DOE Project Final Report

GRANTEE: Center for Lithospheric Studies, The University of Texas at Dallas, P.O. Box 830688 (FA31), Richardson, TX 75083-0688

GRANT: DE-FG0301-ER15166

TITLE: 3-D sedimentological and geophysical studies of clastic reservoir analogs: Facies architecture, reservoir properties, and flow behavior within delta front facies elements of the Cretaceous Wall Creek Member, Frontier Formation, Wyoming

PERSONS IN CHARGE:
Janok P. Bhattacharya, Wk. 713/743-4720, Fax: 713/748-7906, e-mail: jpbhattacharya@uh.edu
George A. McMechan. Wk: 972-883-2419; Fax 972-883-2829; e-mail mcmec@utdallas.edu

Abstract

This project examined the internal architecture of delta front sandstones at two locations within the Turonian-age Wall Creek Member of the Frontier Formation, in Wyoming. The project involved traditional outcrop field work integrated with core-data, and 2D and 3D ground penetrating radar (GPR) imaging from behind the outcrops. The fluid-flow engineering work, handled through a collaborative grant given to PI Chris White at LSU, focused on effects on fluid flow of late-stage calcite cement nodules in 3D.

In addition to the extensive field component, the work funded 2 PhD students (Gani and Lee) and resulted in publication of 10 technical papers, 17 abstracts, and 4 internal field guides. PI Bhattacharya also funded an additional 3 PhD students that worked on the Wall Creek sandstone funded separately through an industrial consortium, two of whom graduated in the fall 2006 ((Sadeque and Vakarelov). These additional funds provided significant leverage to expand the work to include a regional stratigraphic synthesis of the Wall Creek Member of the Frontier Formation, in addition to the reservoir-scale studies that DOE directly funded.

Awards given to PI Bhattacharya included the prestigious AAPG Distinguished Lecture Award, which involved a tour of about 25 Universities and Geological Societies in the US and Canada in the fall of 2005 and Spring of 2006. Bhattacharya gave two talks, one entitled "Applying Deltaic and Shallow Marine Outcrop Analogs to the Subsurface", which highlighted the DOE sponsored work and the other titled "Martian River Deltas and the Origin of Life". The outcrop analog talk was given at about 1/2 of the venues visited.

Results from the Frontier Formation Study

The Frontier Formation is an Upper Cretaceous (Cenomanian-Turonian) clastic wedge that has been broadly interpreted as deltaic in nature (Barlow and Huan, 1966; Bhattacharya and Willis, 2001). Previous work on the Wall Creek Member of the Frontier suggested that it consists of 1-3 sandstone units, separated by marine shales (Merewether et al., 1979; Winn, 1991, Figure 1). Our new stratigraphic work (Fig., 2) shows a far more complicated allostratigraphy, that has defined 7 allomembers (Figure 2), each marked by pebble lags (Howell and Bhattacharya, 2004; Lee et al., 2005 and in press, Sadeque and Bhattacharya, 2004, Sadeque, 2006). Several of the allomembers internally consist of offlapping, lens shaped parasequences, interpreted as prograding delta lobes. Allomember 6 was the focus of detailed studies at two sites, Murphy Reservoir and Raptor Ridge.

The focus at the Murphy Reservoir site (Fig. 3) was to apply GPR to map decimeter scale geometry of a top truncated, fluvial-dominated, lowstand delta front, and to estimate the volumes of the prograding bar deposits of the delta lobe. The outcrop shows a series of inclined, offlapping sandstone and mudstone beds that form an upward coarsening facies succession interpreted as a

prograding delta front (Figure 4). Eleven GPR profiles totaling about 4,400 m were acquired using 50 MHz antennas on a coarsely-spaced 2-D grid of lines lying parallel and perpendicular to the average depositional dip (Figure 3). GPR reflections were detected from within the outcrop to a depth of about 10-15 m. Based on the texture of these reflections, three GPR facies were identified. Four southerly dipping, major surfaces identified in the GPR data are correlated with the boundaries of progradational delta-front facies, stacked as distal mouth-bar deposits in the outcrop (Figure 5). The major boundaries define lithological units with alternating fast and slow sedimentation rates (Lee et al., 2005, in press; Howell and Bhattacharya, 2004). The outcrop consists of relatively clean sandstones that are interpreted to be deposited during floods with high sediment supply, alternating with bioturbated sandstones and mudstones deposited during inter-flood periods with correspondingly low sedimentation rates. These two cyclic lithological units repeat three times over the outcrop extent with no change in dominant average sand-grain size. Subsequent erosion by transgressive ravinement caused the lowstand delta to be significantly truncated after the sandstones were deposited. The bar assemblage volumes at successive stages of growth are estimated using measurements from the outcrop and the GPR data (Figure 6). The migrating bars have an estimated average half length of 650 m; a lower bound on the average volume of the bars is 3.9 million cubic meters. As the volume of the bars increases the bar deposits appear to have a landward as well as a basinward component of accretion (Lee et al., 2005).

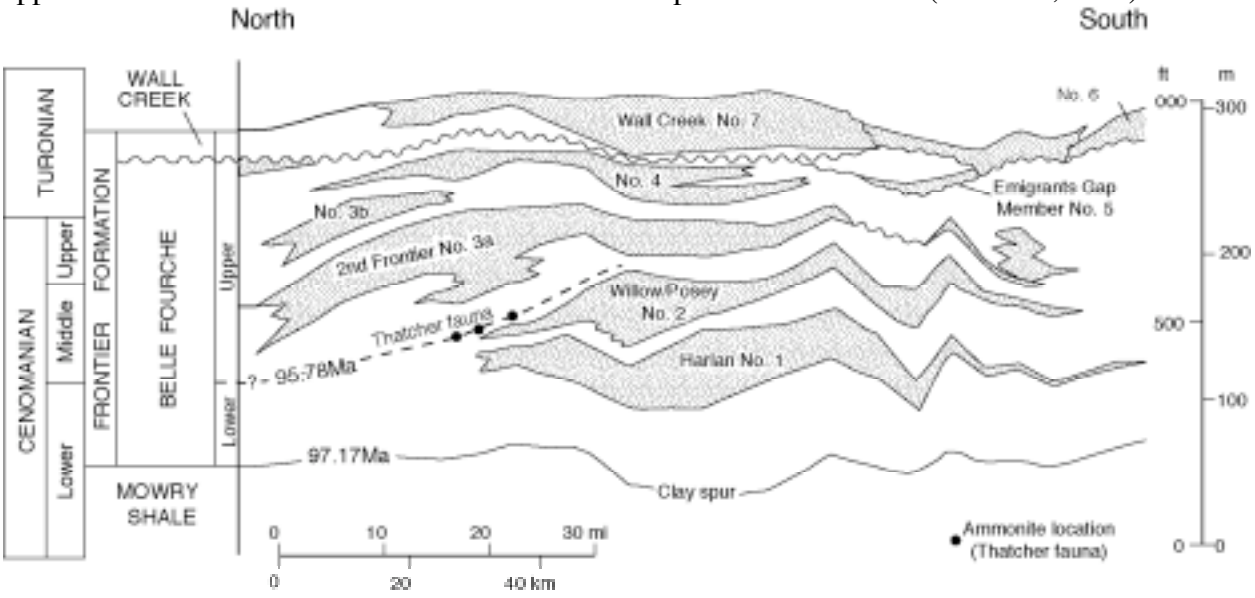


Figure 1. Stratigraphy of the Frontier Formation after Merewether et al (1979) and Bhattacharya and Willis (2001).

