A ground-penetrating radar survey of a delta-front reservoir analog in the Wall Creek Member, Frontier Formation, Wyoming

Keumsuk Lee, Xiaoxian Zeng, George A. McMechan, Charles D. Howell Jr., Janok P. Bhattacharya, Fanny Marcy, and Cornel Olariu

ABSTRACT

Ground-penetrating radar (GPR) measurements, in conjunction with outcrop sedimentology, were carried out at Murphy Creek reservoir in the Upper Cretaceous Turonian Wall Creek Member of the Frontier Formation in Wyoming. The objectives were to apply GPR to map geometrical details of a top-truncated lowstand delta front and to estimate the volumes of the prograding bar deposits of the delta lobe. Eleven GPR profiles totaling about 4400 m (14,435 ft) were acquired using 50-MHz antennas on a coarsely spaced, two-dimensional grid of lines lying parallel and perpendicular to the average depositional dip. Ground-penetrating radar reflections were detected from within the outcrop to a depth of about 10–15 m (33–49 ft). 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. The major boundaries correspond to lithological changes between relatively clean sandstones that are interpreted to have been deposited during floods with high sediment supply, alternating with bioturbated sandstones and mudstones deposited during interflood periods with correspondingly low sedimentation rates. These two lithological units, which also correspond to the two main GPR facies, repeat at least three times with no change in dominant average sand-grain size. Subsequent erosion by transgressive ravinement caused the significantly truncated lowstand delta long after the sandstones were deposited. The bar assemblage volume at successive stages of growth is estimated using measurements from the outcrop

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and the GPR data. The migrating bars have an estimated average half-length of 650 m (2132 ft); a lower bound on the average volume of the bar is 3.9×10^6 m^3 (1.37×10^8 ft^3). As the volume of the bars increases, the bar deposits appear to have a landward as well as a basinward component of accretion.

INTRODUCTION

Two-dimensional (2-D) characterizations of reservoir analogs from outcrops of deltaic sand bodies have received relatively little attention, and there have been no three-dimensional (3-D) studies of deltas despite the importance of delta deposits for studies of energy resources and of fluid transport at environmentally sensitive sites. A survey by Tyler (1988) demonstrated that the conventional development of heterolithic fluvial-deltaic reservoir bypasses or fails to contact 24–69% of the mobile oil originally present. Recent papers document the importance of complex facies architecture and heterogeneities in blocking or bypassing fluid flow in delta-front sandstone reservoirs in the continental United States, Alaska, Europe, and Indonesia (Barton, 1997; Knox, 1997; Sullivan et al., 1997; Tye et al., 1999; Ainsworth et al., 2000).

The Wall Creek Member is of scientific and economic importance, not only because it has produced hydrocarbons from the Salt Creek and Teapot Dome fields (and hence, the site presents a good opportunity to match outcrop analog results to subsurface performance), but also because the depositional setting is analogous to that of many other oil fields such as Prudhoe Bay (Tye et al., 1999). Thus, the results of this study may make an immediate contribution to the improvement of reservoir engineering in Wall Creek fields and longer term contributions to other delta-front reservoirs.

The objectives of this study are to acquire, process, and interpret a grid of 2-D ground-penetrating radar (GPR) profiles, to describe details of the internal architecture of a top-truncated, lowstand delta front, and to estimate the sediment volumes of the migrating distributary mouth bars. The GPR interpretation is guided and constrained by sedimentologic data from outcrops, including an adjacent cliff face.

GEOLOGICAL SETTING

The Wall Creek Member is exposed in east central Wyoming (Figure 1) and lies at the top of the Upper Cretaceous Frontier Formation (Figure 2). The Frontier Formation is a Cenomanian to Turonian age clastic wedge, deposited as a consequence of uplift and erosion during the Sevier orogen (Barlow and Haun, 1966; Dyman et al., 1994). Sandstones and mudstones were deposited as major deltaic complexes into the western margin of the Cretaceous

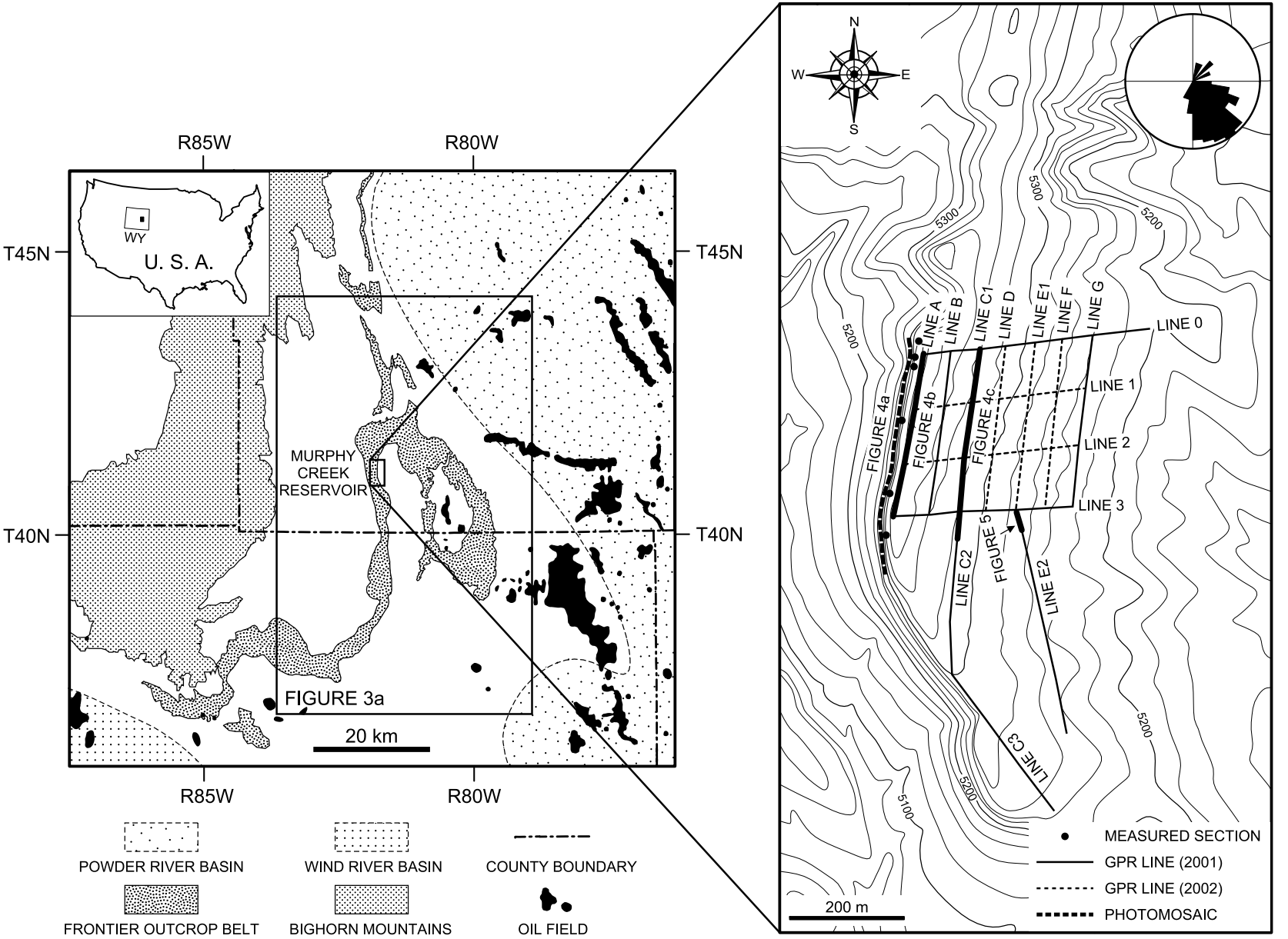


Figure 1. Location of the Murphy Creek reservoir site is on the west margin of the Powder River basin in east central Wyoming, United States. The right panel shows the topography of the study area (with 20-ft [6.096-m] contour intervals), the locations of the GPR survey lines, the photomosaic, and the measured sections. Paleocurrent direction measurements conducted on the topmost parasequence are indicated in the circle. Oil and gas fields are from the public domain Web site http://www.sdvc.uwyo.edu/clearinghouse/mineral.html.

