Analog for Fluvial-Deltaic Reservoir Modeling: Ferron Sandstone of Utah
AAPG Studies in Geology 50
T.C. Chidsey, Jr., R.D. Adams, and T.H. Morris, editors

Searching for Modern Ferron Analogs and Application to Subsurface Interpretation

Janok P. Bhattacharya[1] and Robert S. Tye[2]

ABSTRACT

A quantitative approach to selecting modern-depositional settings analogous to those of the Cretaceous Ferron Sandstone is presented as well as an approach to using these analogs to improve subsurface interpretations. Paleotectonic, paleogeographic, and climatic setting of the U.S. Western Interior are integrated to estimate the size of the Ferron drainage network to be 50,000 km^2 (19,000 mi^2). Estimates of flow depths, flow velocities, and channel cross-sectional areas suggest maximum trunk river paleo-discharge was on the order of 50 x 10^9 m^3/year (250 x 10^9 ft^3/year).

Analogous modern examples include moderate-sized rivers that drain active mountain belts like the Po (Italy), Rhône, (France), and Ebro (Spain). Continental-scale systems, such as the Mississippi (USA), Niger (West Africa), Amazon (South America), and Nile (North Africa) deltas, are not appropriate analogs. Incised-valley systems within the Ferron are comparable in depth (about 30 m [100 ft]) to distributary channels in more continental-scale systems. A key difference is that Ferron valleys are filled with multiple channel deposits, with individual channel fills less than about 9 m (30 ft) deep.

The relatively uniform size of distributary channels suggests that Ferron rivers experienced only a few orders of bifurcation as they flowed across the delta plain. Shoreline and delta-front deposits are wave-influenced. Locally, the basal Ferron deltas were fluvial dominated, although these fluvial-dominated lobes may lie on the downdrift side of asymmetric wave-influenced deltas, similar in plan to the Brazos, Ebro, and Rhône deltas, and to the southern St. George lobe of the Danube delta.

Sizes and geometries of various depositional bodies in modern deltas better constrain estimates of inter-well heterogeneity in subsurface correlations. Correlations of Ferron core and wireline-log datasets are compared with the more complete stratigraphy documented in outcrop. Although the broad clinoform geometry of strata in these deposits can be recreated from subsurface correlations, specific parasequences could not be reliably correlated using only the subsurface data. The subsurface-to-outcrop comparison demonstrates a risk of over-correlating reservoir compartments (i.e. non-connected bodies) separated by minor flooding shales within complex, offlapping fluvial-deltaic reservoir deposits. The Ferron outcrop data provides a measure of uncertainties in correlation of subsurface analogs.

[1]*Geosciences Department, University of Texas at Dallas, Richardson, Texas*
[2]*PetroTel Inc., Plano, Texas*

INTRODUCTION

The Ferron Sandstone Member of the Cretaceous Mancos Shale, a superbly exposed fluvio-deltaic clastic wedge in central Utah, U.S.A., has long been used as an outcrop analog for subsurface fluvial-deltaic reservoirs (e.g. Barton, 1994; Gardner, 1995; Knox and Barton, 1999; and numerous papers in this volume). There are numerous reservoir-characterization studies of Ferron outcrops (Lowry and Jacobsen, 1993; Barton, 1997; Knox, 1997; McMechan et al., 1997; Corbeanu et al., 2001; Novakovik et al., 2002; Forster et al., this volume).

Core and wireline-log data give lithofacies type and thickness (Z dimension), but distributing depositional facies, such as the deposits of channels, bars, splays, and other elements, between wells remains one of the most difficult challanges in subsurface interpretation. Studies of modern depositional settings can be helpful in reservoir analog studies because they provide plan-view geomorphic data about specific depositional elements, such as length and widths of channels and bars, that ideally can be linked to a specific vertical facies association or facies achitectural element in an ancient example (e.g. Bridge, 1993). Sizes and shapes of architectural elements in modern systems are highly variable, although they commonly follow specific trends, such as increasing channel size with increasing drainage basin area. Such trends helps constrain correlation lengths of analog subsurface facies elements.

A traditional practice in interpreting stratigraphic successions is to compare them with modern depositional settings. However, one of the challenges in using data from modern depositional systems is identifying an appropriate analog. Most comparisons between modern and ancient systems tend to be qualitative and anecdotal. Specifically, the Holocene delta lobes and distributary channels of the Mississippi delta have been cited as analogs to the Ferron (e.g. Cotter, 1975a, Moiola et al., this volume), but comparisons have not been rigorous.

We present a quantitative approach to determining the size of the Ferron rivers and associated deltas for comparison to modern systems. We specifically wish to address the question of whether the Ferron compares to the continental-scale Mississippi River and delta system, or whether a smaller system might be more appropriate.

Several recent papers provide a methodology for estimating the paleohydraulics and dimensions of ancient river deposits (e.g. Collinson, 1978; Lorenz et al., 1985; Williams, 1986; Bridge and Tye, 2000; Le Clair and Bridge, 2001). These can be used to estimate the scale of Ferron rivers. With knowledge of the size and discharge of the drainage network, one can constrain the size of the associated deltas, and choose modern-depositional systems most resembling the Ferron, recognizing that there may be several.

Following identification of modern analogs, dimensions of features in the appropriate modern systems are used to enhance subsurface correlations. The second aspect of this paper is a subsurface interpretation of the Ferron Sandstone, using wireline logs and core data, integrating facies-based concepts of stratigraphic correlation, and geomorphic insights from modern analogs in order to demonstrate the stratigraphic uncertainties that are inherent in subsurface studies.

Regional stratigraphic studies of the Ferron Sandstone document several regionally mappable clastic wedges (e.g. Cotter, 1975a, 1975b; Ryer and McPhillips, 1983; Thompson et al., 1986; Garrison and van den Bergh, this volume), each of which contains numerous smaller-scale stratigraphic units. Terminology is variable and includes sequences, parasequence sets, parasequences, and bedsets (Garrison and van den Bergh, this volume; Anderson and Ryer, this volume), and the long, intermediate, and short-term stratigraphic cycles of Gardner et al. (this volume).

As depositional facies vary greatly within the Ferron Sandstone (as described in this volume by Anderson et al., Mattson and Chan, Ryer and Anderson), it is clear that more than one delta type is represented. Therefore, no single modern example will be entirely analogous to the Ferron.

METHOD FOR FINDING A MODERN ANALOG

Finding an appropriate modern analog for an ancient fluvio-deltaic system requires an assessment of temporal and spatial scales in the ancient system. Certain physical processes, such as the formation and migration of bedforms that produce distinctive stratification, operate over time scales of minutes to hours. For example, ripple and dune-scale cross-stratification can be readily compared between modern deposits and ancient rocks. Various bedform-phase diagrams provide a theoretical and experimental framework that can be used for interpreting paleohydraulic conditions. In particular, Rubin and McCulloch (1980) showed that specific bedforms (e.g. ripples and dunes) are stable within specific ranges of flow velocity, flow depth, and grain size (Figure 1). The occurrence of dune-scale bedforms, for example, is only weakly dependent on flow depth but is strongly dependent on grain size and average flow velocity. The size (height) of a dune, in contrast, is strongly dependent on flow depth (LeClair and Bridge, 2001). Dune-scale cross-stratification is therefore particularly useful in determining both velocity and water depth.

Other types of stratification, such as hummocky cross-stratification, may be related to longer-term seasonal processes, such as storms. However, determining

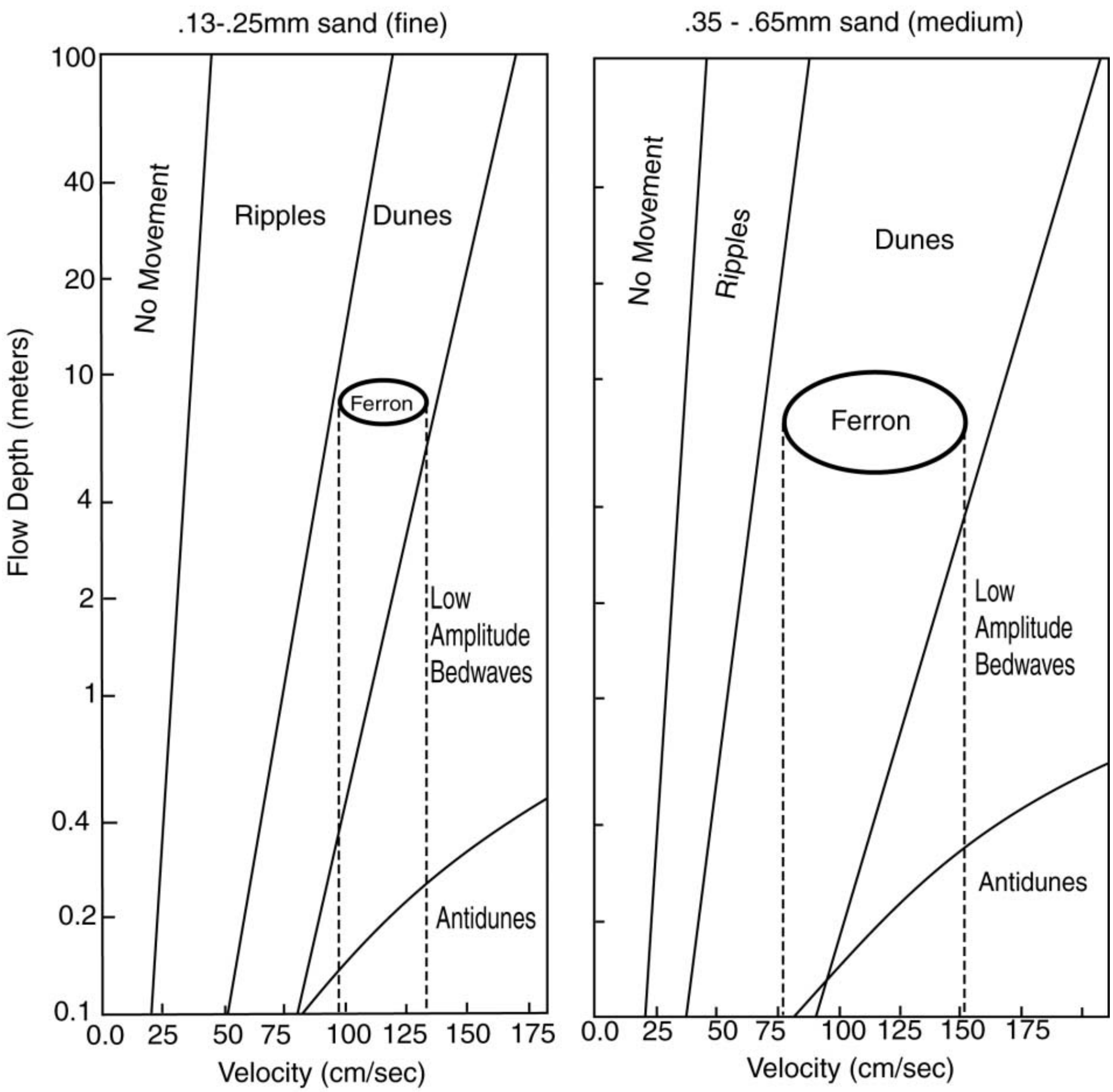

Figure 1. Bedforms, grain size, water depth, and velocity plots modified after Rubin and McCulloch (1980). Range of velocities matching Ferron observations are shown with the circles and suggest a flow velocity of between 75-150 cm/sec (29-59 in./sec). Data show that the presence of dunes is weakly dependent on flow depth, but strongly dependent on grain size and velocity. The size of the dunes, however, is strongly dependent on flow depth (see LeClair and Bridge, 2001).

storm or flood frequency in an ancient example can be difficult, because of an inability to date the rock succession at time scales at which the events occur. For example, large storms are thought to occur at decadal, centennial, or millennial frequencies, but it is very difficult to quantify this frequency in most ancient settings. Long-term processes controlling the distribution and style of sedimentation include tectonic setting, subsidence, and eustasy. Many of these parameters can be estimated. Environmental parameters such as climate, bedrock geology, and topographic relief, control sediment flux and may correlate to tectonic and paleolatitudinal setting. Prevailing paleoclimatic and tectonic conditions within a drainage basin can be estimated using plate tectonic and paleo-oceanographic data to reconstruct the position, size, and elevation of land masses relative to the oceans. Additionally, paleoclimate can be interpreted from examination of floodplain paleosols (Wright, 1992; Mack et al., 1993; Mack and James, 1994).

