GEOLOGIC NOTE

Reconstructing the architecture and sequence stratigraphy of the preserved fluvial record as a tool for reservoir development: A reality check

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ABSTRACT

Driven in part by the need for better information about fluvial systems for the purpose of nonmarine reservoir evaluation and development, much valuable work is now being conducted on modern rivers and their deposits, aided by such techniques as ground-penetrating radar. However, studies of modern and recent systems cannot address the question of the long-term preservability of the present-day deposits. Only studies of the rock record itself can explore this issue. Two separate studies of ancient fluvial systems illustrate some of the problems.

A study of the Hawkesbury Sandstone (Triassic, Sydney Basin, Australia), highlighted the difficulty in interpreting the dimensions of large sand bodies from comparisons with a modern analog, even when very large outcrops are available.

A seismic time-slice study of Pliocene–Pleistocene fluvial systems in the Gulf of Thailand revealed major changes in channel size and fluvial style over short vertical intervals. Braided and meandering systems (meander-belt widths 4 to >10 km [2.5 to >6 mi]) are separated by a few tens of meters of section, or less, and are interbedded with the deposits of much smaller rivers, showing straight, meandering, and anastomosed patterns. Incised valleys and underfit streams are also present. These variations can be interpreted in terms of a sequence model, but they indicate the problems that could arise from the use of a single suite of dimensional variables as input into numerical reservoir heterogeneity and flow models.

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Most numerical simulation models make use of sets of equations relating such parameters as channel width, depth, and sinuosity, but most such equations are generalized across the whole spectrum of fluvial styles and can be conditioned to the reality of individual reservoirs only with difficulty.

The application of the principles of sequence stratigraphy to fluvial deposits is rendered difficult by the complex response to allogenic forcing that characterizes fluvial systems. Episodes of aggradation and degradation that may be used to define sequences, and their bounding unconformities in the stratigraphic record may be the result of the complex interplay of several allogenic mechanisms governing varying stream power and sediment supply, mechanisms that may be operating at different time scales and may be out of phase with each other.

In developing practical solutions for reservoir development, numerical modeling and simulation may provide generalized starting points for the analysis. History matching commonly demonstrates inaccuracies in many initial models. Further progress may be made by direct study of the reservoir itself, using three-dimensional (3-D) seismic and surveillance techniques. There is a continuing role for the study of ancient analogs as providing a realistic database on the long-term preservation styles of fluvial reservoir deposits.

INTRODUCTION

Development geologists and engineers employ models to assist in the characterization of their reservoirs. These models take many forms, including the use of modern analogs of the reservoir's interpreted depositional system, outcrop analogs of a unit assumed to have formed under similar conditions, physical scale models of the depositional system, and numerical simulations of the reservoir built using mathematical shortcuts to simulate the physics of reservoir construction. Many published studies attest to the usefulness of such models, at least as providing first approximations of reservoir character, although it is almost always the case that discrepancies develop between the predicted character of the reservoir and the actual performance of the reservoir, as development proceeds (the issue of history matching). Several general studies of the modeling process have appeared in recent years that have provided excellent introductions to the strengths and limitations of the various approaches (e.g., Alexander, 1993; Bryant and Flint, 1993; Geehan, 1993; North, 1996).

In a lengthy and thorough review of the area of modeling and prediction of subsurface fluvial reservoirs, North (1996) emphasized the complexity and variability of fluvial successions and the difficulties in predicting fluvial architecture in the subsurface. He discussed the various conceptual approaches that have been used to systematize our understanding of fluvial systems, including vertical-profile-based facies modeling, architectural-element analysis, and sequence stratigraphy. He noted the problems caused by the simultaneous actions of the various autogenic and allogenic sedimentary controls. He demonstrated that limits of vertical seismic resolution and the limits imposed by a borehole network, even within a mature basin, may limit the ability of the geologist to accurately define and predict fluvial architecture with the quantitative rigor required by development engineers.

North (1996, p. 451) suggested that the computer models of flow in channels (as now summarized by Bridge, 2003), which provide predictions of vertical profile and paleocurrent variations, are valuable as providing the basis for more reliable reconstructions of channel form and style than earlier, descriptive models, but acknowledged that sufficient data would uncommonly be available from the subsurface to make this a practical tool. These numerical models are based on geomorphic databases of channel dimensions, from which sets of equations have been derived that express the relationships between such parameters as channel width, depth, meander wavelength, discharge, etc. (e.g., Ethridge and Schumm, 1978; Bridge and Mackey, 1993b). North (1996, p. 452) noted the inadequacy of the database on which paleohydraulic reconstructions have been based, the large errors inherent in the standard equations, and the procedural errors involved in using the output from one equation as the input for another. Many studies, including that of Bridge and Mackey (1993b), have addressed the issue of the paucity of data, but the conceptual question discussed by Alexander (1993) and Geehan (1993) remains: how do we know we are using the right analog?

The purpose of this study is to focus on recent work in the area of fluvial architecture and reservoir geology. The need for more effective and efficient modeling methods is driven, in particular, by the expense of developing deep-water offshore fields, where the availability of reliable predictions of reservoir character is essential for the design of cost-effective development infrastructures.

RECENT MODELING WORK ON FLUVIAL SYSTEMS

Petroleum geologists have turned to various types of models to provide quantitative estimates of reservoir architecture and porosity-permeability patterns. Whether these models are based on simulation of physical process (process-based models) or resultant depositional architecture (object-based models), they need to be able to accommodate existing values and known or observed stratigraphy, while being constrained by realistic ranges of variables of the unknowns. For example, channel sand-body width is a critical value in determinations of sand-body interconnectedness. Estimates of this value may be made from available outcrop data or subsurface well correlation, and such estimates rely on prior interpretations of fluvial style, for which existing data summaries and statistical relationships (e.g., Fielding and Crane, 1987; Bridge and Mackey, 1993b) may be useful.