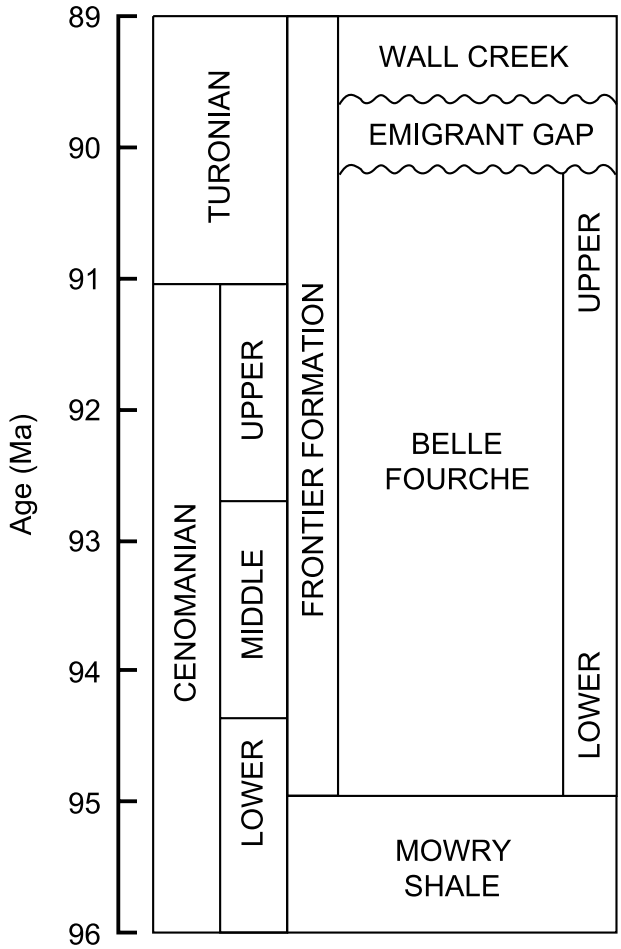


Figure 2. Stratigraphic profile shows the Frontier Formation in the Upper Cretaceous of central Wyoming.

Interior seaway. Regional correlations along the outcrop belt (Figure 3) show that the Wall Creek Member consists of several different coarsening-upward facies successions associated with distinctly different overlapping sandstone bodies separated by prodelta mudstones that form different delta lobes (Howell and Bhattacharya, 2001; Sadeque and Bhattacharya, 2004).

The sandstones of the Frontier Formation were previously interpreted as storm-dominated offshore shelf delta plumes (Winn, 1991), but have recently been reinterpreted as top-truncated deltas (Bhattacharya and Willis, 2001; Bhattacharya et al., 2001; Howell and Bhattacharya, 2001; Sadeque and Bhattacharya, 2004). The exposed sandstone cliffs of the Wall Creek Member contain a series of overlapping wave-, tide-, and river-dominated, top-truncated, lowstand delta lobes that are exposed as a series of sandstone cliffs (Figure 1). The Wall Creek exposure represents shorelines that migrated toward the southeast over a distance of more than 300 km (186 mi).

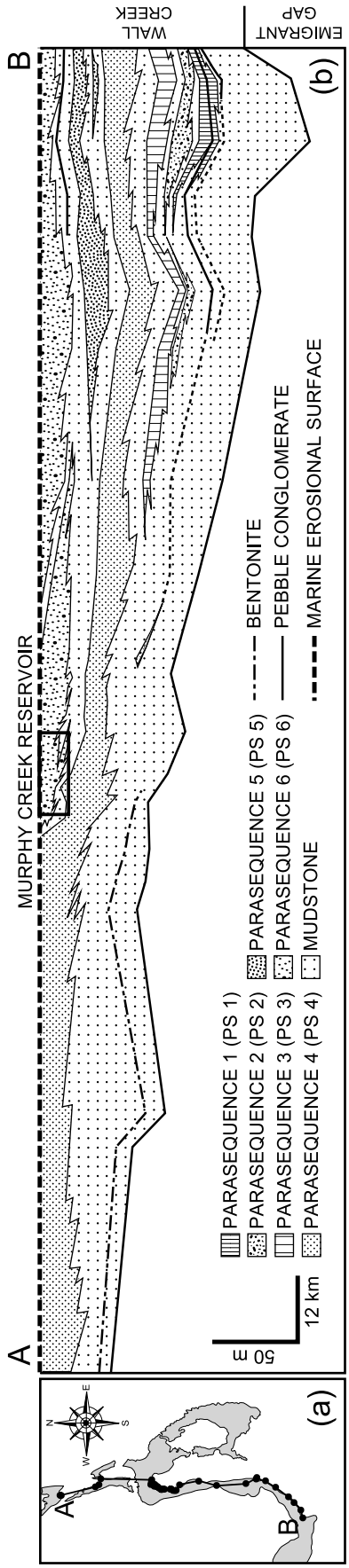


Figure 3. Locations of stratigraphic measured sections, represented by the closed circles (in a), are correlated to produce the regional cross section (b), along the Frontier outcrop belt, containing six parasequences. The area in (a) is outlined in the left panel in Figure 1. The Murphy Creek reservoir site lies in the topmost parasequence (PS6).

A regional stratigraphic correlation (Figure 3) along the eastern flank of the Bighorn Mountains identifies six parasequences (PS 1 to PS 6 from oldest to youngest) in Wall Creek outcrop (Howell et al., 2003). The Murphy Creek reservoir site lies in the uppermost parasequence (PS 6) and shows a slightly coarsening-upward succession of thick sandstones (~12 m; ~39 ft) interbedded with thin mudstone. The sandstone contains well-developed, delta-front clinoforms and provides favorable conditions for GPR data collection.

The sandstone at Murphy Creek reservoir is exposed along approximately 2 km (1.2 mi) of a westward-facing, north-south–oriented cliff face (Figures 1, 4); the top of the sandstone is exposed over a few square kilometers, with relatively little soil cover or vegetation. Based on six measured stratigraphic sections (Figures 1, 4) and detailed mapping of a set of clinoforms, the strata in the cliff face are interpreted as offlapping distributary mouth-bar deposits prograding seaward (Bhattacharya et al., 2002). The overall sequence of the sandstone consists of alternating sandy and slightly more clay-rich layers that intersect the topographic surface and that result in hogbacks by differential erosion of the two lithologies.