The Raptor Ridge project integrated outcrop sedimentology and shallow subsurface Ground Penetrating Radar (GPR) with subsurface cores to image and map the 3D internal facies architecture of dipping, river- wave- and tide-influenced delta front sandstones and mudstones in parasequence 6 (Figure 7). In the Raptor Ridge area (Figure 8), two 2D GPR surveys (100 x 300 m and 160 x 200 m respectively) were acquired at a nominal frequency of 50 Mhz. In addition, two 3D surveys (80 x 30 m and 12 x 12 m) were acquired at 100 Mhz and 200 Mhz respectively. The 12x12 m, 200 Mhz survey was collected specifically to image cemented zones at the top of the outcrop, although we have also used the larger 3D survey to image cements. Dip oriented GPR lines image seaward dipping clinoforms whereas the strike-oriented GPR lines show bi- directional downlap, indicating the overlapping lens-shaped delta front sand body geometries (Figure 9). At the Raptor Ridge site, 10 cores were drilled to an average depth of about 9 m within the GPR survey areas. About 1200 mini-permeameter measurements were collected from the10 cores and outcrop

plugs. 88 routine plug analyses for porosity and permeability, and 23 high precision pulse decay measurements were also made to measure the effective permeability (Kv) across shales.

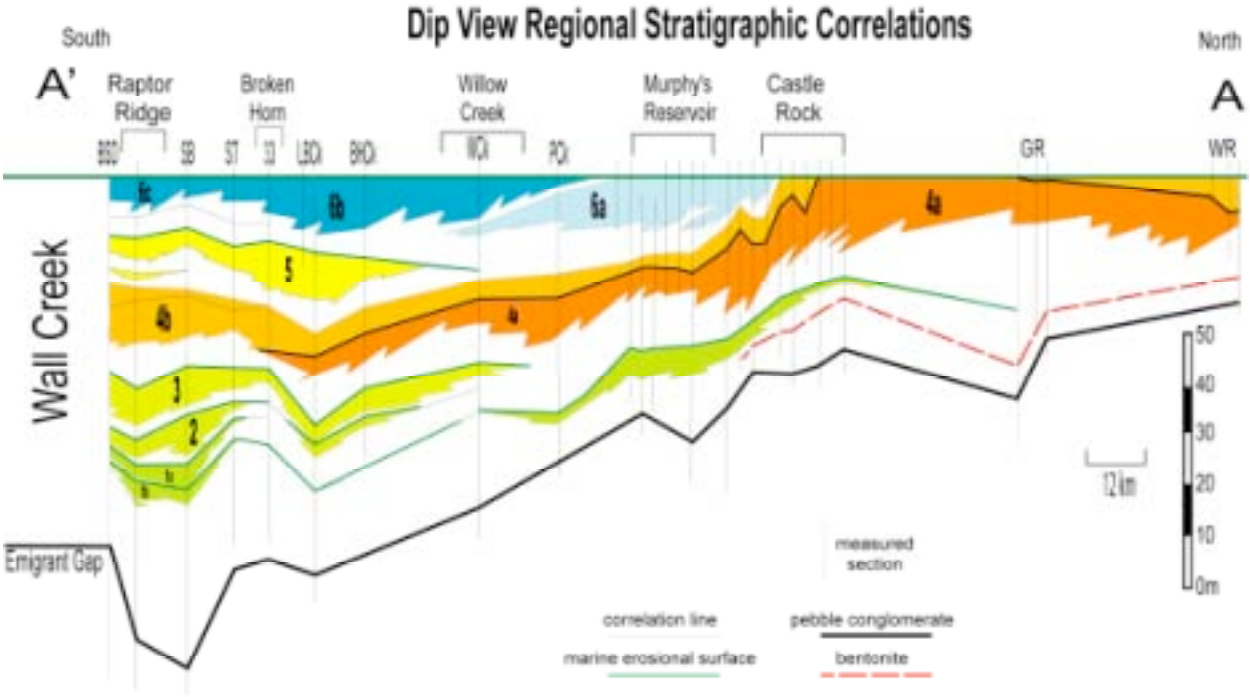
The Raptor Ridge outcrop shows complex seaward and landward dipping, tidally-reworked bar deposits, interbedded with shallow fluvial-dominated subaqueous channel deposits (Figure 7). The paper by Gani and Bhattacharya (in press) describes the basic facies architecture of this system (Figs. 7 and 8). An earlier submission (Gani et al., 2005) focused on more general application of facies architectural analysis to the interpolation of subsurface well data.

Calcite cements nodules represent the most significant barrier to flow at Raptor Ridge (Figure 9). These cements show up as bright spots in the 3D GPR data volumes and we have used a geostatistical analysis of the cements to map these in 3D within the GPR volume. This is the first project ever to image cements in 3D. A detailed petrographic analysis of the Wall Creek cements was initiated to examine the pore-scale attributes of the Wall Creek and to better understand the diagenetic controls on reservoir quality and GOPR response. The study suggests that the calcite cement phase is a late-diagenetic feature (Nyman, 2004; Lee et al., *in press*). Initial results of tracer flow modeling (Tang et al., 2004) show that the cements cause significant fingering effects (Figure 10).

From the education perspective, at UTD the cores have been incorporated into the teaching of our major undergraduate course in sedimentology, a graduate level course in ichnology, as well as an industry short-course on deltas. We have also shipped the cores to several AAPG meetings for core workshops. In the course of the previous projects, we have developed substantial new software for GPR processing and interpretation that is now available for our future proposed studies. This significantly improves the efficiency with which we can handle large data volumes and ensures timely production of publications.