Most attempts to describe and predict fluvial reservoirs based on geological data have made use of outcrop analog data. Bridge and Tye (2000, p. 1217) argued that outcrop ancient-record analogs for subsurface comparisons are rarely adequate because of a lack of fully three-dimensional (3-D) data and uncertainties about the appropriateness of the analog being used for each specific case. In some projects, one or more specific outcrop case studies are referred to; in other cases, use is made of existing statistical relationships for relating to each other the various scale parameters in fluvial systems. Various statistical techniques may be referred to, or numerical modeling of the system may be attempted. But however sophisticated the statistics and the numerical model, ultimately, these projects must resort to some means of determining appropriate input data from the real world of actual fluvial systems.

One of the most detailed studies of this type was the thesis work by Martinius (1996; see also Martinius, 2000), who derived quantitative sand-body, petrological, and petrophysical data from two outcrop studies of Tertiary units in Spain. The use of detailed sedimentological studies in a mature field was described by Tye et al. (1999). Their work on the Ivishak Formation in the Prudhoe Bay field showed that production surveillance data could be used to refine the prevailing sedimentological model and the enhanced recovery design, with subsequent improvements in history matching. Willis and White (2000) provided a very detailed outcrop study of a tidally influenced delta deposit in Wyoming from which they developed probability scale distributions for five distinct facies types and then conducted flow simulations. Karssenberg et al. (2001) attempted to demonstrate the utility of the 3-D numerical model of Mackey and Bridge (1995) by conditioning the model with data from five synthetic wells to generate a realistic simulation. Yu et al. (2002) studied a large outcrop of a Jurassic fluvial system in China and developed from this some generalizations about fluvial architecture and petrophysics that they offered as an analog for interpreting producing reservoirs in east China. Svanes et al. (2004) defined genetic types of sedimentological objects in vertical profile and used these in conjunction with 3-D seismic data to develop a fluid drainage model in a producing field. They pointed out the difficulties in making adjustments to a stochastic reservoir model to accommodate new input from well data or surveillance data (the conditioning problem).

Many workers have noted the inadequacies of facies models and the ambiguities of vertical profile data for interpreting sand-body architecture (e.g., Miall, 1980, 1985, p. 263; 1996, p. 38–42; Collinson, 1986, p. 59–60; Bridge and Tye, 2000, p. 2006; Bridge, 2003, p. 222; Shanley, 2004). But some of the suggested solutions are, in fact, variations on this same approach. Thus, Leclair and Bridge (2001) explored the relationship between cross-bed thickness and bedform height so that the known dependence of bedform height on flow depth may be used to estimate channel depth. Bridge and Tye (2000, p. 1206) offered diagrams that they explicitly label as ''idealized vertical sequences of lithofacies and wire-line-log response'' as improved tools for interpreting channel geometry and width.

Bridge and Tye (2000, p. 1223) claimed to have offered a fresh approach to the quantitative evaluation of subsurface fluvial architecture (Figure 1). They build on new data derived from studies of modern rivers and ancient analogs, but their idealized models do not consider (1) natural variability, including the deposits of uncommon events (Bridge, 2003, p. 223); (2) the difficulty of distinguishing between single and superimposed channels and bars; (3) the problem of interpreting maximum paleochannel depth from the thickness of channel bars; and (4) the issues of preservability of channels and their individual elements.

With the possible exception of the scale (thickness) of individual cross-bed sets, none of the features of vertical profiles that are observable in core, including vertical succession and the nature of bounding surfaces, are amenable to unique interpretations. For example, deposits formed following deep scour may be more preservable than those that form during normal conditions