CHARACTERIZING THE FERRON

Estimating Size of the Ferron Drainage Basin

The Ferron clastic wedge was built by rivers eroding and draining highlands uplifted during the later phase

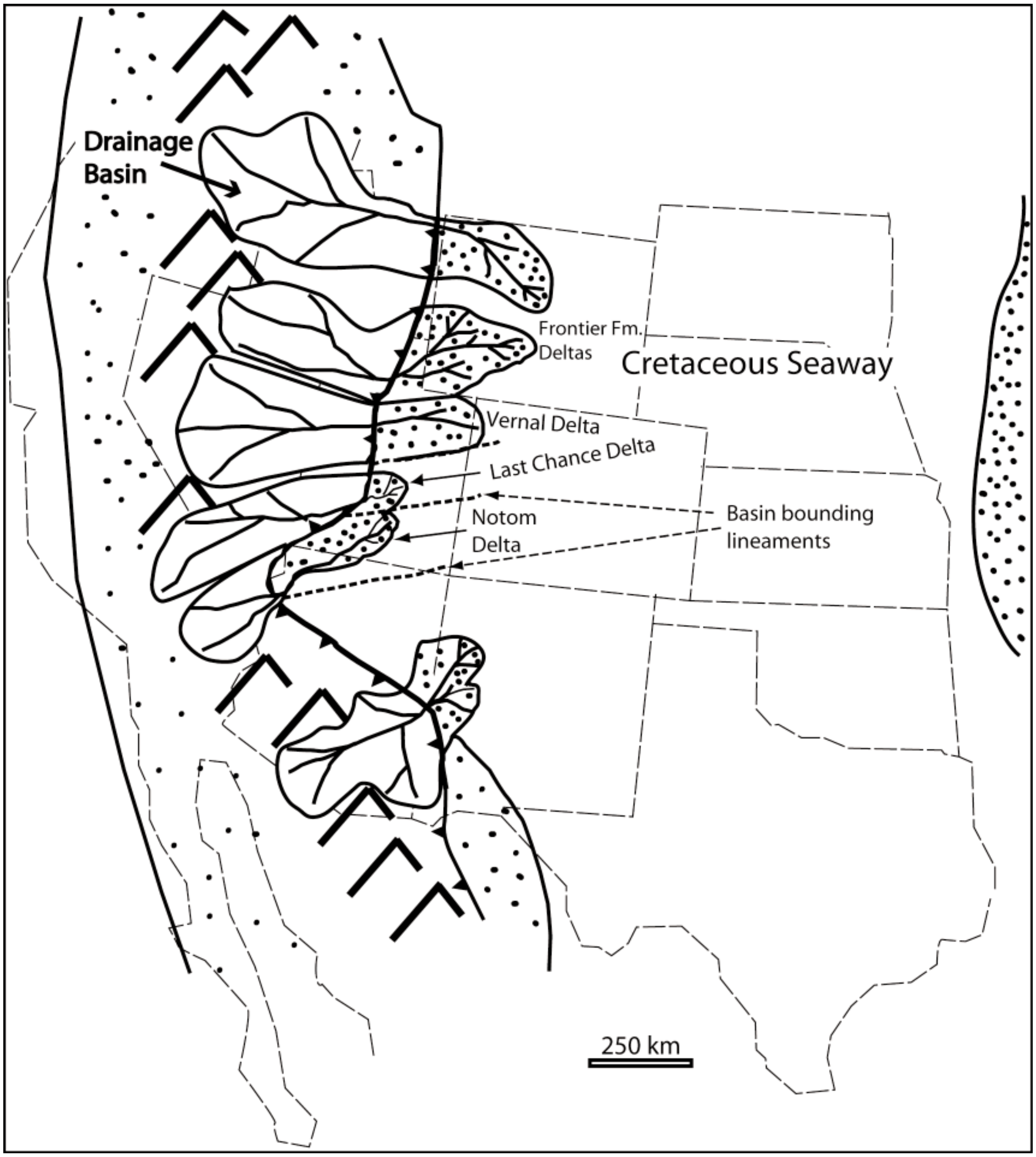

Figure 2. Paleogeographic reconstruction of mid-Cretaceous clastic wedges. Ferron delta complexes lie primarily in Utah. The drainage basin lengths are estimated to be about 1/2 the width of the western lands bordering the Cretaceous Seaway. Drainage basin widths are estimated based on the localization of wedges, assuming each is fed by a different major trunk river, and that drainage divides coincide with major basin lineaments. Aggradational alluvial and delta plains (close stipple) are assumed to begin seaward of the major thrust front. The Last Chance drainage is estimated to be about 500 km (300 mi) in length and about 100 km (60 mi) wide (50,000 km^2 [19,000 mi^2]). Reconstructions are primarily based on Gardner (1995) and Williams and Stelck (1975).

of the Sevier orogeny (Fouch et al., 1983). To the east of the Pavant thrust front, three Ferron depocenters, termed the Vernal, Last Chance, and Notom delta systems (Gardner, 1995; Garrison, this volume) formed in a foreland basin (Figure 2). Gardner (1995) suggests that owing to the segregations caused by major fault lineaments, three drainage basins developed. Gardner (1995) also shows that during Ferron deposition, the distance to the eroding Pavant thrust front was on the order of 100 km (60 mi). Integration of the tectono-stratigraphic interpretations of Gardner (1995) with the general paleogeographic reconstructions of the Cretaceous (Williams and Stelck, 1975) is shown in Figure 2. The drainage basin is interpreted to have been about 500 km (300 mi) long by about 100 km (60 mi) wide, suggesting that the Last Chance delta was fed by a river draining an area of about 50,000 km^2 (19,000 mi^2). Comparing this with the other Ferron drainage basins suggests that they were all on the order of about 10^4 km^2 in area (Figure 2).

Ferron drainage networks appear to have been broadly similar in scale to modern intrabasinal rivers draining active mountain belts, like the Po (Italy - 70,000 km^2 [27,000 mi^2]), the Rhône (France - 96,000 km^2 [37,000 mi^2]), the Ebro (Spain - 83,000 km^2 [32,000 mi^2]), and the Red River (Vietnam - 120,000 km^2 [46,000 mi^2]). Ferron drainages were clearly orders-of-magnitude smaller than continental-scale drainages (10^4 km^2 versus 10^6 km^2 [1500 mi^2 versus 57,000 mi^2]) such as is associated with the Mississippi (USA), Amazon (Brazil), Yellow (China), and Ganges-Brahmaputra (India and Bangladesh) Rivers and their associated deltas (Smith, 1966).

Estimating Climate and Nature of the Receiving Basin

The Ferron Sandstone succession developed at a time generally thought to represent global "greenhouse" conditions that enhanced a major tectono-eustatic sea-level highstand (Dean and Arthur, 1998). This area of Utah lay at a paleolatitude of about 40° N (Ryer and McPhillips, 1983). Abundant coals, gleysols, and a lack of aridisols, caliche, and evaporites in Ferron floodplain deposits indicate extensive lower coastal plain wetlands with a generally high water table (Corbeanu et al., this volume; Garrison and van den Bergh, this volume). Given the global greenhouse setting, the Ferron climate was thus likely humid and sub-tropical.

The intracratonic seafloor over which Ferron depocenters prograded was unlikely to be flat, but rather, consisted of a series of lows and highs that partly controlled local wave and tidal regimes. In the Last Chance delta complex, rivers predominantly flowed northeastward, parallel to the foreland axis (Ryer and McPhillips, 1983; Gardner, 1995; Ryer this volume). Locally, deltas prograded to the northwest, at nearly 90° to the more general northeast progradation (Anderson et al., this volume). The northwest-building deltas are the most fluvial-dominated, probably because they prograded into an embayed area, protected from waves (Anderson et al., this volume; Bhattacharya and Davies, this volume).

Searching for Ferron Trunk Rivers

Major trunk rivers supply sediment to the delta plain and delta front, and are commonly contained within incised valleys, especially where an incised tributary drainage network formed. Delta-plain streams and distributary channels tend to be confined only by aggradational levees, particularly when they build over flat wetlands. Once a trunk stream leaves the degradational region of its valley and becomes unconfined, the river is able to avulse. In many modern delta plains, upper delta-plain channels tend to be few (e.g. Bhattacharya and Giosan, 2003), whereas, multiple distributary channels of various scales occur on the marine-influenced lower delta plain (Figure 3).

Distributary channel bifurcation occurs at a point where the water can no longer flow over the distributary-mouth bar, therefore it splits into two small channels circumventing the bar crest. Channel-bifurcation frequency and branching patterns are strongly dependent on delta type. Multiple bifurcations are favored in low-gradient, fluvial-dominated deltas, where friction exerts a strong control on sediment dispersal and deposition (Welder, 1959; Wright, 1977). This is true whether or not the sediment load is sandy or muddy. Trunk-stream avulsion and distributary crevassing are common processes in fluvial-dominated deltas because hydraulic gradients decrease as rivers and distributaries extend their course.

In wave-modified deltas, much of the sediment delivered to the distributary-mouth bar is carried away by longshore transport. Thus, compared to fluvial-dominated deltas, the progradation rate of wave-influenced deltas is retarded. This allows rivers to maintain a greater slope that inhibits avulsion. As a consequence, wave-influenced deltas typically have only a few active distributary channels, whereas fluvial-dominated deltas have numerous active distributary channels (Figure 3).