Publications, Presentations and Press:

So far we have presented our Wall Creek results in 13 posters and talks at various national and international conferences. We have led 3 industry field trips to the Wyoming field area. In addition to continuing to publish results based on an earlier DOE Grant (DE-FG03-96ER14596), we presently have 10 major papers either published or in press. PI Bhattacharya was awarded the 2002 Frank Kottlowski Memorial Presentation Award for the co-authored talk: “Bhattacharya, J.P., Aiken, C.V., Corbeanu, R.M., McMechan, G.A., Xu, X., Zeng, X., White, C.D. 2002, 3D Outcrop Reservoir Characterization, 2002 AAPG Annual Convention, Houston, TX, Official Program, v. 11, p. A18”, which highlighted our DOE-funded work. He was also awarded the AAPG Distinguished Lecturer for 2005 – 2006, visiting universities and geological societies in Canada and the USA. Of the 25 talks given, about 1/2 highlighted the DOE-funded 3D Outcrop reservoir characterization results. We have also had a several articles written about our work in the AAPG Explorer (April 2001), the Journal of Petroleum Technology [Wallace, R. (2002) 3D Ground penetrating radar used to map reservoir analogs, JPT, February issue, p. 32], as well as the local Dallas paper (Dallas Morning News, Monday, October 15th, 2001). A listing of products stemming for this DOE-funded work is given below.



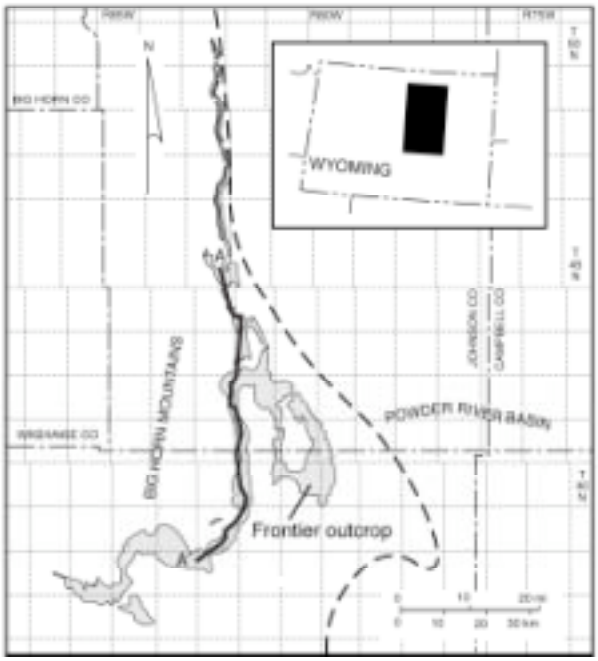


Figure 2. Revised outcrop stratigraphy of the Wall Creek member and base map (from Howell and Bhattacharya, 2004).

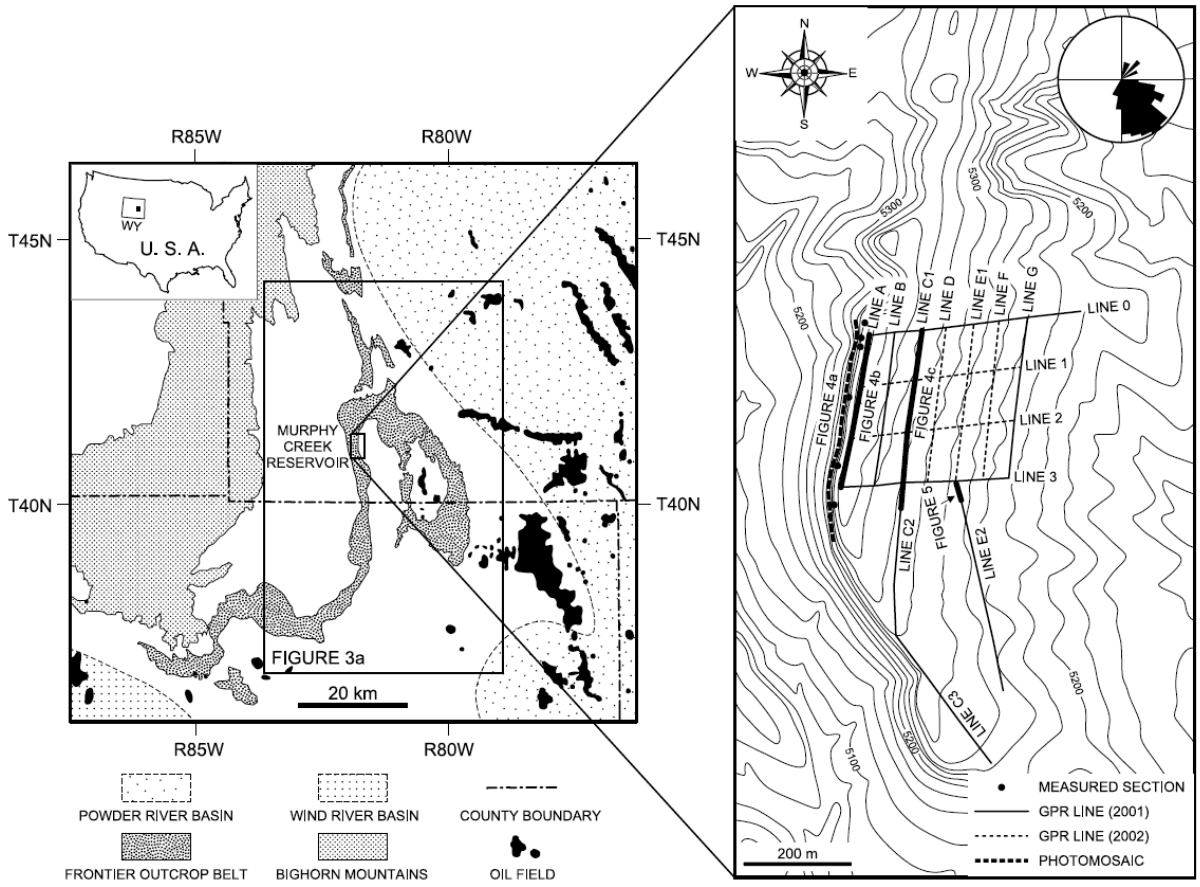
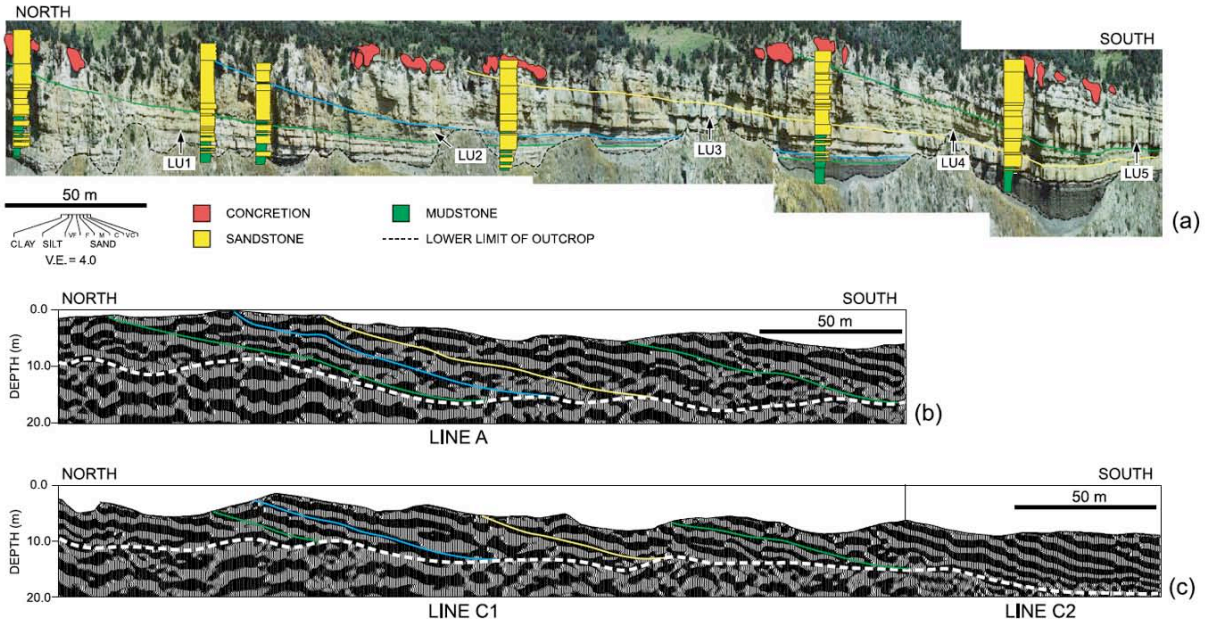