GPR SURVEY LAYOUT, ACQUISITION, AND DATA PROCESSING

The GPR reflection data used in this study were collected at the Murphy Creek reservoir and consist of a grid of 2-D profiles oriented parallel and perpendicular to the depositional dip. The GPR profiles are identified in Figure 1. The total length of all the lines is 4402 m (14,442 ft).

The topography is surveyed along each GPR line by a combination of traditional leveling and a real-time global positioning system (GPS). The GPS topographic data were collected by a real-time kinematic survey with a Leica GPS system 500 at an interval of 2 m (6.6 ft) or less, depending on the topographic features encountered. The relative error in the GPS topographic data was ±0.01–0.02 m (±0.03–0.06 ft). The elevation is higher near the cliff edge than away from it; the topographic surface dips about 8° to the east (Figure 1). The topography along the north-south (stratigraphic dip) lines is relatively flat, with an elevation change of less than approximately 10 m (33 ft) for most of them, whereas on the west-east (stratigraphic strike) lines, the elevation change is approximately 18 m (59 ft).

GPR Data Acquisition and Processing

The GPR data were collected using a Sensors & Software Pulse EKKO IV system with a 1000-V transmitter. The data were collected using 50-MHz antennas, with 3 m (10 ft) offset and 1 m (3.3 ft) station interval. Common-midpoint gathers were collected for velocity analysis.

Preprocessing of the GPR data includes "dewowing, time-zero alignment, and airwave or average removal" (Figure 5). Dewowing removes the low-frequency background discharge curve of the capacitor formed by the antenna and the ground surface. Time-zero alignment shifts each trace in time so that all the direct arrivals (airwaves) line up.

Noisy parts of traces are replaced by weighted averages of the nearest good traces; the weight is inversely proportional to the distance to the good trace used. High-amplitude spikes are removed because, if not corrected, they produce correspondingly strong artifact "smiles" in migration. Editing is done after time-zero correction and before airwave or ground-wave removal.

The direct air- and ground waves have strong amplitudes that obscure near-surface reflections. These waves are removed by subtracting from each trace, within a user-defined time window, the average trace in the neighborhood of that trace; this effectively removes all time-stationary signals like the airwave. Frequency band-pass filtering (6.25–375 MHz) is applied to reduce ambient noise.

Kirchhoff Migration

The GPR data, after preprocessing, were input to prestack Kirchhoff migration (Epili and McMechan, 1996). The migration velocity used is a constant of 0.12 m/ns (0.39 ft/ns) because that value seemed consistent across the survey. To take advantage of this constant velocity, the migration code is modified to analytically compute the traveltimes instead of ray tracing; this significantly reduces the computation time. Migration is from the topographic surface, so no elevation statics are needed.

OUTCROP SEDIMENTOLOGY

Sedimentary Structures and Facies

The Wall Creek Member at Murphy Creek reservoir consists of simple and compound offlapping, meter-thick, coarsening- and thickening-upward bedsets. The

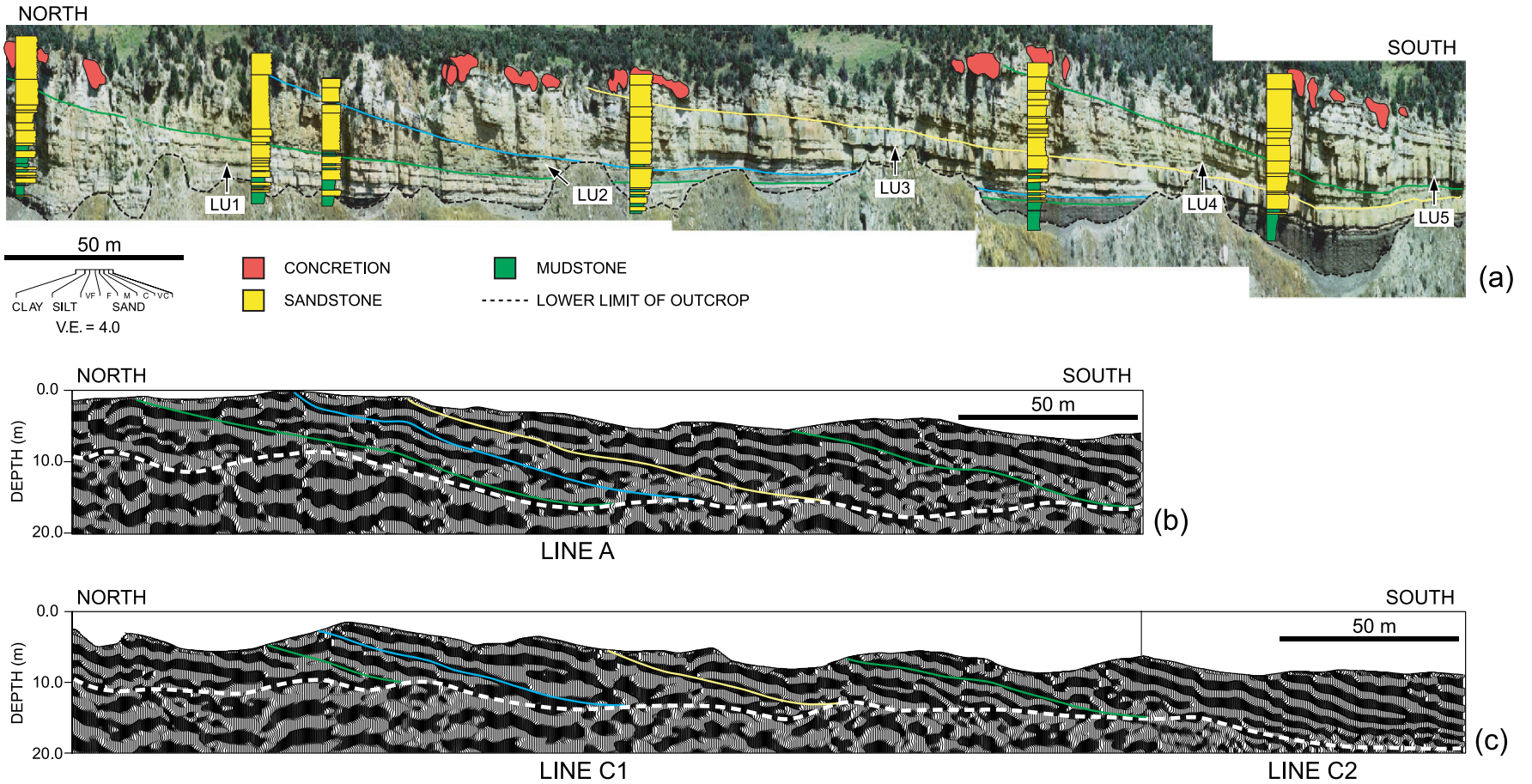


Figure 4. Photomosaic and six measured sections of the cliff face (a) showing southward-dipping clinoforms. The same features are seen in the migrated GPR profiles (b, c). Line A is nearest the cliff face and is parallel to line C, which is 100 m (3300 ft) to the east. The GPR data are plotted with automatic gain control, which boosts the deeper amplitudes. The white dashed line on the GPR profiles marks the deepest coherent and continuous reflectors, which is the depth limit of strata that can be imaged reliably with the GPR data.