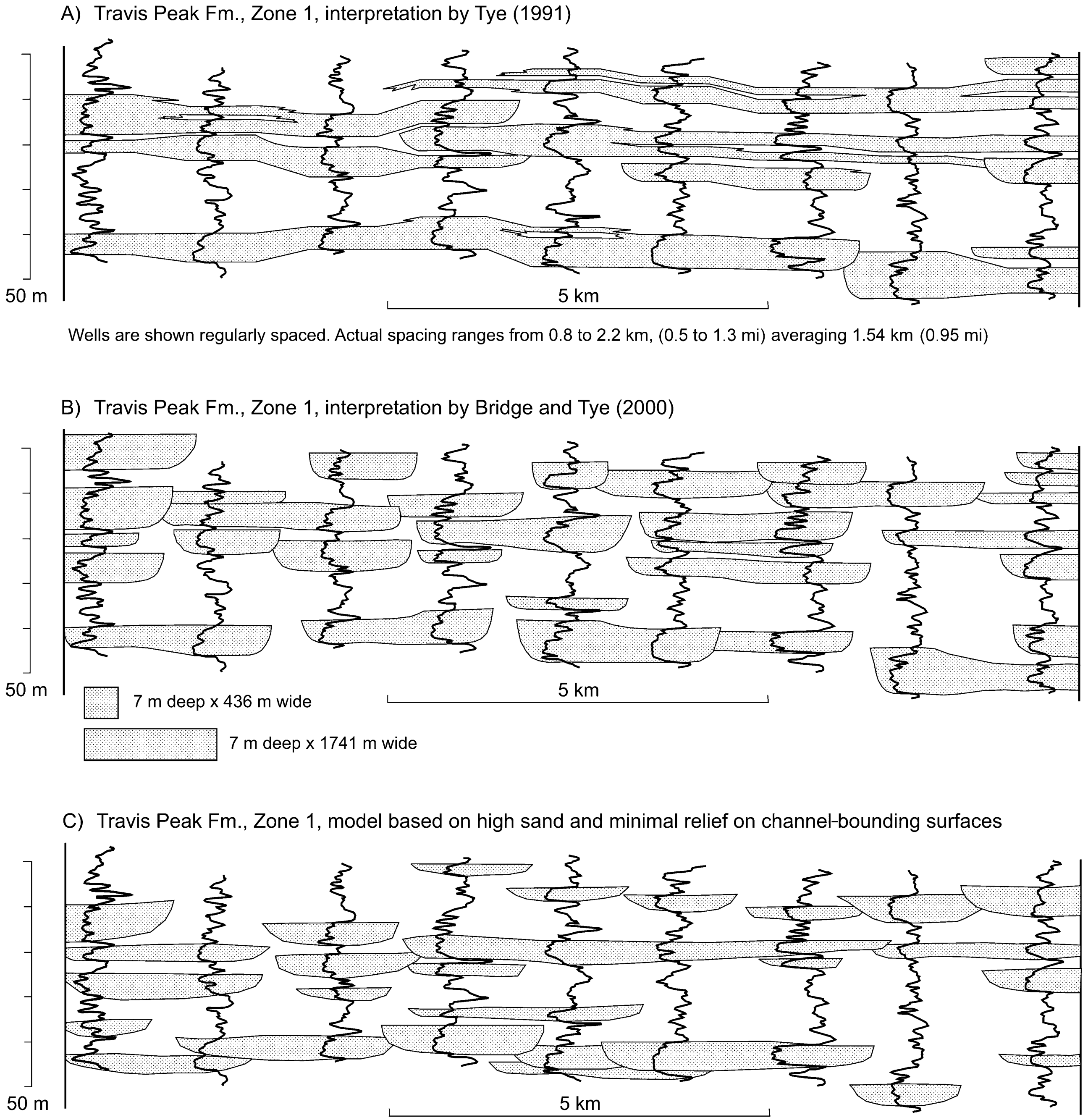

Figure 1. Three interpretations of the braided-fluvial deposits of the Travis Peak Formation, zone 1 (Early Cretaceous, east Texas). (A) Initial interpretation, by Tye (1991) (used with permission from SEPM [Society for Sedimentary Geology]), based on detailed core and isopach mapping study. Arbitrary equal well spacing is used in this and the subsequent diagrams. (B) A reinterpretation by Bridge and Tye (2000), based on assumptions of narrower channel belts. Bridge and Tye (2000, p. 1220) stated: "If maximum bankfull flow depth in the Travis Peak Formation [estimated from core] ranges from 6 to 10 m (20 to 33 ft), mean bankfull flow depth is 3–5 m (10–16 ft), and the range of channel-belt width is predicted to be 436–1741 m (1430–5712 ft) using the empirical equations from Bridge and Mackey (1993b)." But this is not what is shown in this interpretation. Two scaled rectangles, with the dimensions cited here, are shown in (B). According to these estimates, but not as shown in their diagram, most of the sand bodies would not be intersected by more than a single well, and sand-body interconnectedness would be very low, unless there are many more similarly narrow sand bodies between and not intersected by any of the wells. (C) An alternative model developed by this author, based on two basic guidelines for interpreting petrophysical logs: channels normally have flat bases, and the main sand bodies are indicated only by blocky-shaped, low-value gamma-ray signatures.

and are likely to be larger and thicker than average; but how representative are they? Application of the models offered by Bridge and Tye (2000) may suffer from the problems of fragmentary preservation, which is all too common in fluvial systems. Lunt et al. (2004) specifically acknowledged this problem in their article developing a gravelly braided fluvial model, as noted below.

The Bridge and Tye (2000) study made use of the empirical equations of Bridge and Mackey (1993b) to estimate channel-belt width (Figure 1), but given the variability in fluvial form and the geological variability in the processes that govern fluvial style, no objective reason can be provided for preferring one equation over another. The immense natural variability in form and scale is well documented by Gibling (in press).

MODERN RIVER SYSTEMS AS RESERVOIR ANALOGS

A theme throughout the discussions by North (1996) and the concluding remarks in the book of which that article is a part (Carling and Dawson, 1996) is the lack of information about modern rivers, a refrain expressed many times by J. S. Bridge as well. For example, Mackey and Bridge (1995, p. 28) concluded that ''There is a critical need for more comprehensive architectural data from modern fluvial systems, especially data related to processes controlling floodplain geometry and channel pattern over periods of thousands of years.'' They called for more comprehensive physical models of flow, sediment transport, channel geometry, and the effects of tectonism and base-level change. However, the usefulness of such models would still be questionable for the reasons discussed below.

Tye (2004) argued that the documentation of surface form, without the need for subsurface analysis, could provide an invaluable input into reservoir studies by providing constraints on the scale, orientation, and interrelationships between reservoir components, such as channels and bars, so long as the appropriate modern analog had been selected from which modeling input data were derived. He illustrated his argument with examples of the use of measurements on selected modern rivers and deltas as input into an object-based 3-D reservoir model. He acknowledged, however, that his geomorphology approach could not take account of the erosional relationships between successive channel-belt units. This is where knowledge of the subsurface architecture must be added in.

The problem of documenting fluvial architectures from modern river systems has largely been solved by the development of ground-penetrating radar (GPR). This geophysical technique is superbly adapted to documenting the shallow subsurface, providing high-resolution architectural data that can be related precisely to the surface channel and bar morphology (e.g., excellent case studies were provided by Best et al., 2003; Lunt and Bridge, 2004). Both the value and the limitations of modern architectural studies using GPR are well illustrated by the detailed study of the Sagavanirktok gravelly braided river in Alaska by Lunt and Bridge (2004) and Lunt et al. (2004). These articles contain detailed documentation of the channel and bar architecture, documented with numerous GPR profiles. From the GPR data, the authors extracted a set of ''vertical logs of typical sequences through different parts of compound bar deposits and channel fills'' (Lunt et al., 2004, p. 404 and their figure 24d). They also developed a table relating ''stratal thicknesses measured in boreholes'' to the ''widths of different scales of stratasets'' (Lunt et al., 2004, p. 410 and their table 3). They stated that this ''quantitative three-dimensional depositional model . . . will allow prediction of the dimensions and spatial distributions of different scales of stratification . . .'' However, they then go on to say that ''reconstructing the origin and evolution of compound bar deposits from only recent aerial photographs or cores is impossible. It is also impossible to determine from core whether a compound bar was a point bar or a braid bar'' (Lunt et al., 2004, p. 410). They also assembled some modern data relating to the width-depth relationships for the channel-belt deposits of recent braided and meandering rivers and concluded that this ratio is widely variable, and that there may be very little difference between the two river styles in terms of the channel-belt deposits currently accumulating.