Figure 3. Murphy Reservoir study base map (from Lee et al., 2005).



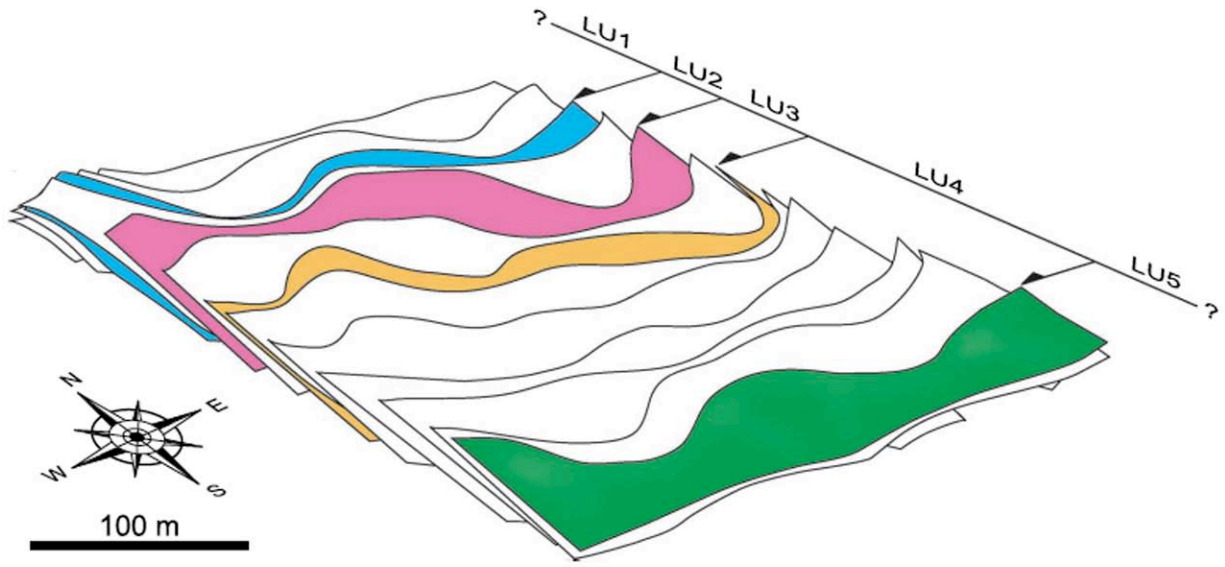


Figure 5. 3D perspective of dipping bar fronts in Wall Creek sandstone at Murphy reservoir (from Lee et al., 2005).

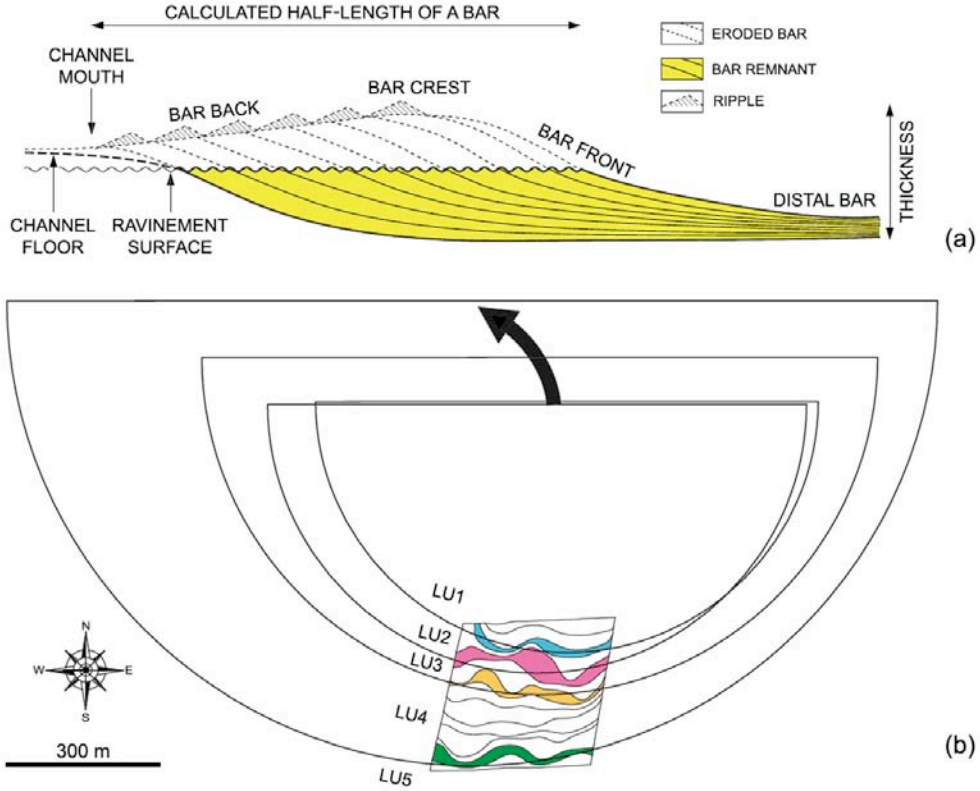


Figure 6. Reconstruction of original bar volume, Murphy reservoir (from Lee et al. 2005).

