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The Studies of Modern Fluvial/Alluvial Depositional Systems as Analogues for Interpreting the Rock Record

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Abstract

The studies of modern depositional systems have been used as analogues for interpreting the rock record for about as long as geologists have existed, and the basic concept is underpinned by Lyell's uniformitarianism. Of all the modern depositional systems commonly studied, it is those of fluvial and alluvial systems in general, which have received the widest and most intense application. Alluvial systems have been of great interest to man since the beginning of human history. Most of the great civilizations and cities were built on major river systems, which provided essential water and transport and naturally, this led to early studies of how these systems worked. Later discoveries of economic minerals in alluvial deposits, gold, diamonds, and of course oil and gas, further increased the research of fluvial systems by academics, governments, and a host of industries.

Arguably, the greatest value provided by modern analogue studies in sedimentology, across all depositional settings, comes from being able to directly observe and study the relationship between the physical process, the deposit and its form in a sedimentary system. This was a major contribution to sedimentology made by industry geologists in the 1970's, particularly the Shell team in Houston. Flume studies and forward modelling have greatly advanced our understanding, but the great laboratory of the natural world is hard to beat. This need to understand process, deposit and form has become increasingly important to the industry of late because of advances in geologic and fluid-flow simulation modelling. It is a requirement of geologic modelling that detailed data concerning the fundamental reservoir rock units or lithofacies are provided. This means that we need to know not only the textural and compositional properties of these lithofacies, but also their proportions and spatial distribution in modern systems in order to create predictive models for distributing reservoir properties between wells in the subsurface. Given that the storage capacity and fluid-flow properties in a reservoir are directly controlled by the lithofacies attributes of porosity and permeability, it is vital for reservoir engineering that the sedimentologist provides high quality, spatial, lithofacies data.

Another key reason for the study of modern analogues by sedimentologists in the industry has been to provide high-quality dimensional data regarding the depositional facies and facies tracts across the full range of depositional systems. Outcrops provide high-quality data concerning the vertical succession of facies but, with rare exception, they provide limited data concerning the lateral continuity of facies because of the limited lateral extent of most outcrops. Rare exceptions include the Cretaceous Book Cliff exposures of Utah, the Tertiary fjord exposures of the Svalbard Islands, and the southern Karoo Permo-Triassic outcrops of South Africa, all of which have been extensively analysed and used as reservoir analogues. The issue with most outcrops is the lack of a third dimension, unless they are cored or have GPR/ERGI. Modern analogues provide information about not only the size and orientation of depositional facies, they also tell us about the spatial distribution and inter-relationships of facies. Although these data are also two dimensional, representing a single snap shot in time, using various coring techniques, shallow seismic and GPR/ERGI, recent studies have provided valuable 3D data on modern systems. This sort of study is most widely done on alluvial systems for the simple reasons of ease of accessibility and relatively low cost, and it is expected to yield valuable data with future

studies. The development of sophisticated software by which to forward model sedimentary systems, using a multitude of autogenic and allogenic inputs, and in some cases even keyed to seismic, is a big step toward being able to understand and build realistic geologic models. But this model building has to be kept honest by being referenced to real world dimensional data at a multitude of scales, and that comes from the study of modern depositional systems. When it comes to modelling fluvial systems, the sediment transport equations that underpin the process side of this forward modelling are all based on the fundamental laws of physics and hydraulic controls, and most of what is known about those processes comes from observations of the natural world, including flume studies. From the dimensional data of ripples and dunes, to the internal texture of dune sets and the larger-scale features of point-bars, all these data can be quantitatively evaluated from the studies of modern fluvial systems.

One of the problems for industry geologists in dealing with the somewhat limited subsurface data set of wireline-logs, core data and seismic, is that there is always uncertainty as to which modern analogue to apply to the subsurface. This is especially true when dealing with alluvial reservoirs, because of the plethora of fluvial styles and the wide range in form, texture and stacking pattern of the resultant deposits. Industry is always looking for techniques to better define the paleogeographic reconstruction and thereby constrain the applied analogue. Palynology has proved to be an invaluable tool for identifying key aspects of the depositional setting, especially in terrestrial and nearshore systems. Palynofacies analysis, which looks at the palynomorph ratios (spores, pollens, dinoflagellates, acritarchs and algae), is able to recognise a host of very specific depositional subenvironments. For example, it can distinguish the various types of channel facies, sorting meandering fluvial channels from distributary channels and tidal channels. Further, it can distinguish between in-channel and channel-margin facies, and the facies of backswamps, lakes, wet swamps, dry swamps, levees, etc. This allows for a much more detailed reconstruction of the paleogeographic setting, distinguishing delta-plain from non-deltaic fluvial facies, and subdividing the delta plain into its component parts of upper and lower reaches. The ability to do this is in the rock record is all based on reference studies of modern analogues.

Ichnology is another powerful tool for sorting subenvironments in alluvial systems in the rock record, and it too is established by reference to modern analogues. The alluvial system displays a high variability in ichnocoenoses; the channel facies have low ichnodiversity because of constantly changing energy and water levels, while the floodplain deposits, including the levees and crevasse splays, display the greatest diversity, abundance and number of ichnocoenoses. The floodplain traces also have the greatest depth of tiering. These, and many other ichnological factors, allow for the identification of specific depositional facies in alluvial rocks in outcrop and the subsurface, and thereby create better paleoenvironmental and paleoecological reconstructions.