Ferron Delta Types

Most Ferron researchers agree that the Ferron deltas were broadly wave-influenced, although the lower seaward-stepping parasequences show greater fluvial influence than the landward-stepping parasequences (e.g. Anderson et al., this volume). Tidal facies have also been recognized, particularly within the upper Ferron parasequences. Anderson and Ryer (this volume, Figure 4) suggest that the lower fluvial-dominated deltaic lobes within parasequence sets Kf-1 and Kf-2 of the Ferron possibly formed within embayments positioned on the downdrift margin of an asymmetric wave-influenced delta. A general model for wave-influenced deltas, presented by Bhattacharya and Giosan (2003; Figure 4), conforms to paleogeographic reconstructions of delta lobes associated with the lower Ferron parasequences, and in particular parasequence Kf-2-Mi (e.g. Figure 4 in Anderson and Ryer, this volume). Paleogeographic maps of Ferron delta-plain channels depict major trunk streams splitting into a few terminal distributary channels. At most, two orders of branching are interpreted (e.g. Anderson et al., this volume, Figures 31 and 33). These paleogeographic reconstructions are quite consistent with the plan-view geometries of modern wave-influenced deltas (Bhattacharya and Giosan, 2003) and contrast with the large, low slope, modern fluvial-dominated deltas, such as the muddy Mississippi and Atchafalaya deltas in the Gulf Coast and the more sandy Colville, Saganavirtok, and Lena Rivers in the Arctic that show up to 10 orders of branching. Truly fluvial-dominated delta lobes are largely formed as crevasse deltas (e.g. Welder, 1959; Wells et al., 1984; Bhattacharya and Davies, this volume) and generally form in bays protected from waves by a wave-formed barrier island (Bhattacharya and Giosan, 2003; Figure 4).

Gardner et al., Garrison and van den Bergh, and Barton (this volume), note a remarkable uniformity on the scale of preserved channel and bar deposits, which also suggests a low order of distributary branching. Cross sections through deltas with many orders of branching should show large variability in the size and

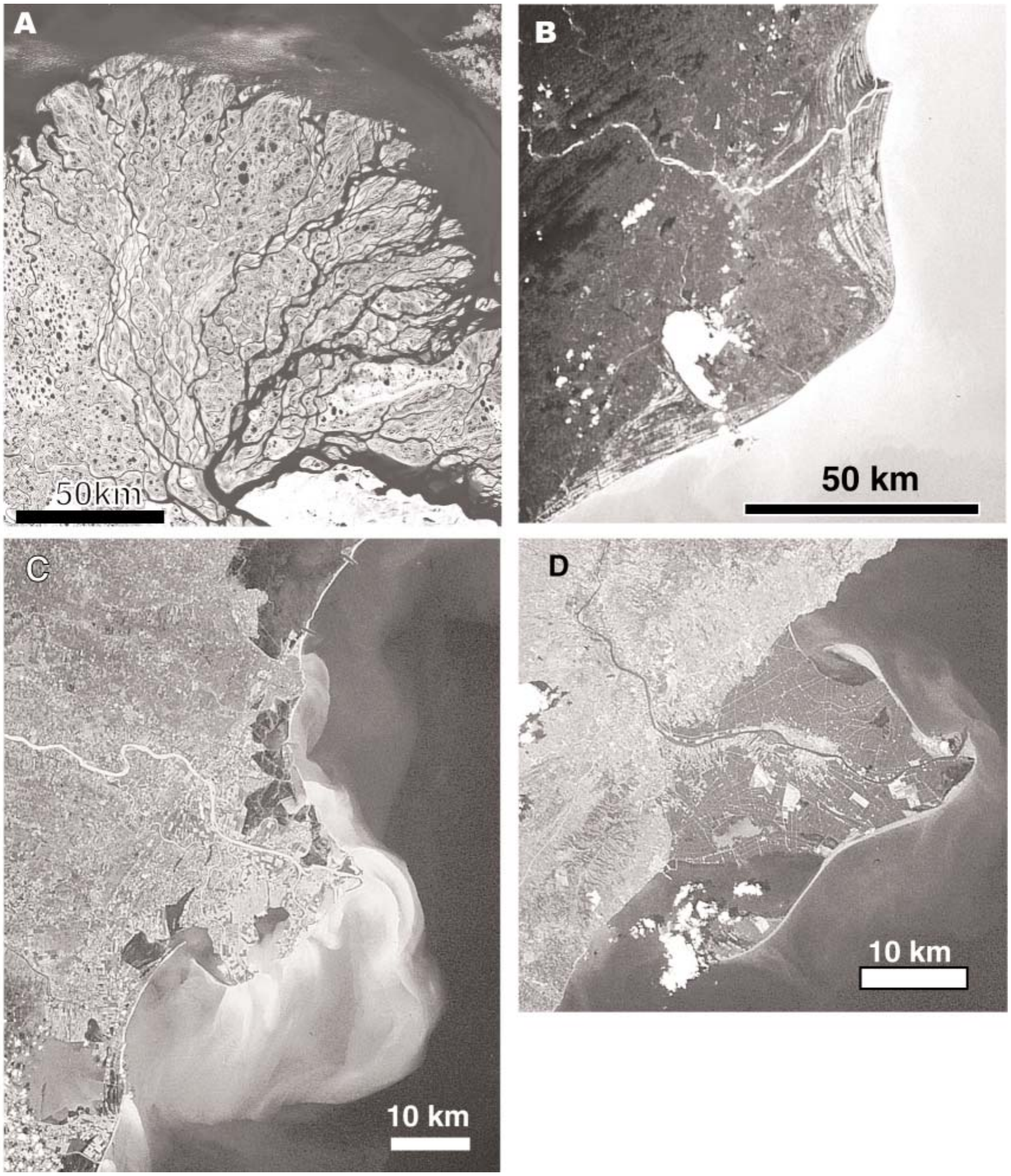

Figure 3. Comparison of distributary channel branching patterns in a fluvial- versus wave-dominated deltaic coastline. (A) Fluvial-dominated Lena River delta (Russian Arctic) shows numerous orders of branching with many tens of terminal distributary channels (photo from NASA Earth Observatory website - http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=10291). (B) Wave-dominated coastline associated with the Paraibo do Sul, Brazilian coast. (C) Po delta, Italy. (D) Ebro delta, Spain. Bifurcation is inhibited in wave-dominated deltas because the river is unable to prograde into the basin as rapidly. This effectively allows the river to maintain its grade, which in turn inhibits avulsion. For the most part, Ferron deltas are interpreted as primarily wave-influenced. The Po and Ebro are considered to be likely modern analogs (photos of the Po, Ebro, and Paraibo do Sul deltas courtesy of W. R. Muehlberger).

distribution of channels than is generally observed in the Ferron Sandstone. This suggests that the largest of the documented Ferron channels are trunk streams.

Valleys or Channels in the Ferron?

Several Ferron studies (Barton et al., this volume, Figures 5 and 17; Garrison and van den Bergh, this volume) interpret multistorey channel belts to lie within incised valleys. Barton et al. (this volume) show 22-24 m (70-80 ft) deep incisions filled by multiple, stacked channel stories each less than 6 m (20 ft) thick (Figure 5). These observations satisfy the definition of incised valleys as "elongate erosional features larger than a single channel" (Dalrymple et al., 1994; Willis, 1997). The multistorey fills clearly show that streams were underfit relative to the larger incised valley (Figure 5).

Rivers confined to valleys are candidates for the

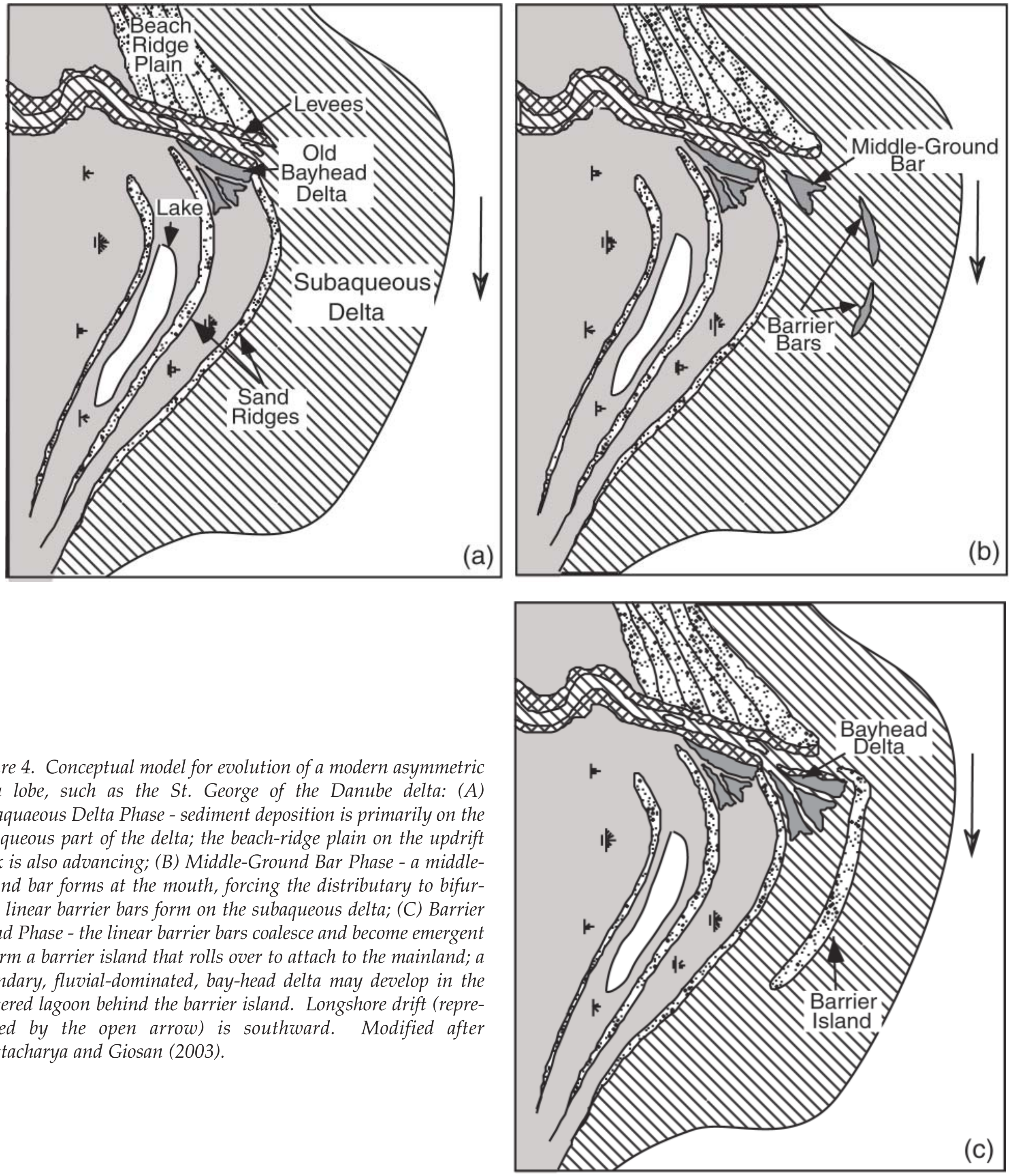

Figure 4. Conceptual model for evolution of a modern asymmetric delta lobe, such as the St. George of the Danube delta: (A) Subaquaeous Delta Phase - sediment deposition is primarily on the subaqueous part of the delta; the beach-ridge plain on the updrift flank is also advancing; (B) Middle-Ground Bar Phase - a middle-ground bar forms at the mouth, forcing the distributary to bifurcate; linear barrier bars form on the subaqueous delta; (C) Barrier Island Phase - the linear barrier bars coalesce and become emergent to form a barrier island that rolls over to attach to the mainland; a secondary, fluvial-dominated, bay-head delta may develop in the sheltered lagoon behind the barrier island. Longshore drift (represented by the open arrow) is southward. Modified after Bhattacharya and Giosan (2003).

largest-scale trunk channels. Therefore, their multi-storey channel-belt deposits provide insight into the depth and width of the formative channel, although the amalgamated character means that channels may be incompletely preserved. Interpretations based on incomplete channel thicknesses may result in underestimation of bankfull channel depth (Bridge and Tye, 2000), although more complete channel fills are found in the higher storeys (Figure 5).