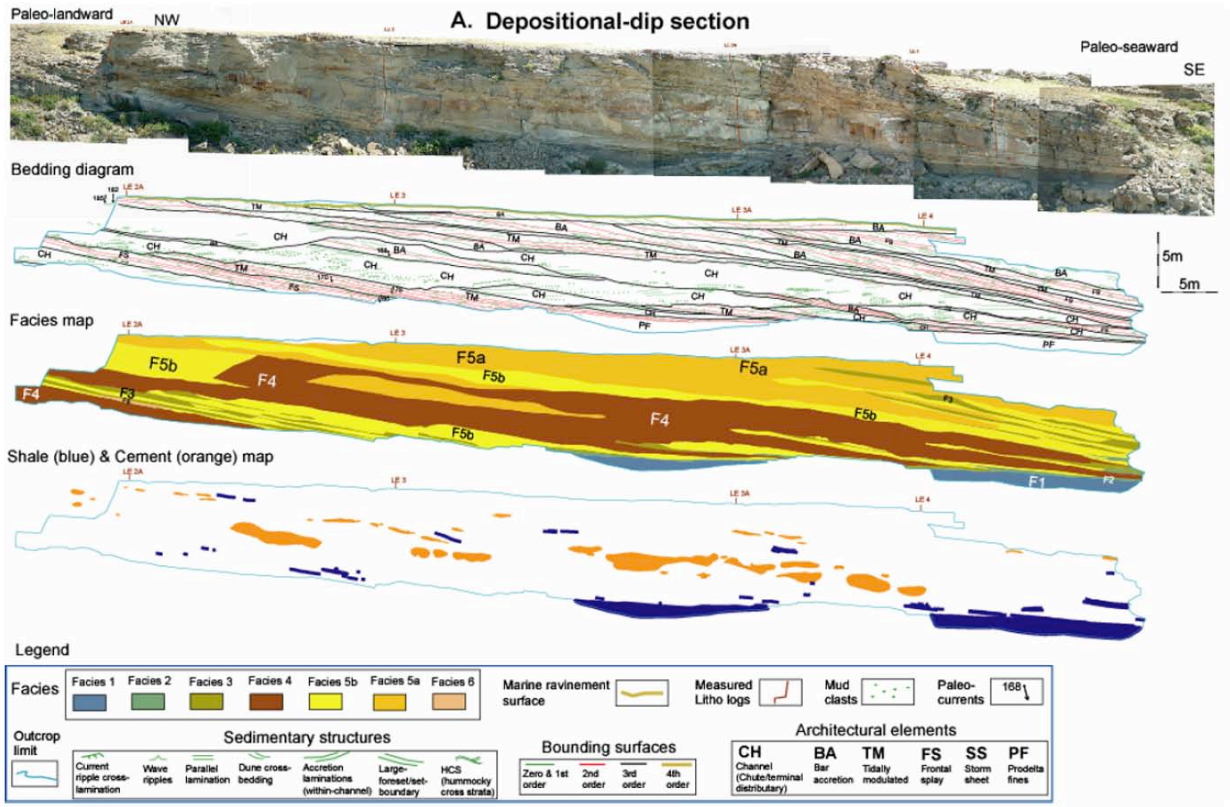


Figure 7. Cross section showing channels, bars and cement facies in the Wall Creek sandstone at Raptor Ridge (from Gani and Bhattacharya, in press).

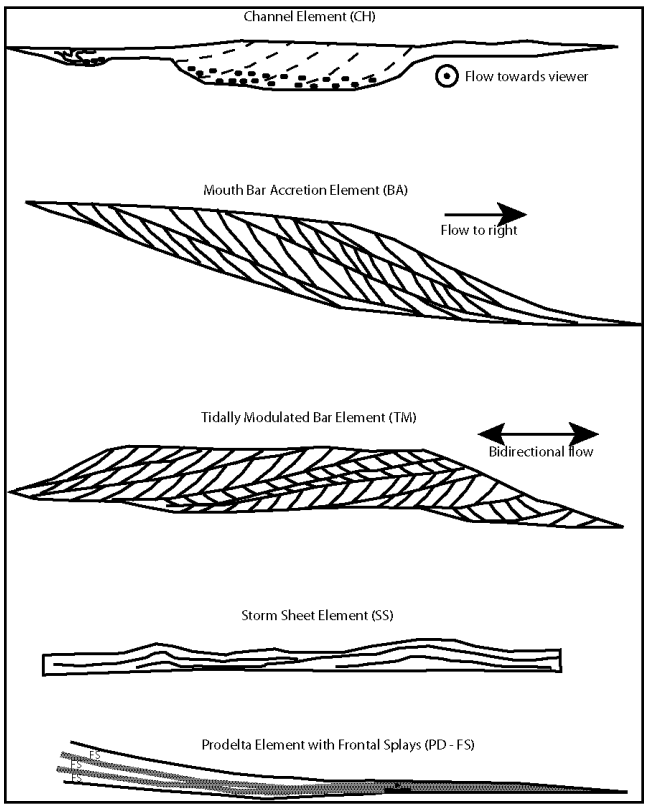


Figure 8. Facies architectural elements at Raptor Ridge (from Gani and Bhattacharya, in press).