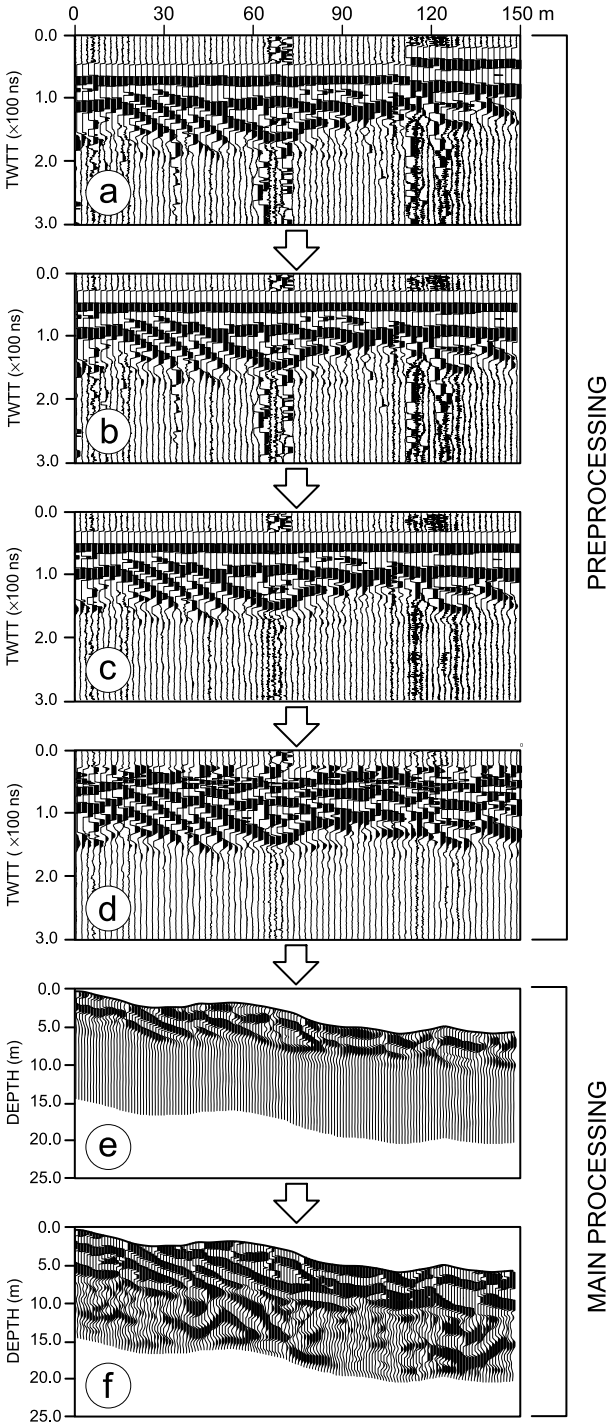


Figure 5. GPR data processing (a) shows the raw field data; (b) after time corrections; (c) after trace editing; (d) after airwave and ground-wave subtraction and filtering; (e) after prestack migration; and (f) the same as (e) but plotted with automatic gain control. These steps are applied to all the GPR data. These data are part of line E2 (see Figure 1).

entire sediment package grades upward from burrowed to current-rippled sandstones and mudstones, into structureless to flat-stratified and ripple cross-laminated sandstones (Figure 6). Bed thicknesses range from a few centimeters to 50 cm (19 in.) thick. Commonly, the bed tops are not preserved because of constant reworking of the seafloor by an active nektonic community. Sigmoidal clinoforms dip up to 5° toward the south (the same direction as paleocurrents). These clinoform bedsets form a shoaling-upward sediment body, which is bound above by a marine erosional surface. Mud content increases, and sandstone lamina sets are mud mantled (5–10 cm [2–4 in.] thick) as clinoforms toe out basinward.

The sandstones are commonly normally graded (fining upward) (Figure 6c, d), and they become wavy bedded and more massive in the upper 5 m (16 ft) (Figure 6a). Trace fossils record an episodic readjustment type of behavior because organisms altered dwelling and feeding structures to respond to changing sedimentation rates. Articulated bivalves are found, suggesting little to no transport or predation.

Two different sedimentation rates are interpreted (Figure 6), and corresponding stacked bedsets are interpreted as distributary mouth bars. The episodic sediment accumulation is recorded by changes in stratification type and trace-maker behavior. Rapid sedimentation and progradation are indicated by the dipping sandstone beds. The sharp-based sandstones suggest a river-dominated depositional environment. The upper wavy and massive sandstones suggest deposition in the wave-influenced middle delta front. The normally graded sandstones are interpreted to represent delta-front hyperpycnal turbidites (Bouma Tab units). These form as rapidly decelerating frontal splays during major river floods. The evidence for rapid sediment accumulation suggests that these deposits record basinward progradation of a fluvially influenced, mixed-process hyperpycnal and hypopycnal delta lobe.

Muddier burrowed intervals represent slower deposition during nonflood periods. Finer grained, poorly stratified, bioturbated sandstones, siltstones, and mudstones are interpreted to represent accumulation during more quiescent periods. The higher bioturbation index of the quiescent lithofacies results from the activity of infaunal, epifaunal, and nektonic organisms at or near the sediment-water interface. The delta topset is not preserved because of subsequent marine ravinement (Howell and Bhattacharya, 2001; Howell et al., 2003, 2004).

The Murphy Creek reservoir site contains concretions, which are typical diagenetic features that may