Although the Mississippi Delta has been used as a modern analog for the Ferron Sandstone (e.g. Cotter, 1975a; Moiola et al., this volume) comparisons have not been rigorous. In fact, a significant Ferron stratigraphic debate is centered on the interpretation of channelized deposits on the order of 20 m (65 ft) deep and a few hundred meters wide. Moiola et al. (this volume) suggest that because these incised features are comparable in size to distributary channels in the modern Mississippi Delta, they are distributary channels. In contrast, Barton et al., and Garrison and van den Bergh (this volume)

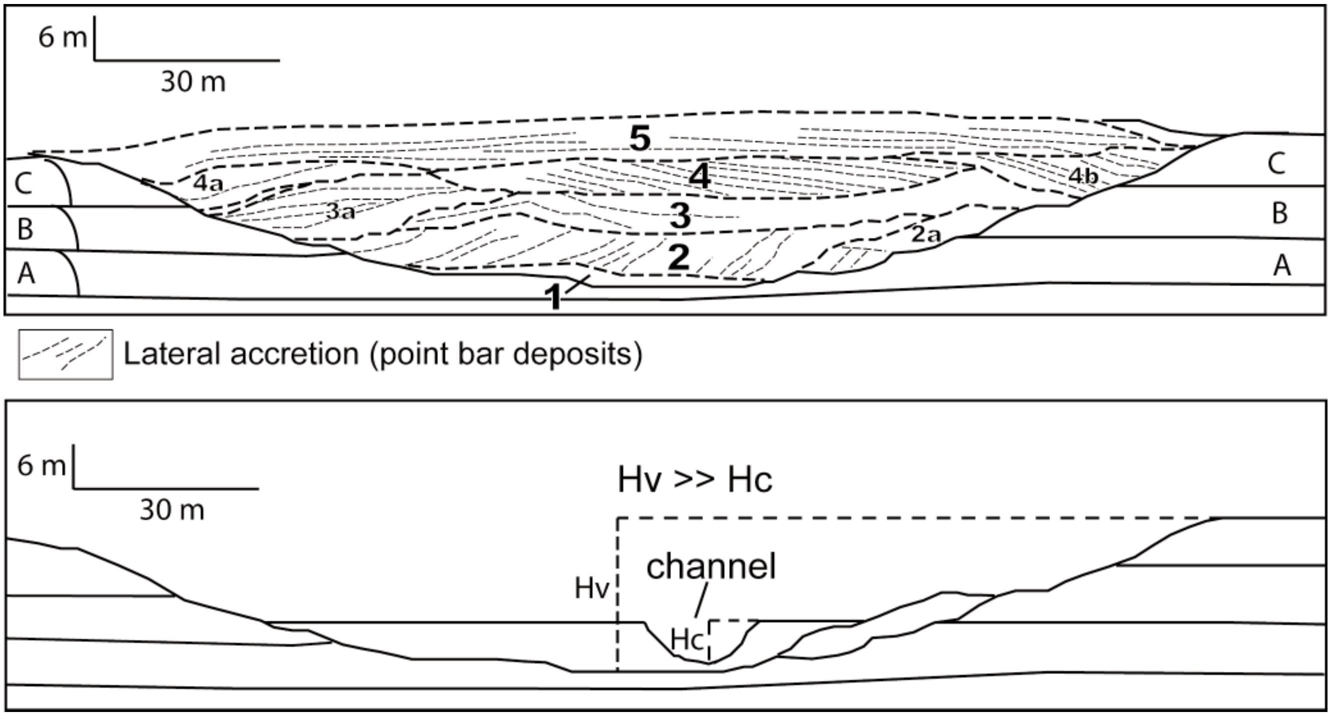

Figure 5. Facies architecture of an interpreted Ferron valley fill in cliffs along Interstate 70. Base of valley erodes into several upward-coarsening parasequences (A, B, C). Valley depth (Hv) is about 21 m (70 ft). In contrast, associated channel depths (Hc) are only about 6 m (20 ft). Valley is filled with five channel storeys (1-5). Lowest channel belt deposit (1) is largely eroded by migration of younger channels. Predominance of laterally accreting bars, define the internal facies architecture of each channel-belt deposit. The bedding geometry shows that the rivers were single thread, meandering streams that gradually filled the larger valley. Calculation of water depth from dune-scale cross-strata within the bar deposits suggests maximum bankfull depth of about 9 m (30 ft). Figure modified after Barton et al. (this volume).

interpret these deposits as incised valleys, that contain the deposits of numerous, vertically stacked, small-scale channels. Thus, these differing opinions are manifested in numerous sequence stratigraphic interpretations of the Ferron. Ryer (this volume) points out that seven sequence boundaries identified in the Ferron by several research groups do not match!

In the previous section we concluded that the Ferron drainage area was far too small for the development of a Mississippi-scale river. Additionally, the ratio of bankfull-channel depth to the maximum-erosion depth defines a valley, not the absolute depth of the incision. In the Ferron Sandstone, the ratio of valley depth to channel depth is about 4.

Estimating Paleodischarge of Ferron Rivers

To compare interpreted Ferron channel belts with modern counterparts it is helpful to calculate a possible discharge for the Ferron rivers. Matthai (1990 [quoted in Mulder and Syvitsky, 1995]) demonstrates that peak-flood fluvial discharge is related to drainage basin area by the equation:

$$\text{Log } Q_{flood} = -0.070\ (\log A^2) + 0.865 \log A + 2.084 \qquad (1)$$

Given drainage area A = 50,000 km^2 (19,000 mi^2), we calculate log Q_{flood} = 5.49. This, in turn, yields a calculated peak flood (Q_{flood}) of 309,029 m^3/sec (10,914,854 ft^3/sec), although there is an order of magnitude uncertainty in this calculation. It is emphasized that this value would not apply year round, would primarily reflect only times of high seasonal discharge, and should not be used to calculate average yearly discharge. Data compiled by Mulder and Syvitsky (1995) suggest that $Q_{flood}/Q_{Average}$ ratios can range over 4 orders of magnitude, from 10 to 10,000. This ratio suggests that average discharge for Ferron rivers could be as high as 30,000 m^3/sec (1,060,000 ft^3/sec) but as low as 30 m^3/sec (1060 ft^3/sec). Clearly the uncertainty in these estimates is large, and results must be interpreted with caution.

A more robust method of estimating discharge is based on the paleohydraulics of the river deposits themselves. We start with the equation for channel discharge:

$$Q = A \times U \qquad (2)$$

where Q = discharge, A = cross-sectional area of the channel (width x depth), and U = average velocity. For this method, estimates of water depth, channel width, and flow velocity (U) are required. Channel velocity could be calculated from the slope, but ancient fluvial slopes are notoriously difficult to estimate, primarily because they are low and range over several orders of magnitude (typically 0.001 to 0.00001). Water depths of the interpreted trunk streams can be readily estimated from the mean preserved thickness of dune-scale cross-strata (Bridge and Tye, 2000; Le Clair and Bridge, 2001) using the equation:

$$H_m = 5.3ß + 0.001ß^2 \quad (3)$$

where $ß = s_m/1.8$, s_m = mean cross-set thickness, and H_m = mean dune height.

To use this technique, it is essential that data on the measured thicknesses of cross-sets be accurately presented. Bridge and Tye (2000) stress that abnormally thick, isolated cross-sets formed by unit bars should be excluded from the data. Based on measured sections presented by Gardner et al. (this volume) and Garrison and van den Bergh (this volume), thickness of dune-scale cross-stratal sets are shown to average 20-30 cm (8-12 in.). Setting s_m = 20-30 cm, the above equation therefore yields a mean dune height of about 59-88 cm (23-35 in.). LeClair and Bridge (2001) further show that flow depth is typically 8 to 10 times mean dune height. This suggests flow depths of between 4.7-8.8 m (15.4-28.9 ft). We thus determine maximum (i.e. bankfull) flow depths to be about 9 m (30 ft).

Channel depth can also be independently estimated from thicknesses of fully preserved bar deposits (i.e. macroform) and channel-fill deposits, typically represented in the uppermost storey within the interpreted valley fills. Thickness of bar-scale macroforms reaches a maximum of about 8 m (26 ft) (Gardner et al., Figure 15, this volume). With the assumption that bar deposit thicknesses are roughly 90% of channel depth (c.f. Bridge and Mackey, 1993) we again estimate a flow depth of about 9 m (30 ft), similar to that calculated above. Maximum thicknesses of channel-fill deposits, based on measured sections presented by Gardner (this volume) and Garrison and van den Bergh (this volume) are also on the order of 9 m (30 ft). These independent estimates of maximum bankfull-channel depth (d_m) all suggest a value of about 9 m (30 ft). Taking the mean channel depth to be approximately 0.57 the maximum-bankfull depth (5.1 m [16.7 ft]) (Bridge and Mackey, 1993) and these equations from Bridge and Tye (2000):

$$w_c = 8.88(d_m)^{1.82} \quad (4)$$

$$w = 59.86(d_m)^{1.8} \quad (5)$$

$$w = 192.01(d_m)^{1.37} \quad (6)$$

where d_m = mean channel depth, gives a channel width (w_c) of 174 m (571 ft) and a range of channel-belt widths from 1135-1800 m (3724-5900 ft). Several of the valley-scale channels in outcrop (9 m [30 ft] deep, 250 m [820 ft] wide) show laterally accreting point-bar deposits (Barton et al., this volume), suggesting single-channel, meandering streams. Equation 6 is most applicable for a high-sinuosity channel. The equations of Fielding and Crane (1987) (equation 7) and Collinson (1978) (equation 8):

$$w = 64.6\ (d_m)^{1.54} \quad (7)$$

$$w = 65.6\ (d)^{1.57} \quad (8)$$

where d = maximum channel depth, give a range of channel-belt widths from 650-2100 m (2130-6900 ft). The value in these calculations is that they give a range of possible channel and channel-belt sizes that compare favorably with outcrop observations where the Ferron channels are confined, or where channel margins are observable (channel not confined within a valley).

Garrison and van den Bergh (this volume) measured channel-belt widths, and thicknesses. They show that maximum thicknesses are 30 m (100 ft) and widths do not exceed 2 km (1.2 mi). Channel widths within the belts average 250 m (820 ft). There is no outcrop evidence that Ferron river channels were wider than a few hundred meters. Numerous unconfined distributary channels occur in the Ferron delta plain (e.g. Corbeanu et al., this volume), but it is impossible to estimate overall stream discharge from these types of channels because it is not known how many distributary channels were active simultaneously.