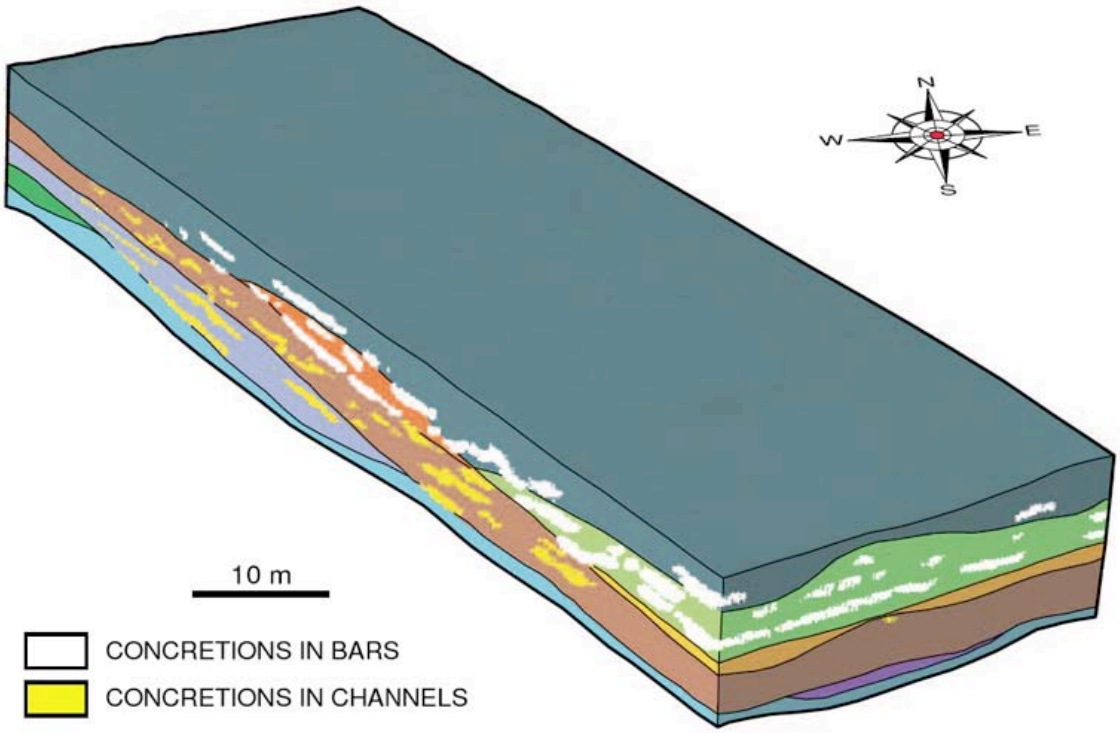


Figure 9. 3D perspective view of Wall Creek #6 sandstone at Raptor Ridge, showing calcite concretions.

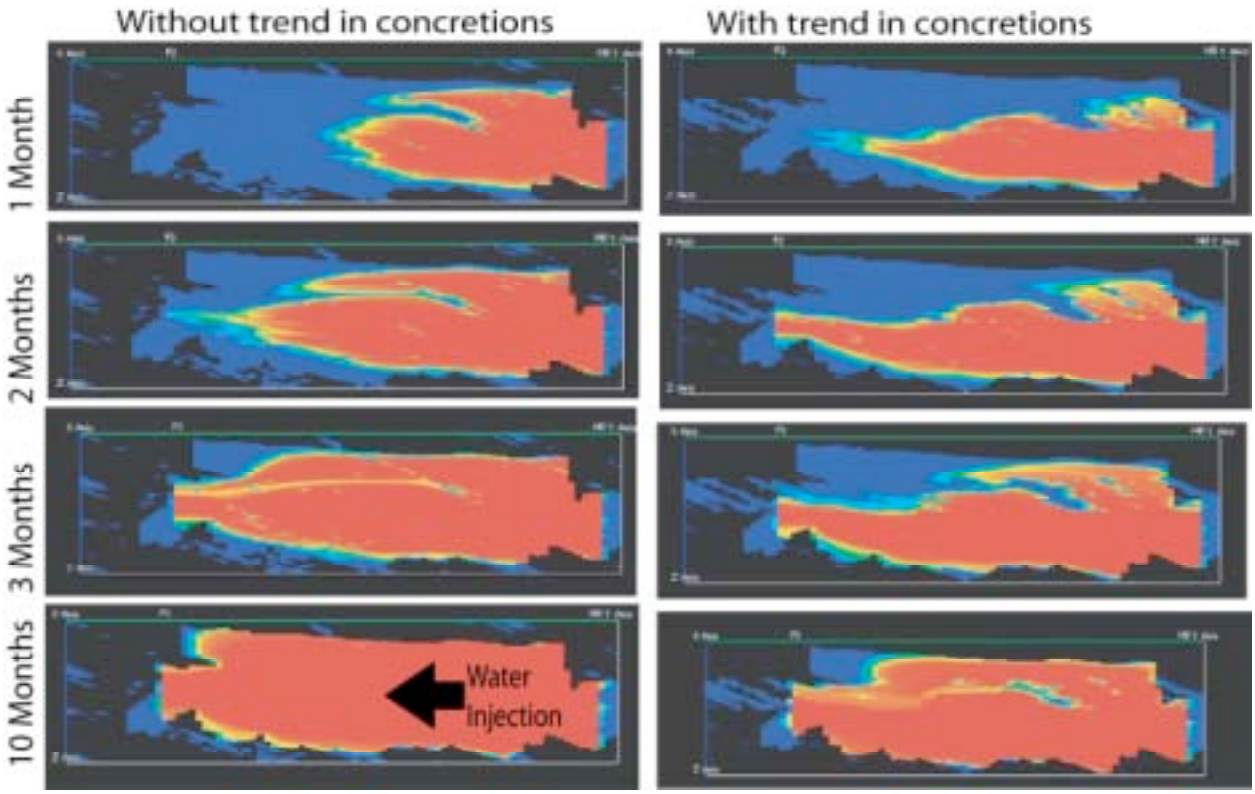


Figure 10. Water flood of Raptor Ridge delta (from Tang et al., submitted).

Papers published, in press or submitted

Tang, H., White, C.D., Gani, M.R., Bhattacharya, J.P., and Lee, K., *submitted*, Geostatistical modeling and flow simulation of diagenesis effects on deltaic-reservoir, Raptor Ridge, Powder River Basin, Wyoming, submitted to AAPG Bulletin.

Vakarelov, B., Bhattacharya, J.P., and Nebrigic, D., 2006, The Importance of High-Frequency Tectonic Sequences during Greenhouse Times of Earth History, Geology, v. 34; p. 797–800; doi: 10.1130/G22348.1

Lee, K., McMechan, G., Gani, M.R., Bhattacharya, J.P., Zeng, X., and Howell, C.D. Jr., i*n press*, 3-D Architecture and Sequence Stratigraphic Evolution of a Forced Regressive Top-Truncated Mixed-Influenced Delta, Cretaceous Wall Creek Sandstone, Wyoming, U.S.A., Journal of Sedimentary Research.

Lee, K., Gani, M.D., McMechan, G.A., Bhattacharya, J.P., Nyman, S., Zeng, X., *in press*, 3-D Facies Architecture and 3-D Calcite Concretion Distributions in a Tide-Influenced Delta Front, Wall Creek Member, Frontier Formation, Wyoming, Submitted to AAPG Bulletin.

