates the initial formation of phase 2: the leaf or nonavulsive stage.

Maximum deposition occurs in the region of maximum kinetic energy dissipation, and a roughly triangular, superelevated region forms at the distal end of the bed-form field (Figures 5C, 5D). Ultimately, optimization requires the flow to split around the elevated region (Figure 5C). In response to continued aggradation, small jets are more strongly developed at the periphery of this leaf-deposit. Figure 5D shows the sedimentary body near the end of the leaf stage. Flow splitting has begun to create knickpoints on either side of the triangular region. These knickpoints will migrate updip, connect to the erosional region near the orifice, and create an incipient channel system. At this stage in the evolution, sediment aggradation resulting from energy dissipation has made "overland" transport of energy much less efficient. Channels become the optimal, low-resistivity pathways to transport energy to the peripheral sites of dissipation or channel mouths where jets can continue to form. In Figure 5E, channels now capture most of the flow, split around the superelevated region, and form two new jets at the edges of the system. We term this channel-splitting avulsion as opposed to channel break-out avulsion which occurs when channels breakthrough superelevated banks. With the onset of avulsion, the body enters phase 3: the tree or avulsive stage. The sedimentary body that began as a jet has evolved into what geomorphologists call a delta.

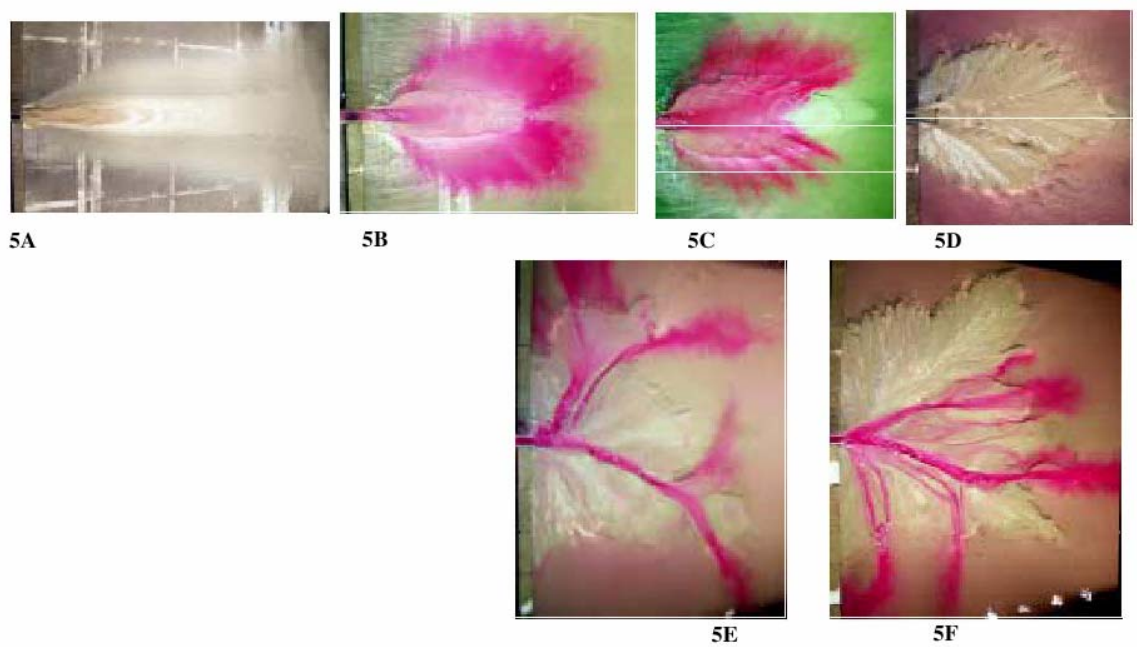

Figure 5. A series of sedimentary bodies built during the same experiment. Flow was continuous and conditions were constant.
A) The initial jet deposit. B) Deposition is beginning to interact with the flow. A bar or "leaf"-like deposit is forming. C) The deposit is more strongly interacting with the flow. Flow splitting is beginning. D) The fully formed "leaf" or bar is formed. E) Avulsion has occurred and channels formed. New jet deposits are developing at the periphery of the deposit forming a tree-like body. F) Avulsion continues. Energy dissipation sites proliferate along the periphery of the body. A delta is formed.