Here, then, is the first of the two major problems with modern analogs for interpreting the ancient record: snapshots of a modern river (surface maps, aerial photographs) do not reveal the internal structure of the bars and channel deposits beneath the surface. For example, an apparently simple point bar in a braided system may, upon dissection or GPR surveying, reveal an internal structure partly composed of the remnants of a different type of bar or of an earlier point bar with a different orientation, upon which the modern bar form has been superimposed by the latest configuration of the adjacent active meander bend. Best et al. (2003) documented the evolution of a single large braid bar in the Jamuna (Brahmaputra) River in Bangladesh. This bar, 1.5 km (0.9 mi) long in a downstream direction, migrated downstream a distance equal to its own length in a little over 1 yr and temporarily doubled in downstream length. How relevant to the study of the ancient record is the detailed documentation of such an ephemeral feature, other than to illustrate short-term bar-forming processes? How much of this bar is likely to make it into the preserved record?

In its simplest condition, the evolution of a braided channel can be considered as the development of opposite-facing low-sinuosity meanders migrating away from a central (midchannel) bar (Bridge, 1993). The work of Ashworth et al. (2000) explicitly ruled out this mode of evolution in the case of the bar they studied, although they made a comparison with the small bar in the Calamus River, Nebraska, analyzed by Bridge et al. (1998), which the latter demonstrated to have grown by a comparable pattern of lateral and downstream accretion from an upstream nucleus. Where bar migration is symmetrical, as proposed by Bridge (1993), channel scour would be expected to sweep out an erosional channel form approximating the width of two channels plus the intervening bar. Assuming two channels of second-order Brahmaputra scale (in the terminology of Bristow, 1987), each 2 km (1.2 mi) wide, and a midchannel bar also 2 km (1.2 mi) wide, if both channels were filled prior to abandonment, this could theoretically generate a second-order sand body bounded by a fifth-order surface (the channel-scale bounding surfaces of Miall, 1988, 1996) on the order of 6 km (3.7 mi) wide. With an average depth of 12 m (39 ft), such a sand body would have a width/depth ratio of 500. However, this scenario is quite speculative. Several groups of researchers have demonstrated patterns of active anabranch migration and bar growth and erosion in the Brahmaputra and Jamuna River (Thorne et al., 1993; Ashworth et al., 2000), which indicate that sand bodies of the full theoretical width estimated here may never develop. Sand bodies bounded by surfaces of fifth-order rank are likely to be substantially less than 6 km (3.7 mi) wide. The final preserved architecture of sand bodies of the type described by Ashworth et al. (2000) would depend on the balance between (1) lateral growth of the bar under conditions of anabranch migration and (2A) erosional incision brought about by events of avulsive anabranch switching or (2B) migration and lateral erosion of an anabranch from another location in the channel belt. Final preserved sand-body widths are presumably somewhere between the hypothetical maximum of 6 km (3.7 mi) and the width of individual bars, a minimum of 1 km (0.6 mi).

The second of the major problems is that well data (including core logs) relating to the internal architecture may be as poor a guide as surface form as a diagnostic tool for reservoir body evaluation. Lunt et al. (2004) reconfirmed the point argued many years ago (e.g., Miall, 1980; Collinson, 1986) that vertical profiles are not reliably diagnostic of fluvial style, let alone of bar character in a river of known style. Even with a detailed core record, it may be difficult to impossible to determine whether a particular vertical profile relates to a single channel-fill record or to superimposed fragments of several or many channel and bar deposits, such as the one documented by Best et al. (2003). Interpretations derived from core should therefore include the development of several alternative scenarios for further testing.

The demonstration of statistical relationships between channel thickness and width may be useful for characterizing individual rivers, but such relationships should be used with great caution in examining the ancient record. The problem is that even detailed GPR documentation of a modern river system relates only to the present-day snapshot of the deposits. On the short term (decades to hundreds of years), the architecture relates to the preservation of fragments of bars and channels formed, modified, and eroded under the existing channel pattern. But none of this present-day deposit has yet made it into the geological record. On the longer term (from thousands of years up to geological time scales), the pattern of preservation is influenced by subsidence rates and climate change. In addition to the fragmenting of channels and bars in the short-term timeframe of channel migration and avulsion, there may be erosional incision caused by channel systems at much later periods, which may partially or completely remove the earlier deposits and which may demonstrate different styles because of changes in long-term allogenic controls. Given slow subsidence rates, it is quite conceivable that a given stratigraphic unit could contain the amalgamated, mutually incised fragmentary deposits of different river styles that were active tens to hundreds of thousands of years apart and which could have generated channel and bar deposits with significantly different internal character and thickness-depth relationships (e.g., see Blum and Törnqvist, 2000; Ethridge and Schumm, in press).

Shanley (2004, p. 171–172) argued that although much geomorphic information is available from studies of modern rivers, "the interplay of subsidence, base level, and magnitude of sediment supply exerts a far greater control on the degree to which fluvial [channel] deposits are amalgamated or isolated than the many short-term processes commonly viewed in the study of modern analogs.'' Gibling (in press) has documented with a thoroughness not previously attempted the enormous range in the dimensions of channel bodies in the modern and ancient record, the variability in sedimentary controls, and the difficulties inherent in interpreting and modeling fluvial systems from limited data. As Ethridge and Schumm (in press) noted: ''Because several controls can produce the same effect (convergence) and one control may produce different effects (divergence), unambiguous interpretations [of the ancient record] are not possible.''