Gani, M.R., and Bhattacharya, J.P., *in press*, Basic Building Blocks and Process Variability of a Cretaceous Delta: Internal Facies Architecture Reveals a More Dynamic Interaction of River, Wave and Tidal Processes Than Is Indicated By External Shape, Journal of Sedimentary Research.

Bhattacharya, J.P., 2006, Deltas, In: Walker, R.G., and Posamentier, H., (eds.) Facies Models revisited, SEPM Special Publication, v. 84, p. 237-292.

Gani, M.R., Bhattacharya, J.P., MacEachern, J.A., *in press*, Using ichnology to determine relative influence of waves, storms, tides, and rivers in deltaic deposits: examples from Cretaceous Western Interior Seaway, U.S.A., in MacEachern, J.A., Bann, K.L., Gingras, M.K., and Pemberton, S.G., eds., Applied Ichnology, SEPM Short Course Notes.

Gani, M.R. and Bhattacharya, J.P., 2005, Bedding correlation vs., facies correlation in deltas: Lessons for Quaternary stratigraphy, In: Giosan, L., and Bhattacharya, J.P., (eds.). River Deltas: Concepts, Models and Examples, SEPM Special Publication v. 83, p. 31-48.

Giosan, L. and Bhattacharya, J.P., 2005, New Directions in Delta Research. In: Giosan, L., and Bhattacharya, J.P., (eds.). River Deltas: Concepts, Models and Examples, SEPM Special Publication, v. 83, p. 3-10.

Lee, K., Zeng, X, McMechan, G.A., Howell Jr., C.D., Bhattacharya, J.P., Marcy, F., Olariu, C., 2005, A GPR survey of a delta-front reservoir analog in the Wall Creek Member, Frontier Formation, Wyoming. AAPG Bulletin, V. 89, No. 9 P. 1139-1155, DOI:10.1306/042705040106.

MacEachern, J., Bann, K., Bhattacharya, J.P., and Howell, C.D., 2005, Ichnology of Deltas. In: Giosan, L., and Bhattacharya, J.P., (eds.). River Deltas: Concepts, Models and Examples, SEPM Special Publication, v. 83, p. 49-85.

Unpublished Field Guides:

Bhattacharya, J.P., Vakarelov, B., Howell, C.D., Jr., Sadeque, J., Tang, H., 2005, Facies Variability, Stratigraphic Compartmentalization, and Tectonic Controls in Mixed-influenced Delta Fronts, Frontier Formation, Powder River Basin, Wyoming, U.S.A., UTD Quantitative Sedimentology Consortium Field Trip, July 29th-August 3rd, 2005, 134p.

Bhattacharya, J.P., Gani, M.D., Howell, C.D., Jr., Nyman, S., Tang, H., 2004, Facies Variability in Mixed-influenced Delta Fronts, Frontier Formation, Powder River Basin, Wyoming,

U.S.A., UTD Quantitative Sedimentology Consortium Field Trip, July 25th-29th, 2004, 119p.

Bhattacharya, J.P., Howell, C.D. Jr., Gani, M. R., White C.D., 2003, Facies Architecture of Topographically-controlled, Top-truncated, Mixed-influenced Delta Lobes, Frontier Formation, Powder River Basin, Wyoming, U.S.A., UTD Quantitative Sedimentology Consortium Field Trip guide, July 31-August 3, 2003. Casper, Wyoming, 99p.

Bhattacharya, J.P., Howell, C.D. Jr., Lee, K., McMechan, G.A., and White C.D., 2002, Scales of facies architecture in top-truncated mixed-influence delta lobes, Frontier Formation, Power River Basin, Wyoming, U.S.A., UTD Quantitative Sedimentology Consortium Field Trip guide, July 10-30, 2002. Casper, Wyoming. 84p.

Abstracts and Presentations:

Bhattacharya, J.P., 2005, Distinguishing Shorefaces versus Delta Fronts in the Rock Record, AAPG Annual Convention, Calgary Alberta.

Hong Tang, H., White, C. D., Gani, M. R., Lee, K., Bhattacharya, J.P., 2005, Geostatistical Integration of Outcrop and Geophysical Data to Describe Diagenetic Heterogeneities for Flow Modeling, Frontier Formation, Wyoming, AAPG Annual Convention, Calgary Alberta.

Bhattacharya, J.P., 2004, Deltas Revisited. AAPG 2004 Annual Convention Abstracts Volume, p. A13.

Gani, M.R., and Bhattacharya, J.P., 2004. Intra-parasequence facies architecture of a delta front deposit: high-resolution outcrop example from the Wall Creek Member, central Wyoming, U.S.A. SEPM Research Conference, Recent Advances in Shoreline-Shelf Stratigraphy, August 2004, Grand Junction, Colorado, USA, p. 7.

Gani, M.R., Bhattacharya, J.P., and MacEachern, J.A., 2004, using Ichnology to Determine Relative Influence of Waves, Storms, Tides and Rivers in Deltaic Deposits: Examples from Cretaceous Delta Complexes in the Western Interior Seaway, Wyoming-Utah, U.S.A. AAPG 2004 Annual Convention Abstracts Volume, p. A49-A50.

Howell, C.D., and Bhattacharya, J.P., 2004, Geology and Stratigraphic Architecture of the Upper-Cretaceous Wall Creek member, Frontier Formation, Powder River basin: An Outcrop Analog for Top-Truncated Mixed-Influence Lowstand Deltas. . AAPG 2004 Annual Convention Abstracts Volume, p. A66-A67.

Lee, K., Gani, M.R., Zeng, X., McMechan, G.A., Griffin, W.R., Sultana, D.N., Bhattacharya, J.P., Aiken, C.L.V., and Xu, X., 2004, GPR Survey of a Delta front reservoir Analog, the Wall Creek Member, Frontier Formation, Wyoming. AAPG 2004 Annual Convention Abstracts Volume, p. A82.

MacEachern, J.A., Bann, K., and Bhattacharya, J.P., 2004, Ichnology of Deltas: Organism response to the dynamic interplay of river-discharge and sediment flux, wave energy, storms events and tidal flux. CSPG 2004 Annual Convention Abstracts Volume.

MacEachern, J.A., and Bhattacharya, J.P., 2004, Ichnology of Deltas: Organism response to the Dynamic Interplay of Rives, Waves, Storms and Tides. AAPG 2004 Annual Convention Abstracts Volume, p. A89-90.