Sedimentological descriptions of the fluvial deposits show a predominance of dune-scale cross-stratified, pebbly, coarse- to medium-grained sandstone, fining upward into fine-grained sandstone and mudstone (Ryer and Anderson, this volume). Ryer and Anderson (this volume) present strong evidence for sinuous channels that migrated laterally (e.g. upward-fining abandoned-channel fills, lateral accretion surfaces). The abundant mud deposited in both the floodplain, prodelta, and offshore areas demonstrate that the Ferron rivers carried a significant muddy load in suspension, as well as a sandy bedload moving primarily as dune-scale bedforms. Channel deposits become increasingly mud rich, down depositional dip and in higher stratigraphic positions (Barton et al., this volume; Gardner et al., this volume).

Flow velocities in the Ferron rivers can be estimated using the method of Rubin and McCulloch (1980). Their method is based on bedform stability as a function of grain size, water depth, and velocity (Figure 1). A flow velocity of between 50-110 cm/sec (20-43 in./sec) is estimated based on grain size (fine sand), water depths (9 m [30 ft]), and the fact that three-dimensional dunes were the primary stable bedforms. Assuming that grain size and sedimentary structures represent high-discharge or early, post-flood depositional conditions, we use 100 cm/sec (1 m/sec [3 ft/sec]) as a reasonable estimate of flow velocity.

A maximum channel depth of 10 m (33 ft) and a width of 250 m (820 ft) gives an average cross-sectional area of on the order of 1250 m^2 (13,460 ft^2). From this it is easy to calculate a discharge (Q_w) of 1250 m^3/sec (50 x 10^3 ft^3/sec). Of course the channel-forming discharge was likely related to times of major floods, so the average discharge is probably lower than 1250 m^3/sec. Assuming that discharge was this high year round, allows us to place an upper limit of maximum possible discharge of about 50 x 10^9 m^3/year or 50 km^3/year (about 250 x 10^9 ft^3/year). This contrasts with the discharge calculated using an estimated drainage area, which suggests maximum possible peak-flood discharge of 309,000 m^3/sec (10,900,000 ft^3/sec) compared to 1250 m^3/sec. The 1250 m^3/sec estimate is, however, within the range of possible average discharge values of 30-30,000 m^3/sec (1060-1,060,000 ft^3/sec) using the alternate approach of Matthai (1990).

COMPARISON OF FERRON WITH MODERN DELTAS

We now have a relatively complete characterization of the Ferron system (although focused primarily on the lower parasequences within the Last Chance delta). Width and depth estimates for Ferron rivers are an order-of-magnitude less than for those of the modern Mississippi, whereas the overall sediment caliber in the Ferron channel and bar deposits is considerably coarser grained. The Mississippi, therefore, should not be used as an analog in comparing the scale of the delta and its associated elements, particularly the major Mississippi distributary channels.

A narrow range in sizes of distributary channels suggests that there were only a few orders of bifurcation. This is consistent with predominantly wave-influenced shorelines and delta fronts in which only fluvial dominance is localized (Figure 3). The Ferron deltas were likely wave-modified and probably asymmetric, similar in plan to the Brazos delta, the Ebro, Rhône, or the southern St. George lobe of the Danube (see summary in Bhattacharya and Giosan, 2003; Figures 3 and 4). Fluvial-dominated lobes may have prograded into bays, protected by wave-formed barrier systems on the downdrift margins of these systems. The low number of bifurcations is characteristic of highly wave-modified delta systems (Figure 3).

The Ferron river systems are more similar to moderate-sized, sandy-bedload rivers such as the Brazos (Texas), or the Po (Italy), Rhône, (France), and Ebro (Spain) that drain off the active alpine systems in central Europe (Figure 3). The Ferron rivers did not drain a craton, and therefore mud-dominated continental-scale systems, such as the Mississippi (USA), Niger (West Africa), Amazon (Brazil), and Nile (North Africa), are not appropriate analogs.

Our calculated estimates suggest that the Ferron rivers were an order-of-magnitude smaller in discharge than the smallest of the world's 25 largest rivers (Meade, 1996). The two smallest of the top 25 rivers (Niger River in Africa and Fly River in Papua New Guinea) have respective water discharges of 190 and 150 x 10^9 m^3/year (950 and 750 x 10^9 ft^3/year) (Meade, 1996) three times larger than the 50 x 10^9 m^3/year (250 x 10^9 ft^3/year) calculated for the Ferron rivers, which as discussed is probably still too high an estimate. Estimates of the Ferron drainage area are also two orders-of-magnitude lower than for continental-scale river systems like the Niger, Amazon, and Mississippi. Additionally, the estimated size of the mapped subaerial delta plains formed by each of the Ferron deltas (10^3 km^2 [240 mi^2]) is an order-of-magnitude less than that for major continental deltas (e.g. Gardner, 1995; Anderson et al., this volume).

Table 1. Summary data for Holocene deltas possibly analogous to Ferron deltas. Data summarized from Russell (1942), Coleman and Wright (1975), Wells et al. (1984), Ecological Research Associates (1983), and van Heerden and Roberts (1988).

	Climate	Basin Area (x 10^3 km^2)	Aluv. Channel Length (km)	Delta Area (km^2)	Discharge (m^3/sec)	No. of Mouths	Tidal Range (m)
Ebro (Spain)	Dry Trop.	89.8	67	624	552	2	0
Colville (Alaska)	Arctic	59.5	481	1687	491.7	19	0.21
Sagavanirktok (Alaska)	Arctic	11.8	55	1178	600	11	0.21
Cubits Gap (Louisiana)	Temp.	3344.6	-	200	2262	8	0.5
Atchafalaya (Louisiana)	Temp.	3344.6	-	125	937	10	0.5
Wax Lake (Louisiana)	Temp.	3344.6	-	107	1537	8	
West Bay (Louisiana)	Temp.	3344.6	-	300	750	6	0.5
Danube (Romania)	Cool Temp.	712.6	774	2740	6250.1	14	0
Magdalena (Columbia)	Humid Trop.	251.7	136	1689	7500	1	1.1
Rhône (France)	Dry Trop.	-	177	1813	13,000 (max.) 360 (min)	6	0
São Francisco (Brazil)	Humid Trop.	602.3	150	734	3420	1	1.86
Last Chance delta	Humid Sub-Trop.	50	100	1000	1250		<2.0

A collection of data on modern deltas (Table 1) that may span the sizes and morphologic types of Ferron deltas include the Ebro (Spain), Colville and Sagavanirktok (Alaska), Rhône (France), Danube (Romania), Magdalena (Columbia), Mississippi River subdeltas (West Delta, Cubits Gap, Atchafalaya, and Wax Lake), and São Francisco (Brazil).

USE OF MODERN ANALOGS FOR SUBSURFACE INTERPRETATION OF FERRON WELL DATA

Having restricted the population of possible modern river and delta analogs for the Ferron Sandstone, the validity and usefulness of using their geomorphic traits (Table 2) were tested on a dataset of 16 wells to guide a subsurface interpretation of the Ferron (Figure 6). Core and wireline-log data include research wells drilled at Ivie Creek (Utah Geological Survey), Muddy Creek (British Petroleum), and a regionally spaced set of wells drilled by ARCO. Well spacing is highly variable. At Ivie Creek and Muddy Creek, closely spaced wells (0.5 km [0.3 mi]) provide control on correlation of facies associations, whereas the distance between the remaining wells leaves much room for interpretation.

Each well has gamma-ray and density logs; most of the ARCO wells also have neutron-porosity logs. Existing core descriptions (Thompson et al., 1986; Utah Geological Survey; and Moiola et al., this volume) for the two lowermost Ferron parasequence sets (Kf-1 and Kf-2; Anderson et al. this volume) provide the basis for our stratigraphic interpretation.

Given the clustered wells at Ivie Creek and Muddy Creek, plus the widely spaced ARCO wells, our assump-

Table 2. Summary statistics for length and width of channels and distributary-mouth bars in various deltaic settings.

	Length (km)			Width (km)			
Colville	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Channels	N/A	N/A	N/A	0.27	0.5	0.78	40
Ab. Channels	0.09	0.39	2.74	0.03	0.05	1.07	140
Distributary Channels	N/A	N/A	N/A	0.05	0.42	2.43	281
Dist.-Mouth Bars	0.14	0.43	6.73	0.09	0.16	2.93	109
Sagavanirktok	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Channels	N/A	N/A	N/A	0.09	0.53	1.25	65
Ab. Channels	0.22	0.53	2.95	0.06	0.09	0.93	75
Distributary Channels	N/A	N/A	N/A	0.05	0.16	0.68	75
Dist.-Mouth Bars							164
Atchafalaya	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Distributary Channels	N/A	N/A	N/A	0.07	0.09	1.78	51
Dist.-Mouth Bars	0.44	2.05	3.43	0.26	1.05	2.07	14
Wax Lake	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Distributary Channels	N/A	N/A	N/A	0.03	0.12	0.78	102
Dist.-Mouth Bars	0.16	0.57	4.94	0.09	0.41	1.33	64
West Delta	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Distributary Channels	N/A	N/A	N/A	0.06	0.22	1.22	73
Cubits Gap	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Dist.-Mouth Bars	0.15	0.17	2.61	0.08	0.16	2.14	46
Rhône	**Min.**	**Mode**	**Max.**	**Min.**	**Mode**	**Max.**	**N**
Distributary Channels	N/A	N/A	N/A	0.5	0.6	1.0	11