Given the normal variability of geological processes, the assumption of architectural complexity and variability should be the null hypothesis for the purpose of exploration and development. For these reasons, it is suggested that the statistical relationships developed for reservoir body dimensions and the numerical models that are based on them (e.g., Bridge and Mackey, 1993a, b; Mackey and Bridge, 1995) are most appropriately used as guides to the development of several alternative scenarios for reservoir interpretation and development. Shanley (2004) demonstrated this approach with the use of an array of different equations for the estimation of sand-body widths from log- and core-derived thickness data.

THE ANCIENT RECORD AS RESERVOIR ANALOG

Geehan (1993, p. 56) stated ''Clearly, outcrops are the only source of geological analog data that show indisputably what is preserved in the geological record, in a form that fully represents all scale of heterogeneity up to the size of the outcrops. Thus, outcrop data must continue to provide our most reliable controls for modeling aspects of reservoir heterogeneity that are not directly measured in the subsurface.'' He pointed out the two principal difficulties with the use of outcrop data: selecting the right analog for a given subsurface project and extracting the necessary 3-D information from outcrop data.

Most of the studies cited above that have used analog data have made use of only one or two outcrop examples as their analog base or have relied on qualitative matching of facies character from vertical profile core and petrophysical data. Some attempt has been made to develop databases and statistical relationships for a wide variety of fluvial systems (e.g., Fielding and Crane, 1987; Bridge and Mackey, 1993b), but for the reasons discussed above, such relationships can provide only the starting point for the prediction work associated with the development of specific ancient reservoir units, given the unique depositional conditions of each such unit. This point is illustrated here with reference to two recent studies of ancient fluvial deposits, which both show considerable internal variability that would defy attempts at developing simple, numerically simulatable reservoir models.

Hawkesbury Sandstone (Triassic), Australia

The Triassic Hawkesbury Sandstone of the Sydney Basin in New South Wales, Australia, is a craton-sourced unit 40–60 m (131–196 ft) thick that was deposited within the foreland basin adjacent to the New England fold belt (Cowan, 1993). Regional transport directions were toward the northeast; the unit extends for 225 km (139 mi) in that direction and occupies a belt 75–100 km (46–62 mi) wide, across depositional strike. The preserved width of the Hawkesbury Sandstone depositional system indicates that the river or rivers responsible for its deposition were free to comb across a wide, flat, alluvial plain. The marked changes in paleocurrent direction recorded in successive channel-fill deposits in the Sydney area sections attest to the lateral mobility of the rivers and the very low depositional gradient in this part of the Sydney Basin.

The Hawkesbury Sandstone is known for the abundance of very large-scale cross-bedding, which has long been interpreted as the product of deposition in large channels of a braided fluvial system (Rust and Jones, 1987; Miall and Jones, 2003). However, the unit is far from uniform in its facies and architecture. Figure 2 illustrates the variability that can be observed within the outcrop belt extending from Sydney south to the Royal National Park and parallel to the strike distance of about 40 km (25 mi). Much of the Hawkesbury Sandstone consists of superimposed planar and trough cross-bed sets (Figure 2C). These are commonly organized into large macroforms (Figure 2B), the scale and architecture of which permit the reconstruction of the scale and style of channels in the Hawkesbury rivers (Miall and Jones, 2003). However, not all of the deposits fit this description. At a location called the Cobblers, some 20 km (12 mi) south of Sydney, cliff exposures reveal a significant thickness of trough- and ripple–cross-laminated sandstone, incised by a large channel with a fill of fine-grained deposits (Figure 2A).