A big issue with alluvial reservoirs is their inherent heterogeneity and just how that affects vertical and lateral fluid flow. High-sinuosity meandering fluvial reservoirs are notorious for their internal baffles and barriers to fluid flow. Studies of modern fluvial analogues have provided good insight into the nature of these baffles and barriers, how they are formed, where to find them, their dimensions and orientation, etc. It is clear from these studies that the characteristics are closely associated with specific alluvial settings. For example, the mud drapes on point-bar accretion surfaces are typically restricted to the upper parts of the point bar in most high-sinuosity fluvial systems. However, they are exceedingly more common and continuous in tidally influenced distributary channels, and are commonly continuous down to the base of the lateral-accretion surface in most tidal channels. These data are referenced to modern analogue studies and examples.

The question arises as to just how representative of the real world spectrum are the current range of analogues? Also, and especially concerning fluvial systems, is it probable that many of our existing analogues are just part of a continuum? We know from hydraulic studies and direct observations of rivers through time, that there is a continuum between braided and meandering fluvial styles. It follows then that in some cases it may be very difficult to uniquely link a subsurface reservoir to a specific modern analogue because it is a hybrid. Temporal and spatial changes in fluvial style may reflect subtle changes in allogenic controls (tectonics, basin subsidence, climate, etc.) that are difficult to predict or define in the subsurface without extremely large data sets.

The industry requirements for reservoir characterisation in general vary according to the stage in the exploration and exploitation cycle. High-quality reservoir characterisation is vital during field development and production, and fortunately, this is commonly made possible by the existence of large data sets from many closely spaced wells involving multiple conventional cores, wireline logs and seismic sections. This facilitates building a high-quality deterministic geologic model that will honour this wide array of data, and be supported by production history matching. However, the challenge comes in the exploration stage of the cycle when the data set is small, with few wells and cores, and limited, low quality, 2D seismic. What is needed in this “creative” period is a good set of predictive stratigraphic models, based on the detailed studies of both modern depositional systems and the rock record, and tied to a sequence stratigraphic framework. In this way, it is possible to build a composite knowledge base that is three dimensional and includes the key characteristics of the basic lithofacies texture and composition, the lithofacies assemblages, the stacking patterns, the connectivity between reservoir sand bodies, and the character of the significant correlatable surfaces (sequence boundaries and flooding surfaces, etc.). These data can then more confidently be applied to the limited industry subsurface data sets of wireline-logs, cores and seismic.

Our research of modern coarse-grained alluvial systems in the Basin-and-Range of the western United States and the Southern Alps of New Zealand provides a number of examples of the value in studying modern depositional systems as analogues for interpreting the rock record, both outcrop and subsurface. This work centered on understanding the sedimentology of alluvial fans, fan deltas, braided rivers and braid deltas by characterising their key depositional processes and deposits, their variability in form, and their evolution through time. Underpinning this study was an industry desire to be able to better characterise coarse-grained alluvial reservoirs; a view created by the discovery of several giant oil fields with coarse-grained reservoirs, e.g., the Prudhoe Bay Field of the North Slope of Alaska. Being able to distinguish between these coarse-grained depositional settings, and define specific depositional facies in the subsurface, was key to providing high-quality reservoir models.

Because alluvial fans are largely the deposits of catastrophic events with a long periodicity, understanding fan depositional processes involves piecing together multiple data sets. These we collected from modern fans around the world, and fans that spanned a range of tectonic and climatic settings, and a range in source-rock composition. Much of the early understanding of fans, in the 1960’s and 1970’s, was based on geomorphic studies, and consequently little was known, or at least documented, concerning the sedimentology and deposits themselves; the emphasis was on the form of the deposit and not its texture. The early facies models for alluvial fans were either cobbled together by extrapolating from the geomorphic literature and hypothesising facies and facies trends, or they were built from an interpretation of a poorly exposed outcrop. These models could not be validated by our extensive field observations of modern fans spanning a wide range of conditions.

Our field studies of modern fans clearly show three end-member fan types based on the deposits and texture, with gradations between all three. These include rock-fall fans, debris-flow fans, and sheetflood fans. A unifying feature is that all fans have high slope (>1.5 degrees), and this characteristic generates the high capacity, high competence, and upper flow-regime conditions for the fluid-gravity flows (water flows) on fans. The resulting waterlaid deposits are typically non-channelised, planar bedded with pronounced coarse-fine couplets, or have low-angle antidunes. These deposits are vastly different from those of even the highest energy rivers, where thick, lower flow-regime, cross-bedded deposits dominate. By studying fans in a range of climate settings, we have shown that the fan type is not controlled by climate or the vegetative cover. Modern fans in the hyper-arid Death Valley of the western USA are virtually identical in form, process and deposit to many fans throughout the Southern Alps of New Zealand. Our comparative studies show that the first-order control of fan type is the source-area lithology, and the individual lithofacies display little systematic down-fan change in texture, but the lithofacies proportions may change depending on the fan type. By contrast, fluvial deposits invariably display systematic down-slope changes in texture, including grain size, sorting and particle shape.

Details of the form, processes and deposits of fans, and being able to separate fans from rivers could only be determined by careful study of modern examples. Being able to distinguish autogenic from allogenic controls, and linking the detailed characteristics of fan sedimentology with a causal mechanism, was only possible because the analyses were of modern dynamic depositional systems. This work on alluvial fans makes it possible to sort fans from rivers, fan deltas from braid deltas, and thereby provide improved analogues for interpreting the rock record in outcrop and in the subsurface.