The evolution of this sedimentary body is driven by optimal dissipation of both kinetic and potential energy. The triangular, superelevated region observed in Figures 5C, 5D, formed by kinetic energy dissipation, initially forces the flow up off the depositional surface and over the superelevated topography. This creates the energy dissipation paradox: as kinetic energy is dissipated in the flow, potential energy is built up in the deposit. Once flow splits as described above, two channels form allowing two new jets to develop adjacent to the elevated region. These jets and their deposits dissipate the potential energy by filling in the low areas adjacent to the original superelevated region, locally raising the depositional surface, minimizing the height gradient, and creating a local surface of equilibrium over which the potential gradient is minimized. The new deposits are also elevated. More potential energy is created as the flow is forced over the tops of these new regions. Flow splitting will occur once again, the potential energy will be converted into kinetic energy, and the kinetic energy dissipated at even more dissipation sites. As this process continues, the deposit grows radially and the sites of flow splitting evolve into a branching network of channels. As the system optimizes the area over which dissipation occurs, and the potential energy dissipation spreads radially minimizing local height gradients, the channel network becomes increasingly branched (Figure 5F).

As Figure 5 illustrates, the jet is the tree-like structure that dissipates kinetic energy in sedimentary systems. Sedimentary bodies evolve into tree-like dissipative structures as the flow pathways and branching channel networks enable optimal dissipation. Avulsion is the process and the channel network is the resulting structure that dissipates the generated potential energy. Figure 5 illlustrates the sedimentary arrow of time or energy-dissipation pathway for flows in shallow water. We believe this pathway describes the evolution of most bed forms, bars in rivers, deltas, crevasse splays, and washover fans. However, it also applies to the evolution of submarine fans. Although the boundary conditions are different, jets, jet deposits, leaf-like bodies, avulsion and the resulting tree-like bodies also form in deep-water deposits (Figures 1, 4; also see Beaubouef et al., 2003).

Conclusion

All sedimentary bodies, from bed forms to submarine fans, form along the scale-and place-invariant sedimentary arrow of time. Some sedimentary bodies evolve in response to a single flow. Generally, these develop only into jet or early leaf deposits because the flow is not of sufficient duration for tree deposits to form. For example, bedforms like current ripples (Figure 4B-1.2) and cross beds are jet deposits. Flow duration was too short to allow these deposits to evolve to the next stage. Bars in rivers (Figure 4B-1.1) evolve from the jet into the leaf stage, but generally floods wane before they can evolve to the tree or delta stage. Other sedimentary bodies evolve in response to multiple flows from the same primary orifice at what is called by us sites of additive energy dissipation. Generally, bodies at these sites evolve into complex tree deposits, such as deltas and submarine fans. But, if enough space is available in the riverbed and the energy flux is sufficient, river bars will also evolve into "deltas" (Figure 4A); or at least, into sedimentary bodies that are identical to deltas in every respect except that they form in the alluvial valley instead of at the river mouth.

We believe that the sedimentary rock record is built of scale-invariant hierarchies of sedimentary bodies. These bodies are similar in shape and property distribution. Furthermore, sedimentary bodies evolve along a well-defined pathway governed by principles of nonequilibrium thermodynamics and energy dissipation. This pathway is scale-invariant and independent of depositional environment. We believe our findings provide 1) a foundation for a better understanding of global constraints on sedimentary body evolution and, 2) a principle for the description, interpretation, and prediction of the types and distributions of sedimentary bodies in a unifying framework more useful than depositional environment or scale. These results also have important implications for the prediction and geologic modeling of sedimentologic properties in hydrocarbon reservoirs.

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