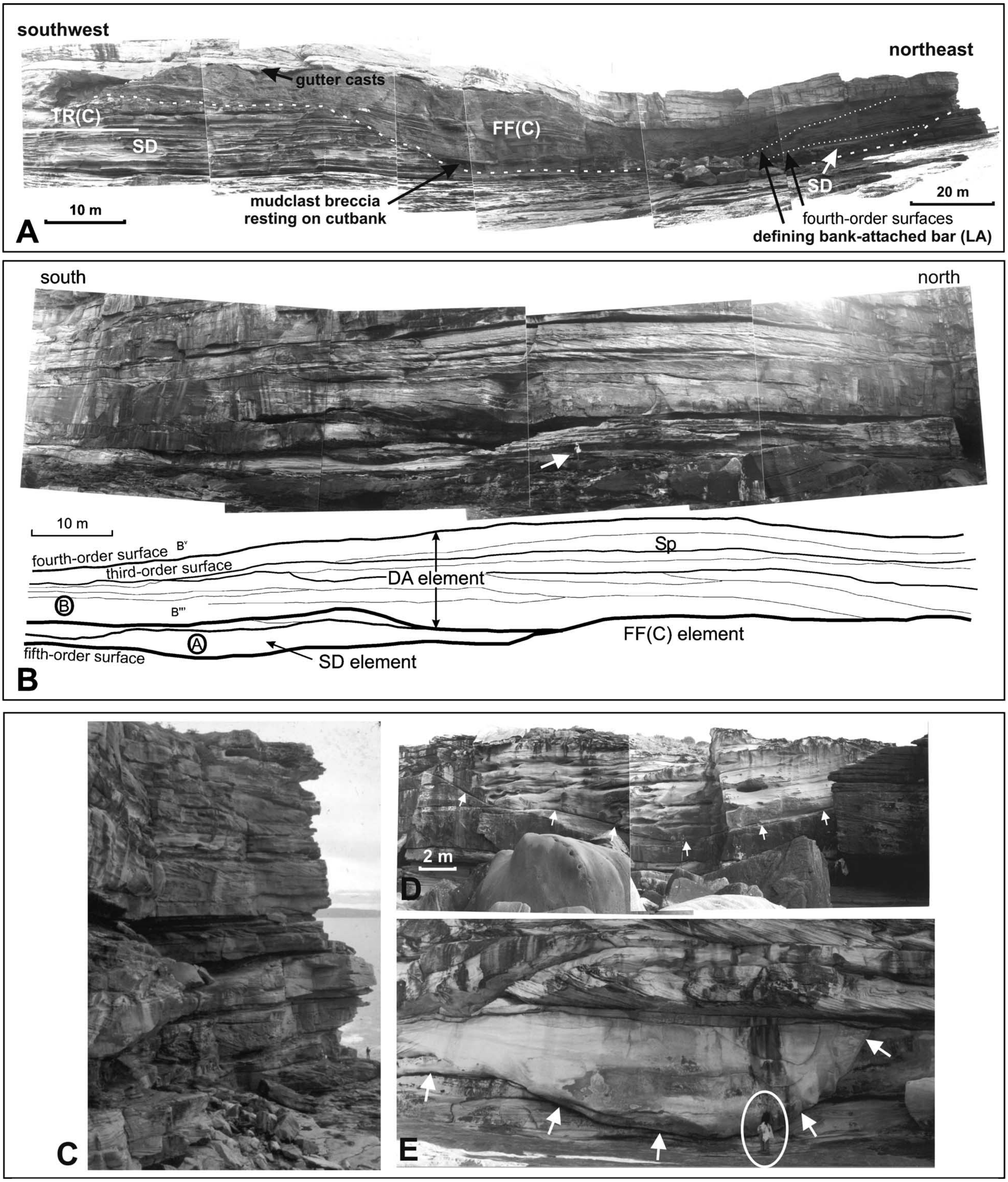

Figure 2. Variability in fluvial architecture of the Hawkesbury Sandstone, near Sydney, Australia. Architectural-element and lithofacies codes and overall interpretations are from Miall and Jones (2003). (A) A channel with fine-grained fill [architectural element FF(C)] incised into a regionally uncommon facies assemblage of trough- and ripple-laminated sandstones [TR(C)], overlying cosets of dune deposits (SD). The outcrop is oriented obliquely to the viewer, such that the right-hand end of the view is farther away. The scale therefore varies form one end of the view to the other. (B) A typical downstream-accretion element (DA) composed largely of superimposed sets of planar-tabular cross-bedding (lithofacies Sp). Arrow indicates person for scale. (C) Typical cliff exposure of the Hawkesbury Sandstone near Bondi, showing superimposed large-scale planar- and trough-cross-bed sets. The figure at the lower right indicates scale. (D, E) Scour hollow deposits (element HO). Person circled for scale in (E). From Miall and Jones (2003); used with permission from SEPM (Society for Sedimentary Geology).

This assemblage is uncommon in the Hawkesbury Sandstone. Elsewhere, scour hollows occur (Figure 2D, E). These are the product of enhanced scour at channel confluences. Their random occurrence throughout the formation is to be expected, but at Curracurrong, 35 km (21 mi) south of Sydney, there is a cluster of at least four of these elements (Miall and Jones, 2003, their figure 10) and scattered occurrences of others. Fine-grained deposits are, in general, uncommon in the Hawkesbury Sandstone. In the 6-km (3.7-mi)-long exposure south of Sydney described in detail by Miall and Jones (2003), there is one unit up to 10 m (33 ft) thick that can be traced for nearly 1 km (0.6 mi) along the cliff face. It is incised by what is interpreted as a small crevasse channel.

The point of this summary is that the fluvial architecture of this unit is quite variable. A detailed statistical study of sand-body dimensions would generate quite different descriptions at three locations within 40 km (25 mi) of each other. No single statistical description would suffice to describe the unit for the purpose of a numerical reservoir model.

Pilong Formation (Pliocene–Pleistocene), Malay Basin

Miall (2002) reported on an analysis of seismic time-slice sections through these deposits, which were deposited in one of the many fault-bounded basins developed as a consequence of the Cenozoic Himalayan orogeny. The data revealed a wide variability in fluvial style in the approximately 60 m (196 ft) of section documented by the seismic data. A sequence model was developed from the data (Figure 3), but in the absence of seismic cross sections (which were not made available to the author at the time), the model was considered to be tentative. Subsequently, a few seismic cross sections have been made available to the author (L. Meagher, 2005, personal communication). These confirm that the list of indicators used to construct the sequence model was, in general, correct, but that the complexity of the fluvial stratigraphy includes much more mutual incision of channels and sequences into each other than had been predicted.

The suite of fluvial styles represented within this relatively small volume of rock (40 km × 70 km × 60 m; 25 × 43 × 196 ft) includes the following: (1) a single, high-sinuosity meander belt 10 km (6 mi) wide with well-developed point bars at the base of an incised valley approximately 40 m (131 ft) deep; small, V-shaped, incised tributary systems feed into this main valley; (2) a braided channel system up to 4 km (2.5 mi) wide; (3) smaller meandering systems with meander belts ranging from 0.3 to 3.3 km (0.2 to 2 mi) across; (4) low- to high-sinuosity single-channel rivers lacking discernible channel-belt deposits; (5) underfit streams with large meanders defined by the bends of a system of small-scale meanders; meander belts up to 0.8 km