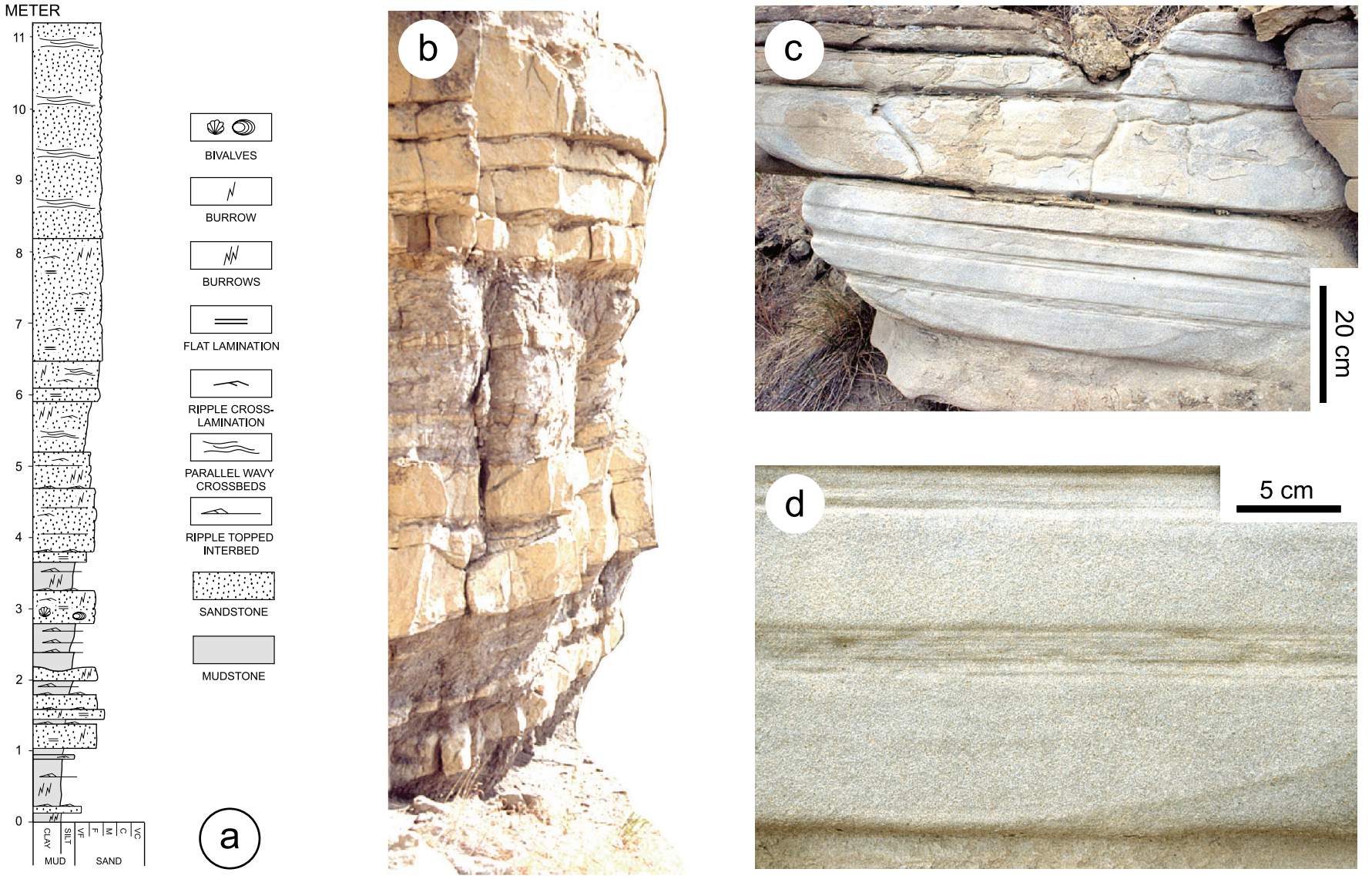


Figure 6. A measured section (a) and a representative photo (b) show an overall coarsening- and thickening-upward sequence interpreted as the record of delta progradation. The lower 5 m (16 ft) are composed of interbedded sandstones and mudstones deposited in the prodelta to delta-front transition. The upper 5 m (16 ft) are wavy and more massive sandstones deposited in a wave-influenced middle delta front. Photo (b) shows heterolithic facies in the lower part of the facies succession (corresponding to approximately 0–4 m [0–13 ft] in a). Individual sandstone beds (c) show amalgamated, structureless to parallel-laminated sandstones. The close-up (d) shows normal grading and a structureless to parallel-laminated transition.

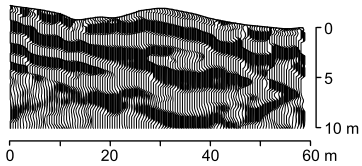
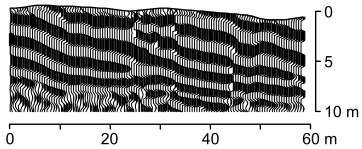
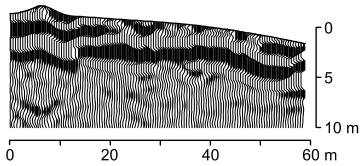
GPR FACIES	DESCRIPTION	EXAMPLE	INTERPRETATION
GPR FACIES 1	Moderate- to high-amplitude, moderate- to good-continuity reflections with structurally irregular zones		Bioturbated muddy facies with poorly defined sandstone interbeds
GPR FACIES 2	High-amplitude, good-continuity reflections with uniformly dipping patterns		Well-defined offlapping sandy layers
GPR FACIES 3	Low- and high-amplitude, good-continuity reflection; relatively flat		Surficial soil or eroded bedrock

Figure 7. GPR facies recognized in this study and their geological interpretation.

affect fluid flow in the sandstone reservoirs (Dutton et al., 2002). The cementation is in patchy, elongate, tabular reddish calcite concretions in the host sandstone (Nyman, 2003). The concretions are widely distributed, which is typical of calcite cementation in sandstone (Bjorkum and Walderhaug, 1990; McBride, 1997; Dutton et al., 2002).

Lithostratigraphic Units

Four (colored) lithostratigraphic boundaries are identified where the depositional patterns change (Figure 4a). The major boundaries are interpreted as representing bedset (mouth bar) surfaces and show a pronounced southward dip. The layers thin and downlap onto the underlying mudstone. Five lithostratigraphic units (LU1 to LU5, from oldest to youngest) are identified between the bounding surfaces. Despite little local variance in average sand-grain size (implying a constant sediment source over time), the lithostratigraphic units are interpreted as compound bedsets of migrating bars consisting of delta fronts developed by different depositional events. LU1, LU3, and LU5 were deposited by high-energy (flood) conditions, whereas LU2 and LU4 were deposited in a relatively quiescent (interflood) depositional environment.

GPR INTERPRETATION

The migrated GPR sections show top-truncated dipping reflectors on the north-south lines and relatively flat features on the west-east lines, which are consistent with the cliff outcrop (Figure 4). Three GPR facies are recognized, namely, 1, 2, and 3 (Figure 7). The GPR facies are better distinguished in the dip direction than in the strike direction; GPR profiles are correlated with the outcrop exposed along the cliff face. Each GPR facies was interpreted using the basic principles of seismic interpretation techniques on the basis of reflection amplitude, continuity, and configuration (Mitchum et al., 1977, Brown and Fisher, 1980).

Ground-penetrating radar facies 1 consists of reflections of moderate to high amplitude and moderate to good continuity. It is interpreted as representing a bioturbated, somewhat muddier facies with poorly defined sandstone beds (LU2 and LU4 in Figure 4). This radar facies corresponds to a fairly constant, moderate GPR penetration.

Ground-penetrating radar facies 2 is characterized by uniformly southward-dipping reflectors of high amplitude and good continuity. This facies corresponds spatially to well-stratified, medium-scale bedded clean sandstone (LU1, LU3, and LU5 in Figure 4). Although discontinuous reflections are also seen locally, GPR

facies 2 shows a relatively deeper penetration than the other facies and occurs most clearly and dominantly on the extended lines (lines C2, C3, and E2).

Ground-penetrating radar facies 3 is characterized by high-amplitude signals from the shallowest structure, beneath which is a low-amplitude zone. This occurs in two situations; one is the topographic lows between the hogbacks, and the second is at the south and east extremities of the survey lines (lines 0, C3, and E2), where the topography has flattened. Both are consistent with surficial weathered and soil layers of relatively high electrical conductivity (which attenuates the deeper GPR signals).

Another distinct reflection pattern is recognized in GPR facies 1 and 2. This configuration contains shallow, locally isolated, rounded, high-amplitude reflections, below which high attenuation is observed. The high-amplitude ellipsoidal anomalies are visible only in the upper part of GPR profiles and cut across the dipping GPR surfaces. Concretions with similar behavior are observed only at the top of the outcrop along the cliff face (Figure 4a). Thus, the high-amplitude ellipsoidal reflectors are probably indicators of concretions.