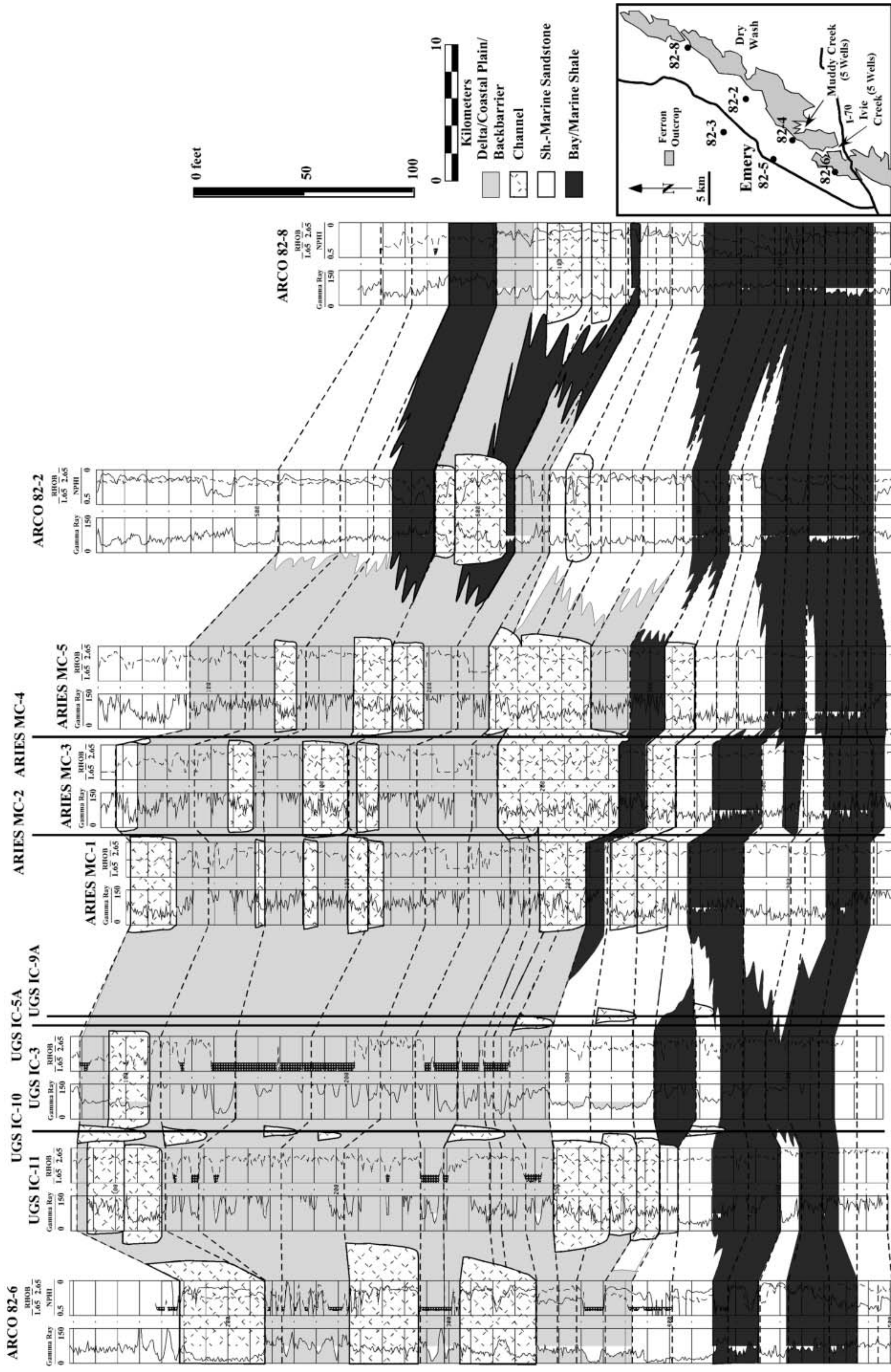

Figure 6. Correlation of Ferron subsurface data not incorporating dimensions based on modern analogs.

Table 3. Fluvial channel, distributary channel, distributary-mouth bar, and shoreface dimensions summarized from 671 paralic sandstone bodies. From Reynolds (1999).

Sandstone Body Type	Length (km)			Width (km)		
	Min.	Mean	Max.	Min.	Mean	Max.
Fluvial Channels	N/A	N/A	N/A	0.06	0.76	1.4
Distributary Channels	N/A	N/A	N/A	0.02	0.52	5.9
Dist.-Mouth Bars	2.4	6.48	9.6	1.1	2.87	14
All Shoreface/Shelf Sandstones	47	93.2	190	1.6	25.4	106

tion is that the well data are a reasonably unbiased sample of the lower Ferron stratigraphy. Our hypothesis is that subsurface interpretations integrating core data with modern analog observations are superior to those made in which geomorphic guidance from modern analogs are lacking. The exercise also allows us to estimate the degree of stratigraphic uncertainty inherent in subsurface data sets compared to continuously exposed outcrop data sets.

To evaluate the hypothesis, our stratigraphic interpretation was compared to the cross sections based on nearly continuously exposed outcrops presented by Garrison and van den Bergh (this volume; their Figure 3). Parasequences within parasequence sets Kf-1 and Kf-2 were correlated in all the wells using genetic-sequence and allostratigraphic concepts (Figure 6; c.f. Van Wagoner et al., 1990; Cant, 1992; Bhattacharya, 1993; Posamentier and Allen, 1999). We deliberately did not refer to the detailed outcrop stratigraphies presented in this volume to constrain our correlations. The intent was to illustrate the degree to which a more-or-less random series of wells represents the actual stratigraphy.

A stratigraphic cross section paralleling the Ferron outcrop belt (Figure 6) shows the parasequences, bounding surfaces, and facies associations bundled into transgressive – regressive cycles, similar to those described by Anderson et al. (this volume) and Ryer (this volume). Moiola et al. (this volume) attribute many of the bounding surfaces to be localized flooding surfaces created through delta-lobe abandonment.

In making subsurface interpretations given only wireline logs and cores, one can measure facies associations, and bedset and bed thicknesses in addition to interpreting unconformities. Lorenz et al. (1985), Fielding and Crane (1987), Bridge and Tye (2000), and Le Clair and Bridge (2001), provide insights into how thickness data can facilitate estimating channel dimensions. Additionally, Reynolds (1999) gives good thickness-to-width relationships for paralic facies associations (Table 3).

In a revised Ferron cross section (Figure 7), the size, connectivity, position, and frequency of occurrence of specific facies elements (e.g. fluvial, distributary, and tidal channel; distributary-mouth bar; bay/lagoon; shoreface) were governed by geomorphic constraints based on these published thickness versus width datasets. Channel dimensions were varied according to whether the channel's interpreted environmental setting was fluvial, distributary, or tidal in nature. Fluvial and distributary-channel dimensions were estimated using the methods previously described and those of Bridge and Tye (2000). Also, size ranges for distributary channels and distributary-mouth bars in various river-influenced deltas were incorporated (Table 2). The number of interwell channels and their connectivity were estimated using the net-to-gross observed in each stratigraphic interval (Bridge and Mackey, 1993). Correlations at Ivie Creek and Muddy Creek, where well spacing is as close as 0.5 km (0.3 mi), demonstrate the localized extent of the distributary channels (Figure 7). Had we assumed that distributary channels were at the scale of the Mississippi delta, we would have correlated them over longer distances. The proportion and dimensions for tidal-inlet channels are based on thickness-to-width relationships of Holocene examples (Tye and Moslow, 1993).

A third correlation (Figure 8) assumes that the multistorey channel sandstones are incised valleys. A major difference between it and Figure 7 is the over-correlation of channel facies, especially in the uppermost part of the Ferron Sandstone.

The subsurface and outcrop cross sections (Figure 7, and Figure 3 of Garrison and van den Bergh, this volume) capture the progradational and aggradational stacking pattern of multiple Ferron parasequences and the flooding surfaces separating them. Three sequences (FS1, FS2, and FS3) identified by Garrison and van den Bergh (this volume) are projected onto Figure 7; although, their placement on the wireline logs is approximate.

This comparison illuminates interpretive differences and difficulties between outcrop and subsurface interpretations. Given the greater exposure and more complete sampling, the outcrop interpretation contains a greater diversity in interpreted facies associations, an increased number of identified parasequences and bedsets, and consequently greater stratigraphic fidelity.

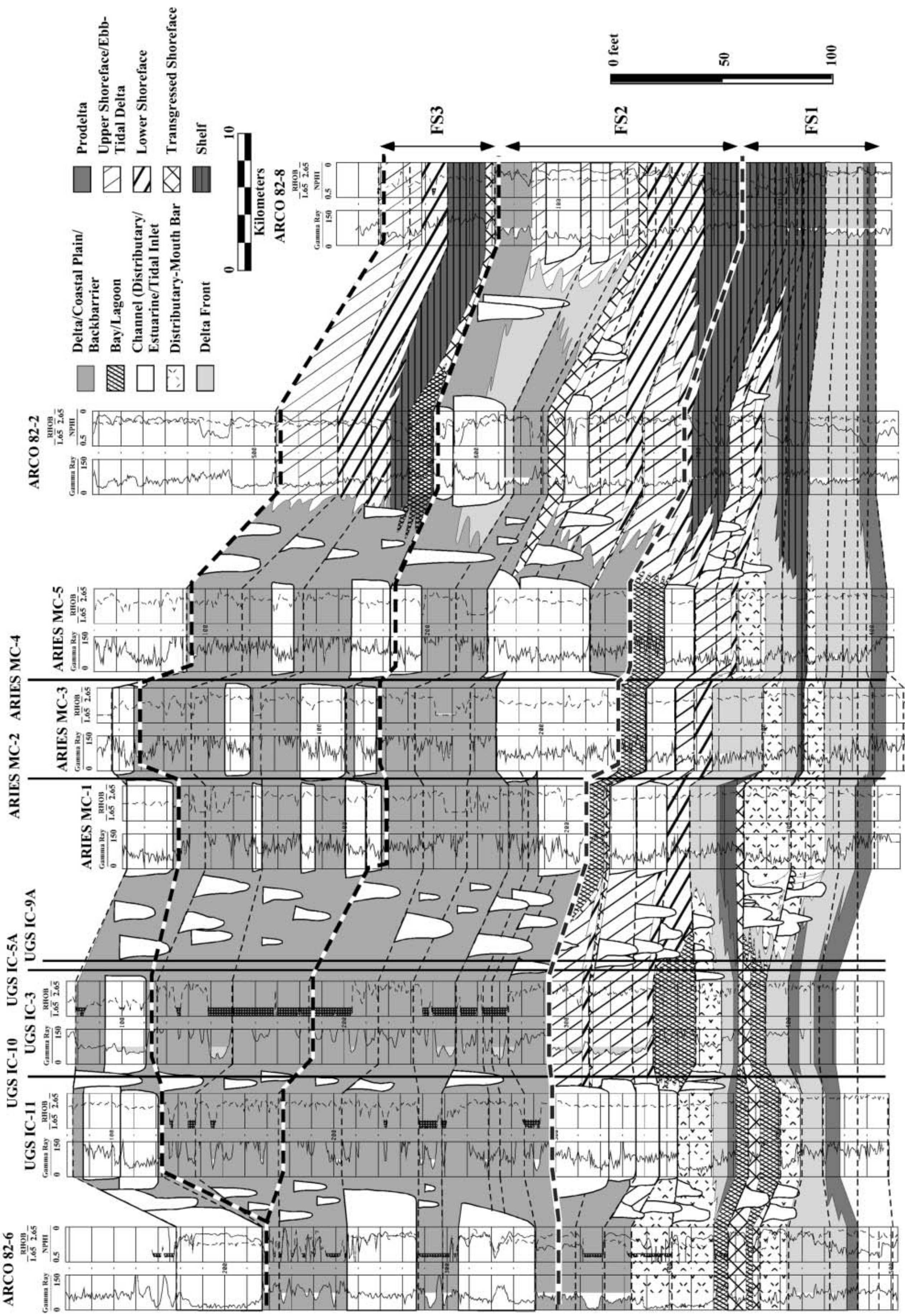

Figure 7. Correlation of same Ferron cores, interpolating detail from modern analogs. Note additional channel elements interpolated between wells.

Table 4. Distributary channel and distributary-mouth bar dimensions in river-dominated and wave-reworked progradational parasequences in the Last Chance delta. From Garrison and van den Bergh (this volume).