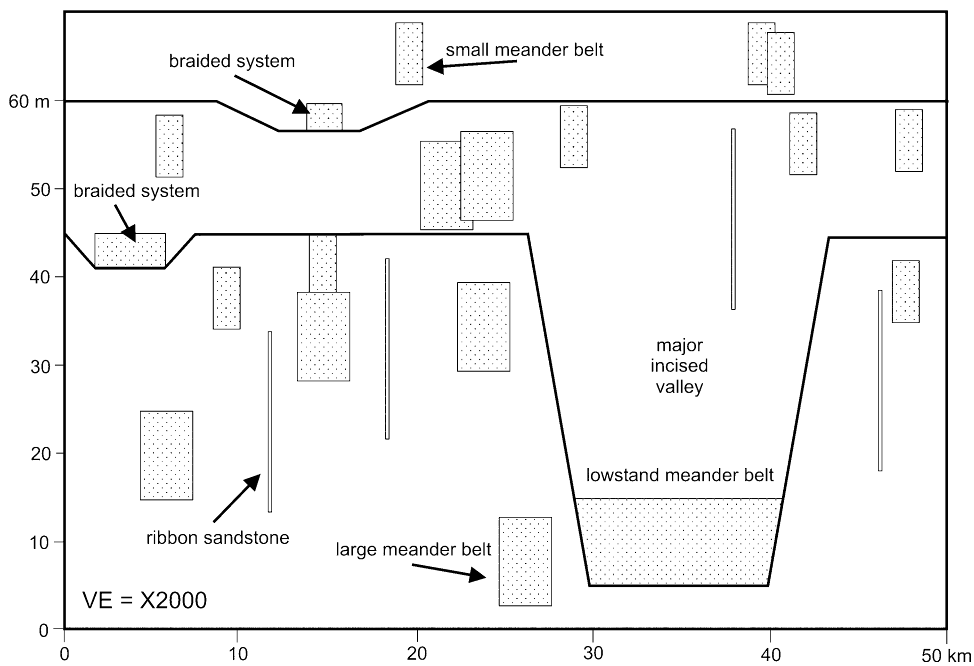

Figure 3. Reservoir model for the Pilong Formation (Pliocene–Pleistocene), Malay Basin (from Miall, 2002, used with permission from AAPG). Reservoir blocks are drawn to indicate the wide range of sizes and positions of channel units, based on an analysis of seismic time-slice images. Solid lines are sequence boundaries. Recent data made available to the author indicate a much greater degree of mutual incision of the sequences and their component channel bodies than shown in this diagram.

(0.5 mi) across are present along some of these rivers; (6) small channels having the appearance of tidal creeks.

Since Figure 3 was constructed, additional data have been shown to me (L. Meagher, 2005, personal communication) that indicate a considerably greater density of channel bodies and of mutually incising sequence boundaries than are shown in this diagram. A certain predictability to this model is present, in that predictive ideas were used to build it (beware, therefore, of the tautology or circular reasoning involved in its application), but the model also indicates enormous local variability in fluvial style. If there is, indeed, more mutual sequence incision than indicated in this model, then even the predictions of stratigraphic separation of fluvial styles based on the sequence model (lowstand, transgressive, and highstand systems tracts, etc.) would not be borne out, and we could expect that several of the types of channel forms listed above would occur at the same stratigraphic levels, separated by sequence-bounding erosion surfaces.

Other Ancient Fluvial Deposits

Many other examples could be cited of ancient fluvial units that illustrate major changes in fluvial style laterally or vertically. For example, Bristow (1993) demonstrated the existence of two coexisting braided river systems of markedly different sizes in the Carboniferous record of northern England. López-Gómez and Arche (1993) described several changes in fluvial style through a 170-m (557-ft)-thick Triassic succession in Spain and so on. Gibling (in press) compiled data showing that sand bodies interpreted to be deposited by meandering streams range from 100 to 15,000 m (330 to 49,200 ft) in width, with width/thickness ratios ranging from less than 10 to nearly 1000. Braided sheet sandstones show an even greater range of variability. These and many other examples indicate why numerical models, which can only display a narrow range of sand-body dimensions and spacings, are commonly unrealistic.

FLUVIAL SEQUENCE STRATIGRAPHY

To complete this discussion, brief reference is made here to modern concepts regarding the sequence stratigraphy of fluvial deposits.

By far, the most useful general discussion of this topic remains the ground-breaking work of Shanley and McCabe (1994). Among the major contributions of this work were the following points:

1. Establishment of the independence and disconnectedness of sea level control near the coast and tectonic control inland
2. Development of a preliminary model linking fluvial style and channel density to changes in accommodation through a base-level cycle
3. Noting the presence and significance of incised valleys formed during the falling leg of the relative base-level cycle
4. Noting the possible importance of marine (especially tidal) influences at the midpoint of sequences developed in coastal areas

Useful additional suggestions were contained in the model proposed by Wright and Marriott (1993), especially their remarks concerning the development of paleosols on the interfluves corresponding to sequence boundaries in upland areas.

However, one of the defining characteristics of fluvial systems is their complex response to allogenic forcing (Schumm, 1977, 1993; Blum and Törnqvist, 2000). For example, the response of coastal fluvial systems to base-level change depends on a variety of factors, including the difference in slope between the river at the coast and that of the continental shelf offshore, and also depends on the energy level of coastal-marine processes (Miall, 1991; Schumm, 1993; Leckie, 1994). Under certain circumstances, as the cited authors have demonstrated, sea level rise may be a time of coastal fluvial incision because of aggressive coastal erosion causing shoreline retreat, and in other situations, sea level fall may be accompanied by aggradation of fluvial systems, where the shoreline retreats across a very gently dipping continental shelf. Like most natural systems, there is also a lag between changes in a forcing function and the response of the system, and such a lag may not be constant across a given sedimentary basin.

Sequences are recognized and mapped on the basis of their defining sequence boundaries. The development of an erosional sequence boundary indicates an episode of negative accommodation, or erosion, whereas the sequence between the boundaries indicates an episode of aggradation reflecting net positive accommodation. In the case of coastal-fluvial to shallow-marine systems, a relatively simple relationship between accommodation and sea level change may be assumed, subject to the possible complications noted above. However, such is not the case for inland fluvial systems.