Structural Correlation with Outcrop

The outcrop at the Murphy Creek reservoir site (Figure 4) is about 400 m (1312 ft) long and is correlated with the GPR data. This correlation assumes that the bounding surfaces are the same in the outcrop section and the stratigraphic profiles and in the GPR profiles. The four main surfaces identified in the GPR data (Figure 4b, c) correspond to those in the outcrop. In the outcrops, more surfaces lie between the major boundaries, but these fall below the GPR resolution as they thin southward.

The GPR lines A and C (Figure 4b, c) are approximately 10 and 110 m (33 and 360 ft) away from the outcrop (to the east), respectively. These two parallel GPR lines show the southward-offlapping reflectors in the same order as those in the outcrop. Lateral variability in sedimentation inhibits a direct correlation of GPR facies directly with the lithofacies in the outcrop. Lithofacies vary laterally between the bounding surfaces, containing more clay in the seaward direction. As a result, the GPR facies are also correspondingly laterally variable.

The GPR facies can vary with lithofacies. Electrical property contrasts that determine GPR facies depend on subsurface features, including lithological changes, water distribution, and sedimentary structures (Neal et al., 2002). The GPR facies do not necessarily match with internally changing sedimentary facies (van Dam and Schlager, 2000). The delta front is the most active zone of a delta complex, internally as well as externally, and contains high regional-scale sediment variability (Willis et al., 1999). Bioturbation may also modify the grain size distribution in the delta complex. The bioturbation is slight where deposition is rapid and becomes more intense as sedimentation rate decreases (Bhattacharya and Walker, 1992; Reading, 1996).

Architecture of the Murphy Creek Reservoir Site

Figures 8 and 9 contain line drawings of the sedimentological boundaries (and, thus, the internal structures) extracted from the GPR lines (see Figure 1 for profile locations). The strike lines are west-east trending and show very low-angle, parallel, wavy reflections (Figure 8). The subparallel reflections are interpreted as strike-oriented sections through foreset beds prograding at the delta front (Smith and Jol, 1997).

The dip lines are oriented north-south, running slightly oblique to the main paleotransport direction (Figure 1), and were recorded parallel to each other with line spacing of about 50 m (164 ft) (Figure 1). The dip lines (Figure 9) show top-truncated, low-angle, southerly dipping, offlapping reflections. A few of the dipping layers are truncated by the younger overlying layers and can be seen thickening to approximately 10 m (33 ft). The layers can be traced downdip for about 80 m (262 ft), suggesting that their original bed forms are substantially longer. The southward-dipping reflectors are interpreted as delta-front clinoforms composed of bar deposits that prograde basinward.

For interpretation of the 3-D facies architecture, we use the GPR data volume, the photomontage, and the sections measured at the outcrop. The intersecting dip and strike GPR profiles allow the bedding surfaces to be correlated in 3-D. The surfaces in the 3-D volume (Figure 10) are based on the GPR data (excluding the profile extensions [lines E2, C2, C3, and part of line 0]). Individual surfaces (including major bounding surfaces) apparently downlap because they are beneath the resolution of GPR. In the outcrop, the beds actually converge as they thin into the underlying prodelta. Overall, a similar pattern of gently dipping bedding surfaces can be seen throughout the dip lines, which are well correlated across the gently undulating surfaces in the east-west strike lines.

We interpret the gentle undulations to be related to a depositional pattern of distributary mouth bars,

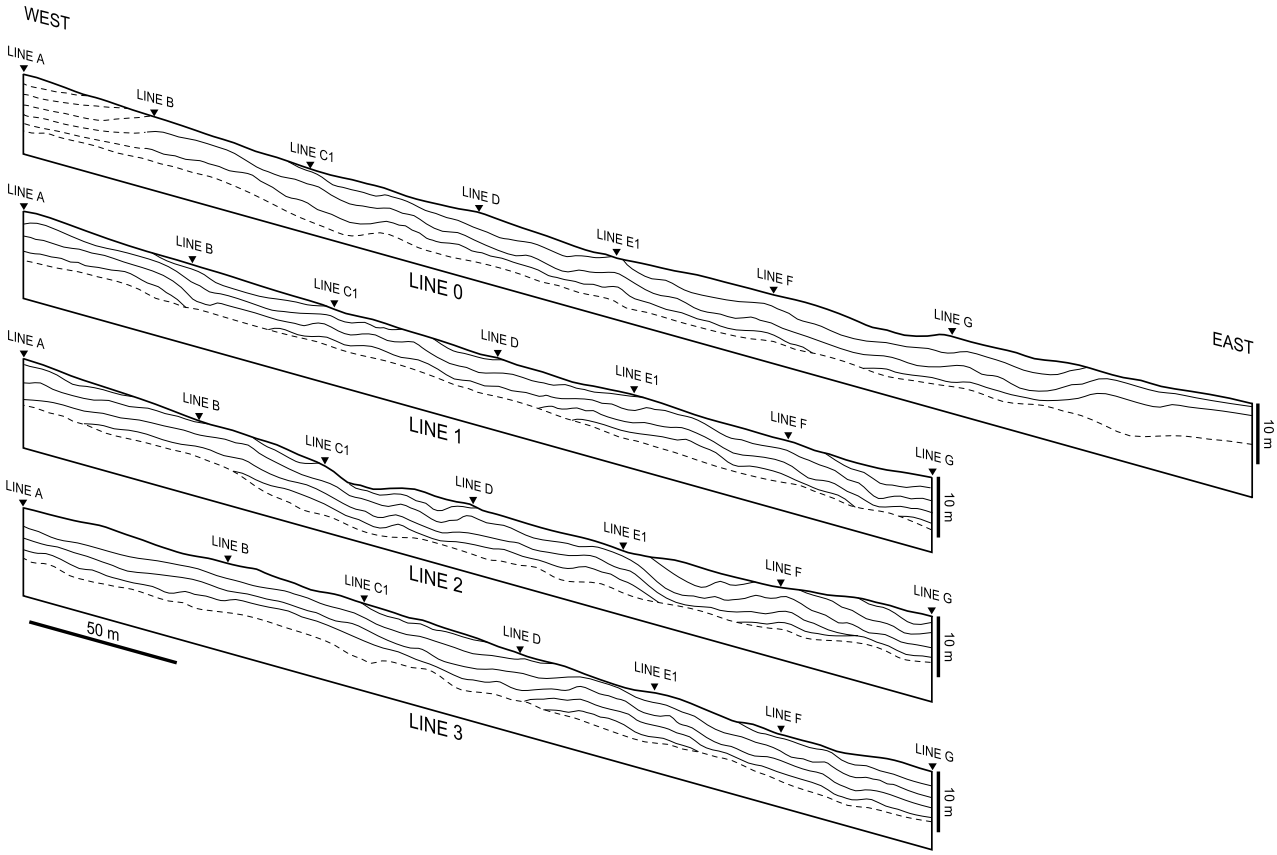


Figure 8. Line drawings of migrated GPR lines 0–3 in the strike direction (Figure 1) showing subparallel, wavy GPR reflections, which are interpreted as the strike direction of delta foresets. Ground-penetrating radar tie points are indicated by inverted triangles.

which are simultaneously deposited with the neighboring bars in a delta lobe, resulting in the formation of an interfingered distal bar complex (Coleman and Prior, 1980; Bhattacharya and Walker, 1992). Within the GPR volume, the interfingering zone is not directly observed because of the lack of sufficient radar resolution but is inferred from a series of apparently continuous horizontal reflections from one bar to the next.