Last Chance Delta	Length (km)	Width (km)	Thickness (m)	Length/Thickness Aspect Ratio	Width/Thickness Aspect Ratio	Length/Width Aspect Ratio
Distributary Channels	N/A	0.364	9.7	N/A	38.0	N/A
Dist.-Mouth Bars	3.67	2.69	8.9	512	169.4	2.5

However, considering that in the absence of the outcrop data, Figures 7 and 8 could represent equi-probable stratigraphic interpretations, its similarity to the work of Garrison and van den Bergh (this volume) is reassuring. For instance, at the base of FS1 (Figure 7), both interpretations show bay/lagoonal deposits separating parasequence set 1 from parasequence set 2. In outcrop, the bay/lagoonal deposits grade into prodelta/offshore sediments between Ivie Creek and Muddy Creek. In the subsurface section, the bay/lagoonal deposits are correlated continuously between Ivie Creek and Muddy Creek as if they are landward facies equivalents of distributary channel and distributary-mouth bar deposits in well MC-1. This illustrates the greatest difference between the two interpretations and a drawback to subsurface interpretations – the inability to recognize and correlate all parasequences and to potentially over-correlate potential reservoir compartments. This is a particularly common problem where subsurface data undersample complex stratigraphic features, such as offlapping clinoform strata. Data from modern environments can help make predictions about the maximum likely extent of a clinoform feature, such as a delta lobe, although to date, there are far more data on channelized facies elements. Additionally, although Ferron channel widths average less than 0.5 km [0.3 mi]) (Table 4), the lateral continuity of amalgamated channel deposits (channel belts) demonstrated by Garrison and van den Bergh (this volume) is generally greater than that shown in Figure 7, but not as much as shown in Figure 8. Thus, the subsurface interpretation in Figure 7 is optimistic in estimating the continuity of shallow-marine facies associations (i.e. delta front, shoreface) in parasequences but pessimistic in estimating the dimensions and number of channel deposits. The over-thick channel-belt deposits could also represent candidates for incised valley fills, as illustrated in Figure 8, which would result in interpretation of several additional sequence boundaries. The valley systems would correlate over larger distances than smaller distributary channels. However, even with such excellent datasets, correlation of sequence boundaries is far more uncertain than correlation of the flooding surfaces (Ryer, this volume).

In evaluating the probability that Figure 7 accurately represent the Ferron geology, and using Garrison and van den Bergh's work as the ground truth, this subsurface Ferron interpretation falls on the low side of a most-likely case scenario, with a greater level of compartmentalization of sandstone bodies than is seen in the outcrop. Figure 8 tends to over-correlate the channel sandstones.

Making multiple interpretations of the same subsurface data set can be a valuable method in determining the range of stratigraphic uncertainty. If the degree of uncertainty can be incorporated in building two- or three-dimensional reservoir models, then the risk associated with a development program can be better evaluated. In a sense, the question for a reservoir geologist should not be, "how big is a distributary channel (or any other facies architectural element)," but "what is the range of possible or most likely sizes." This is the scale of reservoir description at which data from modern depositional analogs can be most useful.

CONCLUSIONS

Integration of the tectono-stratigraphic interpretations of Gardner (1995) with the general paleogeographic reconstructions of the Cretaceous (Williams and Stelck, 1975) suggests that the Last Chance delta was fed by a trunk river draining an area of about 50,000 km^2 (19,000 mi^2). This drainage basin area can in turn be used to estimate maximum flood discharge (Matthai, 1990) which suggests that peak flood discharges could have been as high as 300,000 m^3/sec (10,600,000 ft^3/sec), although estimates using this method vary over several orders of magnitude. More robust calculations of river discharge, based on paleohydraulic estimates of channel-flow depths, cross-sectional channel areas, and flow velocity, suggest maximum discharge of $Q_w = 50 \times 10^9$ m^3/year (about 250 x 10^9 ft^3/year).

Discharge estimates for Ferron rivers are orders-of-magnitude less than for those of the modern Mississippi River, whereas the overall sediment caliber in the Ferron channel and bar deposits is considerably coarser grained. Some of the larger-scale Ferron trunk rivers lie within 20 m (60 ft) deep incised valleys. Although these valleys are comparable in scale to distributary channels in continental-scale deltas, like the Mississippi, such comparisons can be misleading. Anecdotal comparisons of ancient delta systems with well-studied modern continental-scale systems, such as the Mississippi, may

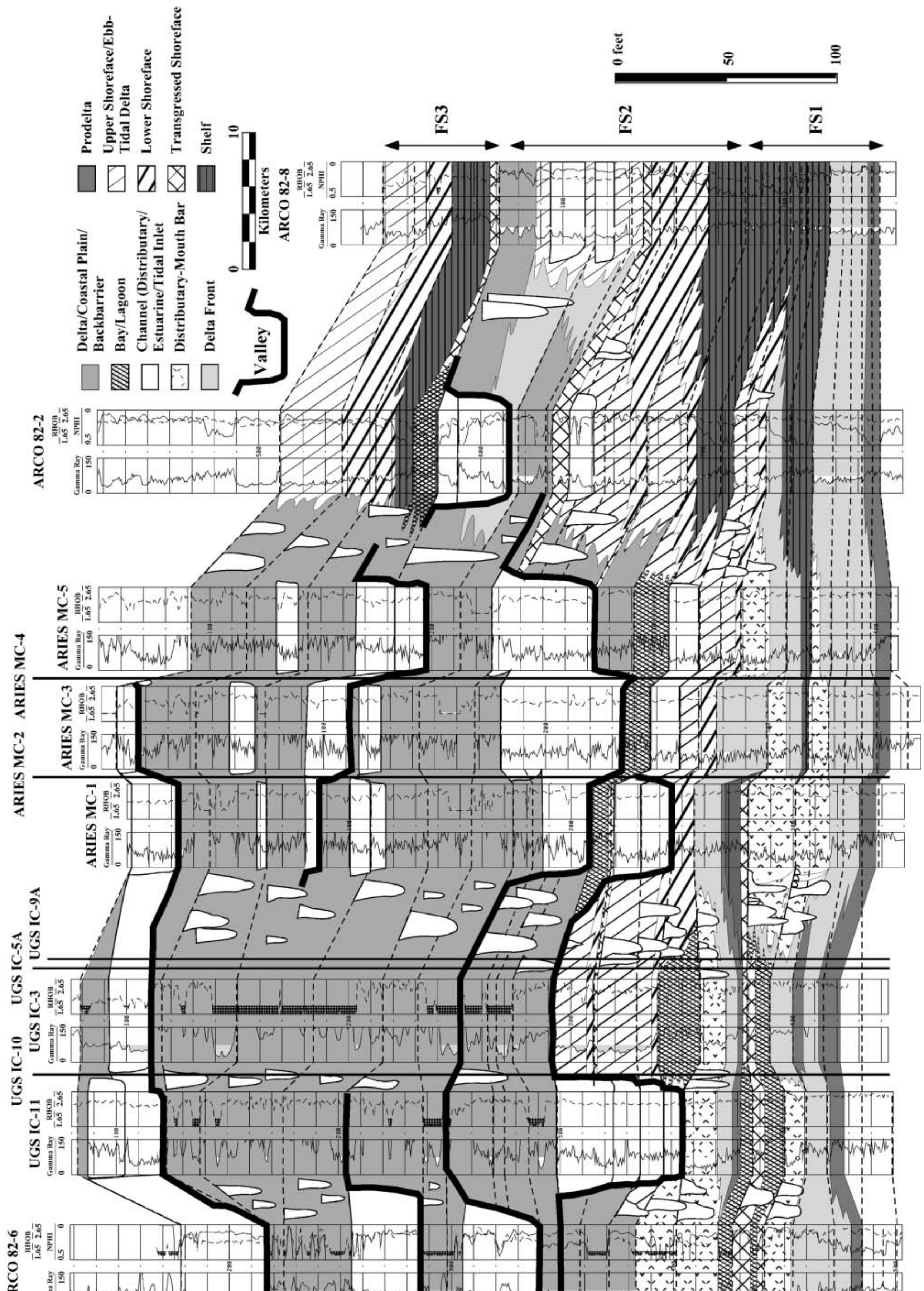

Figure 8. Third correlation of Ferron cores, interpreting stacked channel sandstones as incised valleys. Note tendency to over-correlate upper valley fill as a continuous sandstone.

result in erroneous interpretations of valleys as distributary channels (Bhattacharya et al., 2001). Ferron channels were on the order of 5-9 m (16-30 ft) deep, compared to the greater depths of continental-scale rivers. Recognition of valleys within the Ferron Sandstone suggests significant erosion and has important sequence stratigraphic implications.

A lack of size variability of distributary channels suggests that there were only a few orders of bifurcation. The low number of bifurcations is characteristic of highly wave-modified delta systems. Shoreline and delta-front facies are predominantly wave-influenced, with only local fluvial dominance. The Ferron deltas were likely wave-modified and probably asymmetric, similar in plan view to the Brazos, Ebro, and Rhône deltas, or the southern St. George lobe of the Danube (see summary in Bhattacharya and Giosan, 2003; Figure 4). Fluvial-dominated lobes may have prograded into bays, protected by wave-formed barrier systems on the downdrift margins of deltaic depocenters.

Lastly, dimensional compilations from modern analog data can be used to better constrain interwell heterogeneity in subsurface correlations. Comparison of subsurface-type correlations of Ferron core and wireline log datasets with the detailed outcrop stratigraphy shows that despite capturing the clinoform geometry, several parasequences could not be reliably distinguished in the subsurface data. Over-correlating shallow-marine reservoir compartments in subsurface interpretations is a danger. In the Ferron subsurface example, the lateral continuity of shallow-marine facies associations was overestimated, whereas the sizes and number of channel facies associations interpreted were underestimated. The Ferron outcrops are an excellent guide to evaluating correlation uncertainties in subsurface settings.

ACKNOWLEDGMENTS

This paper has benefited from discussions with numerous experts, both in fluvial sedimentology and in Ferron stratigraphy. Mark Barton, John Bridge, Gus Gustason, Tom Ryer, Mike Gardner, John Holbrook, John Milliman, and James Syvitsky provided us with many valuable ideas. W. R. Muehlberger at the University of Texas at Austin kindly provided access to the NASA shuttle photographs of the Ebro, Po, and Paraibo do Sul deltas included in Figure 4. Brian Willis and James MacEachern provided helpful reviews. We also thank memoir editor, Tom Chidsey for inviting this contribution. Gus Gustason and Tom Ryer are also thanked for introducing us to these fabulous outcrops, back in 1991. Despite all of the input, we take full responsibility for any shortfalls, pitfalls, or errors in our interpretations. Funding for this research was provided to by BP, ChevronTexaco, and the American Chemical Society, ACS-PRF Grant # 35855-AC8 to J.P. Bhattacharya. This is contribution number 1003 of the Geosciences Department, University of Texas at Dallas.

REFERENCES CITED

Barton, M. D., 1994, Outcrop characterization of architecture and permeability structure in fluvial-deltaic sandstones, Cretaceous Ferron Sandstone, Utah: Ph.D. dissertation, University of Texas at Austin, Austin, Texas, 259 p.

—1997, Application of Cretaceous Interior Seaway outcrop investigations to fluvial-deltaic reservoir characterization – pt. 1, predicting reservoir heterogeneity in delta front sandstones, Ferron gas field, central Utah, *in* K. W. Shanley and R. F. Perkins, eds., Shallow marine and nonmarine reservoirs, sequence stratigraphy, reservoir architecture and production characteristics: Society for Sedimentary Geology (SEPM) Gulf Coast Section Foundation 18th Annual Research Conference, p. 3-40.

Bhattacharya, J. P., 1993, The expression and interpretation of marine flooding surfaces and erosional surfaces in core; examples from the Upper Cretaceous Dunvegan Formation in the Alberta foreland basin, *in* C. P. Summerhayes and H. W. Posamentier, eds., Sequence stratigraphy and facies associations: International Association of Sedimentologists Special Publication No. 18, p. 125-160.