Studies of late Cenozoic nonmarine sediments inland from the Gulf Coast, and in the Netherlands, in particular, have demonstrated that cycles of aggradation and degradation may be exactly out of phase with those that reflect sea level change at the shoreline. For example, during glacial phases, sea levels fell, leading to coastal incision and the formation of sequence boundaries in coastal and shelf deposits. However, the cold climates that developed contemporaneously inland led to a reduction in vegetation cover and to increases in sediment load and, thus, to aggradation in many inland fluvial systems. Incision of these deposits, and the formation of what would be mapped as sequence boundaries, tended to occur during the warmer, interglacial phases, when sediment yield was reduced by a renewed vegetation cover of the watersheds, at the same time as aggradation and onlap occurred in coastal valleys in response to the increasing accommodation (Törnqvist, 1993; Törnqvist et al., 1993; Vandenberghe, 1993; Vandenberghe et al., 1994; Blum, 1994; see summaries of these ideas in Miall, 1996; Blum and Törnqvist, 2000).

In general terms, fluvial style and shifts from aggradation to degradation reflect the balance between stream power and sediment supply (Blum and Törnqvist, 2000, their figure 8; based on Lane, 1955). Given that both these factors are controlled by climate change and by tectonism, and given that both these allogenic controls may undergo change at different geological rates, which are commonly out of phase with each other, it would seem wise to assume Schumm's complex response as the norm.

Modern work is demonstrating that the processes of orbital forcing were probably ubiquitous throughout geologic time (Fischer, 1986; de Boer and Smith, 1994; Shackleton et al., 1999). Although there is an increasing body of work documenting subtle Milankovitch cycles' influences on sedimentation in the marine record, studies of its effects on fluvial systems are few (Olsen, 1990; de Boer et al., 1991). Changes in global climate, changes in seasonality, and changes in equator–polar climate contrasts are driven by orbital forcing on time scales of tens to hundreds of thousands of years, which could potentially affect sediment load-stream power characteristics on a time scale corresponding to the geological superimposition of successive channel belts in a major fluvial system. Such effects could be entirely independent of sea level changes and also occurring at different rates and out of phase with the tectonic controls on basin subsidence and source-area uplift. This is yet another reason to avoid making simplistic generalizations about fluvial style through any given ancient deposit, especially one where a limited database has led to the use of generalized facies models or numerical simulations to provide input into reservoir studies.

RESERVOIR SEDIMENTOLOGY: DISCUSSION

The invariable starting point for most detailed reservoir studies is the construction of a flow model based on one or more modern or ancient analogs. This article has attempted to demonstrate that little can be expected for such models beyond the provision of a general starting point because of the following realisms about fluvial systems.

1. There exists a very wide variety of fluvial form in modern rivers and the ancient record, making the choice of appropriate analog very difficult.
2. Fluvial style is uncommonly constant laterally or vertically through most real stratigraphic units because of the constant interplay of several allogenic controls acting on different time scales.
3. Given the complex-response character of fluvial systems to allogenic forcing, including the tendency for systems to lag behind changes in forcing functions at varying rates, the predictability of fluvial architecture areally and stratigraphically is quite limited; this is the case despite the emergence of generalized concepts from the field of sequence stratigraphy and the increasing use of numerical simulation to test out fluvial response to physical change.

A continuing effort to develop numerical simulations as the basis for reservoir engineering models is present. Databases of fluvial architecture from which such models have been developed remain inadequate to encompass the within-formation and between-formation variability that has been documented in fluvial systems that, in turn, reflect the enormous natural variability in sediment type, discharge magnitude and variability, and the tectonic and climatic controls under which fluvial systems form. The researchers who are most deeply engaged in research on modern fluvial systems (notably J. S. Bridge; references given above) state clearly themselves that the type of data commonly available (log and core data) is inadequate for the purpose of constraining reservoir models for specific reservoir units. In addition, numerical simulation models cannot readily mimic the changes noted in realism 2 above.

Two further observations follow from this assertion:

1. Although the continuing work on researching and documenting the architecture of modern fluvial systems is instructive, this line of work (as argued above) can only be a starting point in contributing to the objective of understanding the long-term accumulation of fluvial systems, as represented by the ancient record, because by its nature, such research cannot investigate the question of the long-term preservability of depositional and erosional processes under the influence of long-term, and possibly variable, allogenic controls.
2. Studies of the ancient record must be the focus of attempts to understand the ancient record because reservoirs are themselves representatives of the ancient record. This might seem obvious, but there have been objections to the use of ancient-record analogs for the purpose of reservoir studies based on the argument that they are poorly exposed, that outcrop studies do not provide 3-D data, and so on. However, several developing techniques avoid these problems, in addition to the obvious one that more carefully designed outcrop studies in areas where 3-D data can be obtained can still contribute much to the developing analog database of actual ancient fluvial systems. Recommendations for additional work include
   a. Outcrop studies of ancient deposits supplemented by GPR surveys of the deposits immediately behind a well-documented outcrop face: Few such studies have yet been reported. Examples include Gawthorpe et al. (1993), Stephens (1994), Corbeanu et al. (2001), and Hongmei and White (2003).
   b. Seismic documentation of fluvial styles, especially the use of horizontal (time-slice) sections: The use of this type of data is becoming more and more commonplace. It provides the potential for the actual mapping of a reservoir body instead of imaginative reconstructions based on scattered vertical-profile data, although the latter may be useful for fine-tuning an environmental and reservoir interpretation. Examples are Weber (1993), Hardage et al. (1994), Radovich and Oliveros (1996), Ryseth et al. (1998), Langenberg et al. (2002), Morend et al. (2002).
   c. The application of various history-matching techniques to improve reservoir models, including four-dimensional seismic surveillance studies, and pressure-testing data to explore the connectedness of reservoir bodies (Putnam and Oliver, 1980; Lorenz et al., 1991; Thakur, 1991; Martin, 1993).

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