The bedsets bounded by the major GPR surfaces correspond either to sand-rich bars (LU1, LU3, and LU5 in Figure 4) or bioturbated sand bars with higher clay content (LU2 and LU4 in Figure 4). From north to south, we see at least three repetitions of sand-rich bar deposits followed by bioturbated bar deposits. The maximum thickness of each unit ranges between 5 and 10 m (16 and 33 ft).

DEVELOPMENT OF MOUTH-BAR COMPLEXES

From the GPR interpretation, at least three flood-induced cycles of sedimentation can be identified. Each cycle consists of two phases, one with high and one with low sedimentation rate; however, there appears to be negligible change in average sand-grain size during the deposition of the distal delta-front bars through the whole section. The stratigraphic evolution of the Murphy Creek reservoir site is discussed below at the compound bedset level (Figure 10).

In the Upper Cretaceous, a deltaic environment was established as a clastic wedge that prograded east and south away from the Sevier orogenic belt into a foreland basin (Howell et al., 2004). During this time, a point-source fluvial delivery (i.e., a lowstand river system) fed the clastic sediments into the basin, building a delta on to a preexisting muddy platform along the western flanks of the Cretaceous epicontinental seaway (Bhattacharya and Willis, 2001). During this period, the bed load was transported through the channels by the fluvial-related current, forming the sandstone of LU1 as a successive bedset of a sandy bar in a distal delta front. The bedset was deposited by a flood in which the sediment load discharged from the river mouth was relatively high. After flooding, a subsequent bar (LU2) was formed as the delta prograded basinward, and low sediment supply caused LU2 to be highly susceptible

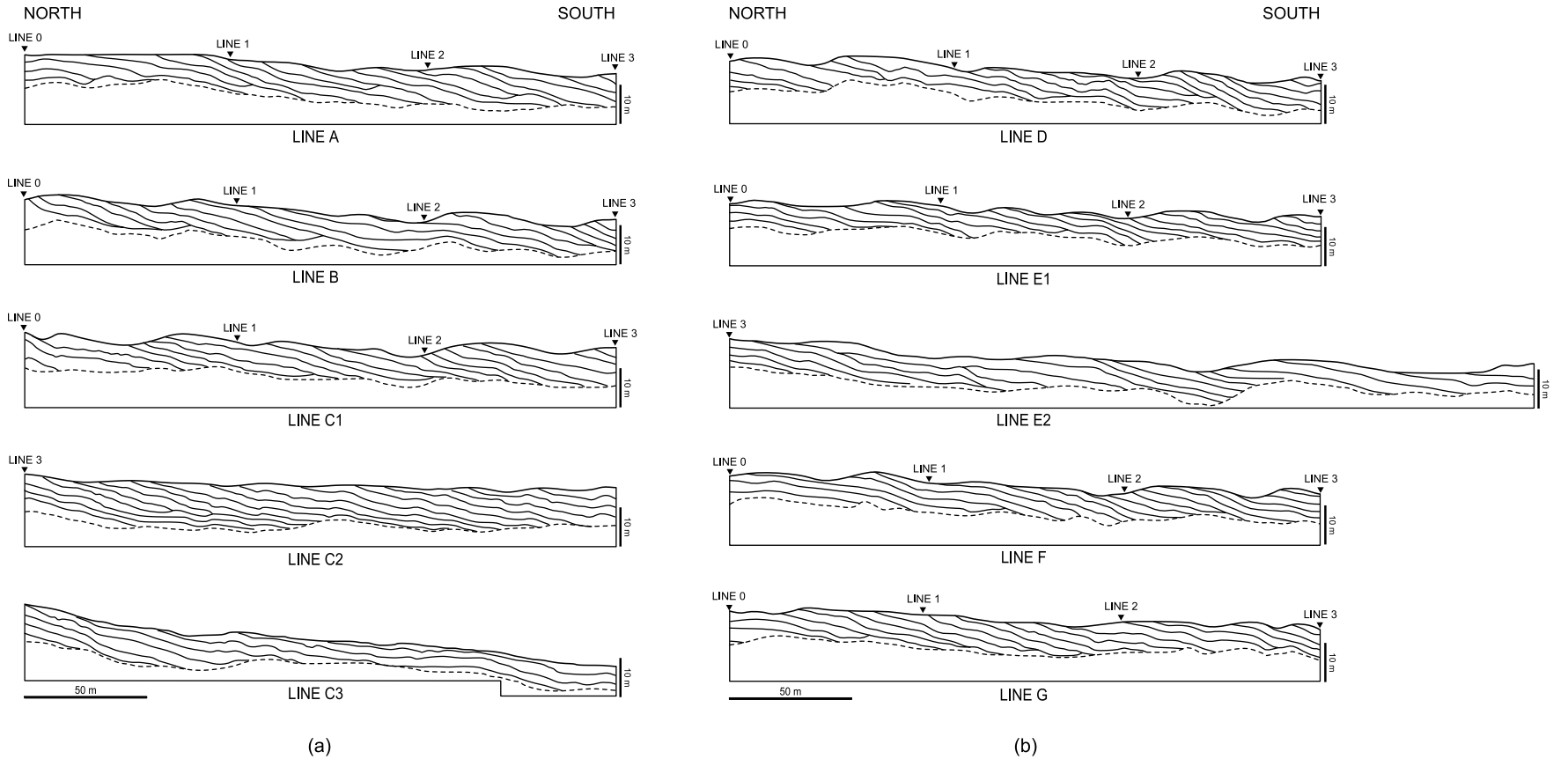


Figure 9. (a) Line drawings of migrated GPR lines A–G in the dip direction (Figure 1) showing southerly dipping reflections, which are interpreted as top-truncated prograding delta foresets. Ground-penetrating radar tie points are indicated by inverted triangles. Lines C1, C2, and C3 are a single line that is broken into three segments for display. (b) The continuation of the lines in (a). Lines E1 and E2 are a single line that is broken into two segments for display.