Bhattacharya, J. P., and L. Giosan, 2003, Wave-influenced deltas - geomorphological implications for facies reconstruction: Sedimentology, v. 50, p. 1-24.

Bridge, J. S., 1993, The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers, *in* J. L. Best and C. S. Bristow, eds., Braided rivers, Geological Society Special Publication No. 75, p. 13-71.

Bridge, J. S, and S. D. Mackey, 1993, A theoretical study of fluvial sandstone body dimensions, *in* S. S. Flint and I. D. Bryant, eds., The geological modeling of hydrocarbon reservoirs and outcrop analogues: International Association of Sedimentologists Special Publication No. 15, p. 3-20.

Bridge, J. S., and R. S. Tye, 2000, Interpreting the dimensions of ancient channel bars, channels, and channel belts from wireline-logs and cores: AAPG Bulletin, v. 84, no. 8, p. 1205-1228.

Cant, D. J., 1992, Subsurface facies analysis, *in* R. G. Walker and N. P. James, eds., Facies models – response to sea level change: Geological Association of Canada, St. John's, Newfoundland, p. 27-45.

Coleman, J. M., and L. D. Wright, 1975, Modern river deltas - variations of processes and sand bodies, *in* M. L. Broussard, ed., Deltas - models for exploration:

Houston Geological Society, p. 99-149.

Collinson, J. D., 1978, Vertical sequence and sand body shape in alluvial sequences, *in* A. D. Miall, ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 577-586.

Corbeanu, R. M., K. Soegaard, R. B. Szerbiak, J. B. Thurmond, G. A. McMechan, D. Wang, S. H. Snelgrove, C. B. Forster, and A. Menitove, 2001, Detailed internal architecture of a fluvial channel sandstone determined from outcrop, cores and 3-D ground-penetrating radar - example from the Mid-Cretaceous Ferron Sandstone, east-central Utah: AAPG Bulletin, v. 85, p. 1583-1608.

Cotter, E., 1975a, Deltaic deposits in the Upper Cretaceous Ferron Sandstone, Utah, *in* M. L., Broussard, ed., Deltas, models for exploration: Houston Geological Society, p. 471-484.

—1975b, Late Cretaceous sedimentation in a low-energy coastal zone - the Ferron Sandstone of Utah: Journal of Sedimentary Petrology, v. 45, no. 3, p. 669-685.

Dalrymple, R. W., R. Boyd, and B. A. Zaitlin, 1994, History of research, valley types and internal organization of incised-valley systems, *in* R. W. Dalrymple, R. Boyd, and B. A. Zaitlin, eds., Incised-valley systems - origin and sedimentary sequences: Society for Sedimentary Geology (SEPM) Special Publication No. 51, p. 3-10.

Dean, W.E., and M. A. Arthur, 1998, Cretaceous Western Interior Seaway drilling project - an overview, *in* W. E. Dean and M. A. Arthur, eds., Stratigraphy and paleoenvironments of the Cretaceous Western Interior Seaway, USA: Society for Sedimentary Geology (SEPM) Concepts in Sedimentology and Paleontology No. 6, p. 1-10.

Ecological Research Associates, 1983, Sagavanirktok River - hydrology and hydraulics: Environmental Summer Studies (1982) for the Endicott Development, v. II : Physical Processes, p. 31-43.

Fielding, C. R., and R. C. Crane, 1987, An application of statistical modeling to the prediction of hydrocarbon recovery factors in fluvial reservoir sequences, *in* F. G. Ethridge, R. M. Flores, and M. D. Harvey, eds., Recent developments in fluvial sedimentology: Society for Sedimentary Geology (SEPM) Special Publication 39, p. 321-327.

Fouch, T. D., T. F. Lawton, D. J. Nichols, W. B. Cashion, and W. A. Cobban, 1983, Patterns and timing of synorogenic sedimentation in Upper Cretaceous rocks of central and northeast Utah, *in* M. W. Reynolds and E. D. Dolly, eds., Mesozoic paleogeography of west-central United States: Society for Sedimentary Geology (SEPM) Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 2, p. 305-336.

Gardner, M. H., 1995, Tectonic and eustatic controls on the stratal architecture of mid-Cretaceous stratigraphic sequences, central western interior foreland basin of North America, *in* S. L. Dorobek and G. M. Ross, eds., Stratigraphic evolution of foreland basins: Society for Sedimentary Geology (SEPM) Special Publication No. 52, p. 243-281.

Knox, P. R., 1997, Application of Cretaceous Interior Seaway outcrop investigations to fluvial-deltaic reservoirs II - example from Gulf of Mexico reservoirs, Frio Formation, South Texas, *in* K. W. Shanley and R. F. Perkins, eds., Shallow marine and nonmarine reservoirs, sequence stratigraphy, reservoir architecture and production characteristics: Society for Sedimentary Geology (SEPM) Gulf Coast Section Foundation 18th Annual Research Conference, p. 127-138.

Knox, P. R., and M. D. Barton, 1999, Predicting interwell heterogeneity in fluvial-deltaic reservoirs - effects of progressive architecture variation through a depositional cycle from outcrop and subsurface observations, *in* R. Schatzinger and J. Jordan, eds., Reservoir characterization-recent advances: AAPG Memoir 71, p. 57-72.

Le Clair, S. F., and J. S. Bridge, 2001, Quantitative interpretation of sedimentary structures formed by river dunes: Journal of Sedimentary Research, v. 71, p. 713-716.

Lorenz, J. C., D. M. Heinze, J. A. Clark, and C. A. Searls, 1985, Determination of widths of meander-belt sandstone reservoirs from vertical downhole data, Mesaverde Group, Piceance Creek Basin, Colorado: AAPG Bulletin, v. 69, p. 710-721.

Lowry, P., and T. Jacobsen, 1993, Sedimentology and reservoir characterization of a fluvial-dominated delta-front sequence – Ferron Sandstone Member (Turonian), east-central Utah, USA, *in* M. Ashton, ed., Advances in reservoir geology: Geological Society of America Special Publication No. 69, p. 81-103.

Mack, G. H., W. C. James, and H. C. Monger, 1993, Classification of paleosols: Geological Society of America Bulletin, v. 105, p. 129-136.

Mack, G. H., and W. C. James, 1994, Paleoclimate and the global distribution of paleosols: Journal of Geology, v. 102, p. 1360-1366.

Matthai, H. F., 1990, Floods, *in* M. G. Wolman and H. C. Riggs, eds., The geology of North America: Geological Society of America, Surface Water Hydrology, v. 0-1, p. 97-120.

McMechan, G. A., G. C. Gaynor, R. B. Szerbiak, 1997, Use of ground-penetrating radar for 3-D sedimentological characterization of clastic reservoir analogs: Geophysics, v. 62, p. 786-796.

Meade, R. H., 1996, River-inputs to major deltas, *in* J. D. Milliman and B. U. Haq, eds., Sea-level rise and coastal subsidence: Kluwer Academic, p. 63-85.

Mulder, T., and J. P. M. Syvistky, 1995, Turbidity currents generated at river mouths during exceptional discharges to the world's oceans: Journal of Geology, v. 103, p. 285-299.

Novakovic, D., C. D. White, R. M. Corbeanu, W. S. Hammon III, J. P. Bhattacharya, and G. A. McMechan, 2002, Hydraulic effects of shales in fluvial-deltaic deposits - ground-penetrating radar, outcrop observations, geostatistics and three-dimensional flow modeling for the Ferron Sandstone, Utah: Mathematical Geology, v. 34, p. 857-893.

Posamentier, H. W., and G. P. Allen, 1999, Siliciclastic sequence stratigraphy – concepts and applications: Society for Sedimentary Geology (SEPM) Concepts in Sedimentology and Paleontology, no. 7, 210 p.

Reynolds, A. D., 1999, Dimensions of paralic sandstone bodies: AAPG Bulletin, v. 83, no. 2, p. 211-229.

Rubin, D. M., and D. S. McCulloch, 1980, Single and superimposed bedforms - a synthesis of San Francisco Bay and flume observations: Sedimentary Geology, v. 26, p. 207-231.

Russell, R. J., 1942, Geomorphology of the Rhône Delta: ANNALS, Association of American Geographers, v. 32, no. 2, p. 49-254.

Ryer, T. A., and M. McPhillips, 1983, Early Late Cretaceous paleogeography of east-central Utah, *in* M. W. Reynolds, and E. D. Dolly, eds., Mesozoic paleogeography of west-central United States: Society for Sedimentary Geology (SEPM) Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 2, p. 253-272.

Smith, A. R., 1966, Modern delta comparison maps, *in* M. L. Shirley and J. A. Ragsdale, eds., Deltas in their geologic framework: Houston Geological Society, p. 233-251.

Thompson, S. L., C. R. Ossian, and A. J. Scott, 1986, Lithofacies, inferred processes, and log response characteristics of shelf and shoreface sandstones, Ferron Sandstone, central Utah, *in* T. F. Moslow and E. G. Rhodes, eds., Modern and ancient shelf clastics - a core workshop: Society for Sedimentary Geology (SEPM) Core Workshop No. 9, p. 325-361.

Tye, R. S., and T. F. Moslow, 1993, Tidal inlet reservoirs - insights from modern examples, *in* E. G. Rhodes and T. F. Moslow, eds., Marine clastic reservoirs: New York, Springer-Verlag, p. 77-99.

van Heerden, I. L., and H. H. Roberts, 1988, Facies development of Atchafalaya delta, Louisiana - a modern bayhead delta: AAPG Bulletin, v. 72, no. 4, p. 439-453.

Van Wagoner, J. C., R. M. Mitchum, K. M. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores and outcrops: AAPG Methods in Exploration Series No. 7, 55 p.

Welder, F. A., 1959, Processes of deltaic sedimentation in the lower Mississippi River: Defense Technical Information Center, Alexandria, Virginia, 90 p.

Wells, J. T., S. J. Chinburg, and J. M. Coleman, 1984, The Atchafalaya River delta - generic analysis of delta development: U.S. Army Corps of Engineers, New Orleans District, Technical Report HL-82-15, Contract No. DACW39-80-C-0082, 89 p.

Williams, G. D., and C. R. Stelck, 1975, Speculations on the Cretaceous paleogeography of North America, *in* W. G. E. Caldwell, ed., The Cretaceous System in the Western Interior of North America: The Geological Association of Canada Special Paper No. 13, p. 1-20.

Williams, G. P., 1986, River meanders and channel size: Journal of Hydrology, v. 88, p. 147-164.

Willis, B. J., 1997, Architecture of fluvial-dominated valley-fill deposits in the Cretaceous Fall River Formation: Sedimentology, v. 44, p. 735-757.

Wright, L. D., 1977, Sediment transport and deposition at river mouths - a synthesis: Geological Society of America Bulletin, v. 88, p. 857-868.

Wright, V. P., 1992, Paleopedology, stratigraphic relationships and empirical models, *in* I. P. Martini and W. Chesworth, eds., Weathering, soil and paleosols: Amsterdam, Elsevier, Developments in Earth Surface Processes, no. 2, p. 475-499.