Nyman, S.L., Gani, M.R., Bhattacharya, J.P., and Lee, K., 2004, Origin and 3D Distribution of Calcite Concretions in a Delta-Front: Cretaceous Wall Creek Member, Frontier Formation, Wyoming. Geological Society of New Zealand 2004 Annual Conference Programme and Abstracts Volume, p. 78.

Bhattacharya, J.P., Gani, M.R., Howell, C.D., and Olariu, C., 2004. Bedding correlation versus facies correlation in deltas: lessons for Quaternary stratigraphy, 5th International Conference on Asian Marine Geology, IGCP-475 Delta MAP/APN Mega-deltas in Asia, 13-18th January, 2004, Bangkok, Thailand, Program and Abstracts, p.22.

Bhattacharya, J.P., Willis, B.J., Howell, C.D., and Olariu, C., 2003, Top-truncated, structurally-confined lowstand deltas, AAPG Southwest Section Meeting, March 2-4, 2003, Program with Abstracts, p.20.

Gani, M.R., and Bhattacharya, J.P., 2003, Bed-scale facies architecture of an ancient delta lobe deposit of the Wall Creek Member, Central Wyoming, U.S.A., 2003 AAPG Annual Convention, Salt Lake City, UT, Official Program, v. 12, pA59.

Howell, C.D., Bhattacharya, J.P., Robinson, A.B., Griffin, W.R., 2003, Topographically controlled, mixed-influence top-truncated deltas: Turonian Wall Creek member, frontier Formation, Powder River Basin, Wyoming, U.S.A., 2003 AAPG Annual Convention, Salt Lake City, UT, Official Program, v. 12, p. A81.

Howell, C.D., Bhattacharya, J.P., Robinson, A.B., Griffin, W.R., 2003, Topographically controlled, mixed-influence top-truncated deltas: Turonian Wall Creek member, frontier Formation, Powder River Basin, Wyoming, U.S.A., 2003 AAPG Annual Convention, Salt Lake City, UT, Official Program, v. 12, p. A81

Bhattacharya, J.P., Aiken, C.V., Corbeanu, R.M., McMechan, G.A., Xu, X., Zeng, X., White, C.D. 2002, 3D Outcrop Reservoir Characterization, 2002 AAPG Annual Convention, Houston, TX, Official Program, v. 11, p. A18.

Bhattacharya, J.P, Howell, C.D., Marcy, F., George A. McMechan, G.A., , Cornel Olariu, C., Zeng, X. 2002, Facies architecture of an ancient delta front deposit using GPR: Cretaceous Wall Creek Member, Frontier Formation, Wyoming. 2002 AAPG Annual Convention, Houston, TX, Official Program, v. 11, p. A18.

Dissertations and MS Theses:

<u>DOE-funded</u>

Gani, M.R., 2005, 3-D Facies Architecture of River Deltas: Lessons from the Turonian Wall Creek member, Central Wyoming, UTD PhD Dissertation, 148p.

Nyman, S., 2004. Provenance and Diagenesis of the Cretaceous Wall Creek sandstone, Frontier Formation, Western Flanks of the Powder River Basin, Wyoming, UTD M.Sc. Thesis, 107p.

Awards based on DOE Funded work:

AAPG Distinguished Lecturer 2005-2006.
Best Oral Presentation, CSPG 2004 Annual Meeting.
Houston Geological Society, Best Oral Paper Award, 2002.
Frank Kottlowski Memorial Presentation Award, AAPG/EMD, 2002.

BIBLIOGRAPHY

Barlow, J. A., and J. D. Haun, 1966, Regional stratigraphy of Frontier Formation and relation to Salt Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, p. 2185–2196.

Bhattacharya, J.P., and Willis, B.J., 2001, Lowstand Deltas in the Frontier Formation, Powder River Basin, Wyoming: Implications for sequence stratigraphic models, U.S.A., AAPG Bulletin, v. 85, p.261-294.

Gani, M.R., and Bhattacharya, J.P., *in press*, Basic Building Blocks and Process Variability of a Cretaceous Delta: Internal Facies Architecture Reveals a More Dynamic Interaction of River, Wave and Tidal Processes Than Is Indicated By External Shape, Journal of Sedimentary Research.

Howell, C.D., and Bhattacharya, J.P., 2004, Geology and Stratigraphic Architecture of the Upper-Cretaceous Wall Creek member, Frontier Formation, Powder River basin: An Outcrop Analog for Top-Truncated Mixed-Influence Lowstand Deltas. AAPG 2004 Annual Convention Abstracts Volume, p. A66-A67.

Lee, K., Zeng, X, McMechan, G.A., Howell Jr., C.D., Bhattacharya, J.P., Marcy, F., Olariu, C., 2005, A GPR survey of a delta-front reservoir analog in the Wall Creek Member, Frontier Formation, Wyoming. AAPG Bulletin, V. 89, No. 9 P. 1139-1155

Lee, K., Gani, M.D., McMechan, G.A., Bhattacharya, J.P., Nyman, S., Zeng, X., *in press*, 3-D Facies Architecture and 3-D Calcite Concretion Distributions in a Tide-Influenced Delta Front, Wall Creek Member, Frontier Formation, Wyoming, Submitted to AAPG Bulletin.

Merewether, E. A., W. A. Cobban and E. T. Cavanaugh, 1979, Frontier Formation and equivalent rocks in eastern Wyoming: The Mountain Geologist, v. 16, p. 67–101.

Nyman, S., 2004. Provenance and Diagenesis of the Cretaceous Wall Creek sandstone, Frontier Formation, Western Flanks of the Powder River Basin, Wyoming, UTD M.Sc. Thesis, 107p.

Sadeque, J., and Bhattacharya, J.P., 2004, Integrated Stratigraphic Study of the Turonian Wall Creek member, Frontier Formation, Powder River basin, Wyoming. AAPG 2004 Annual Convention Abstracts Volume, p. A121.

Sadeque, J., 2006, Regional Reservoir Compartmentalization within Offlapping, Top-Truncated, Mixed-Influenced Deltas, Wall Creek Member, Frontier Formation, Powder River Basin, Wyoming, 156p.

Tang, H., White, C.D., Gani, M.R., Bhattacharya, J.P., and Lee, K., *submitted*, Geostatistical modeling and flow simulation of diagenesis effects on deltaic-reservoir, Raptor Ridge, Powder River Basin, Wyoming, submitted to AAPG Bulletin.

Winn, R. D., 1991, Storm deposition in marine sand sheets: Wall Creek Member, Frontier Formation, Powder River Basin, Wyoming: Journal of Sedimentary Petrology, 61, 86–101.