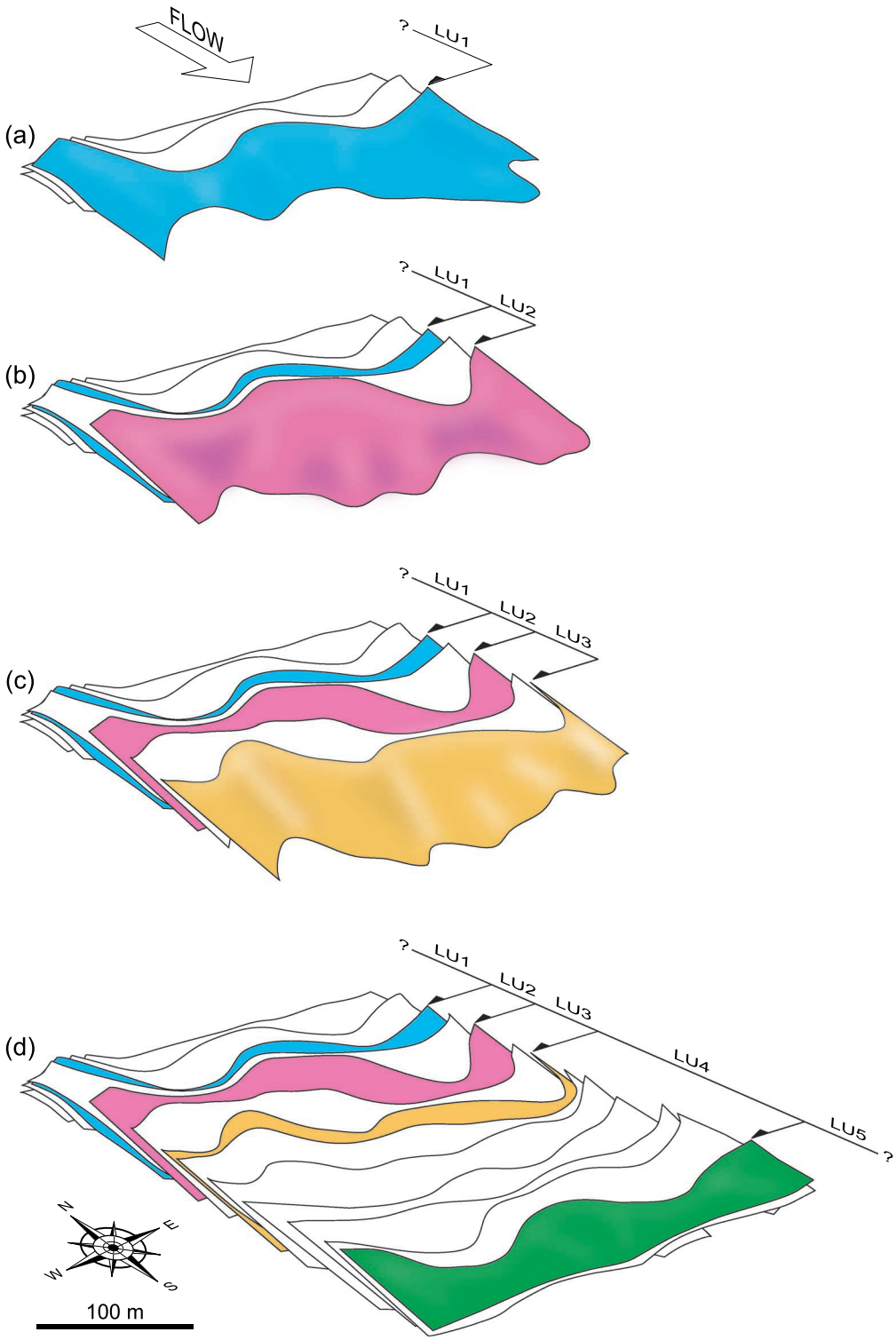


Figure 10. Stages in the development of the prograding distal delta-front bars at the Murphy Creek reservoir site. LU1 (a) and LU2 (b) are composed of a cycle of flood and inter-flood phases. LU3 and LU4 comprise a subsequent cycle; LU5 is the start of another.

to bioturbation, followed by LU3 marking another flood-induced cycle of sedimentation. LU3 was formed as a rapidly prograding bar with an increase of sedimentation rate that locally truncates the bedset of LU2. The second sedimentation cycle (LU3) was capped by a muddier postflood deposit (LU4), indicating reduced sediment supply. The thickness of LU4, however, is more than twice that of LU3, indicating that

LU4 either is more proximal to the bar crest or was deposited for a longer period of time.

The third cycle starts with LU5, but we do not see its top because it is not exposed. If the uniformly dipping reflectors on line C2 represent a bedset of rapidly prograding sandy bar, LU5 would be thicker than any of the other units. These cycles, which are a consequence of sedimentation rate, continued for a long period of time until they were eroded by a significant transgressive ravinement, resulting in a top-truncated delta front. The foresets of the delta front are partially preserved, but the delta tops (including the distributary channels) were eroded away (Howell and Bhattacharya, 2001), although the channels have been described in outcrops of PS 6 (see Figure 3) farther south (Gani and Bhattacharya, 2003).

We interpret alternating high and low sediment rate during the seaward growth of distributaries and sediments of the delta front. This alteration occurred without significant changes in average sand-grain size, which is consistent with sedimentation whose primary control is changing sediment supply from the sediment source instead of changing sediment sources.

ESTIMATION OF DEPOSITIONAL VOLUME

Mouth bars are composed of four principal regions: bar back, bar crest, bar front, and distal bar (Wright, 1977). The suggested depositional patterns of a top-eroded migrating bar at the Murphy Creek reservoir site resulting from ravinement erosion are shown in Figure 11a.

We assume that the Murphy Creek reservoir site is a distal part of the river-dominated delta where the sediments may be radially distributed through the distributary channels, forming mouth bars. Many bars coalesce over time and become incorporated into a bar assemblage resulting in semicircular, fan-shaped structures (Coleman and Prior, 1980). Progradation of the delta followed the dominant southeast paleocurrent direction (Figure 1). As the bar deposits were growing steadily basinward, it appears that the local channel mouth moved slightly landward (northwest) (Figure 11b). This may correspond locally to a component of landward accretion (i.e., upstream growth) of the distributary mouth bars on decadal timescales at a constant relative sea level (van Heerden and Roberts, 1988) for a modern analog.

To estimate the bar volume, we define the thickness as the vertical extent of a succession between the bar crest to the distal bar, and the length of the migrating bar as the horizontal distance from the channel mouth to bar front (because the distal bars are not visible with GPR; Figure 11a). The thickness of the bar was inferred from the outcrop. The measurement was conducted on the thickest interval of each bar succession between major boundaries, except for LU5 because this youngest unit is not clearly complete. The complete thickness is estimated by doubling the observed (truncated) thickness, assuming that the bar complex is cut down to half of its original height by transgressive erosion (Cattaneo and Steel, 2003), but the actual amount of erosion is not known. The half-length of each bar is derived from the radii of curvature of arcs fitted approximately to the four major GPR bounding surfaces (Figure 11b) to estimate the center of curvature, where we assume that the local point sediment source is located. The average of the estimated bar lengths is about 1300 m (4265 ft).

The volume of each bar is approximated by multiplying their areal extent by their average thickness (Table 1). The area covered by the migrating bars is obtained from the empirical relationship in figure 3 of Van Wagoner et al. (2003), between the area and length of sedimentary bodies. The volume of each bar is converted to possible fluid volume using a porosity of 20%, which is consistent with the average porosity values measured in outcrop samples in the topmost parasequence (PS 6) along the Frontier outcrop belt (Figure 3). The total potential fluid volume for LU1 to LU4 is thus estimated to be 2.0×10^7 bbl (3.1×10^6 m^3). This estimation has not considered allocyclic controls, including receiving basin geometry, regional tectonic stability, rates of subsidence caused by compaction of newly deposited sediments, or rate of sea level change.

SUMMARY

The geometry of a top-truncated, lowstand delta front was delineated with about 4400 m (14,435 ft) of GPR data collected at the Murphy Creek reservoir in the Upper Cretaceous Turonian Wall Creek Member of the Frontier Formation, in Wyoming, United States. A photomontage and the GPR lines oriented along depositional dip show inclined foreset beds with tangential bottomsets dipping south, slightly oblique to the major paleocurrent direction, and are interpreted as delta-front clinoforms.

Within the GPR volume, three different GPR facies were identified, but they are difficult to correlate directly with the lithofacies in the outcrop because of

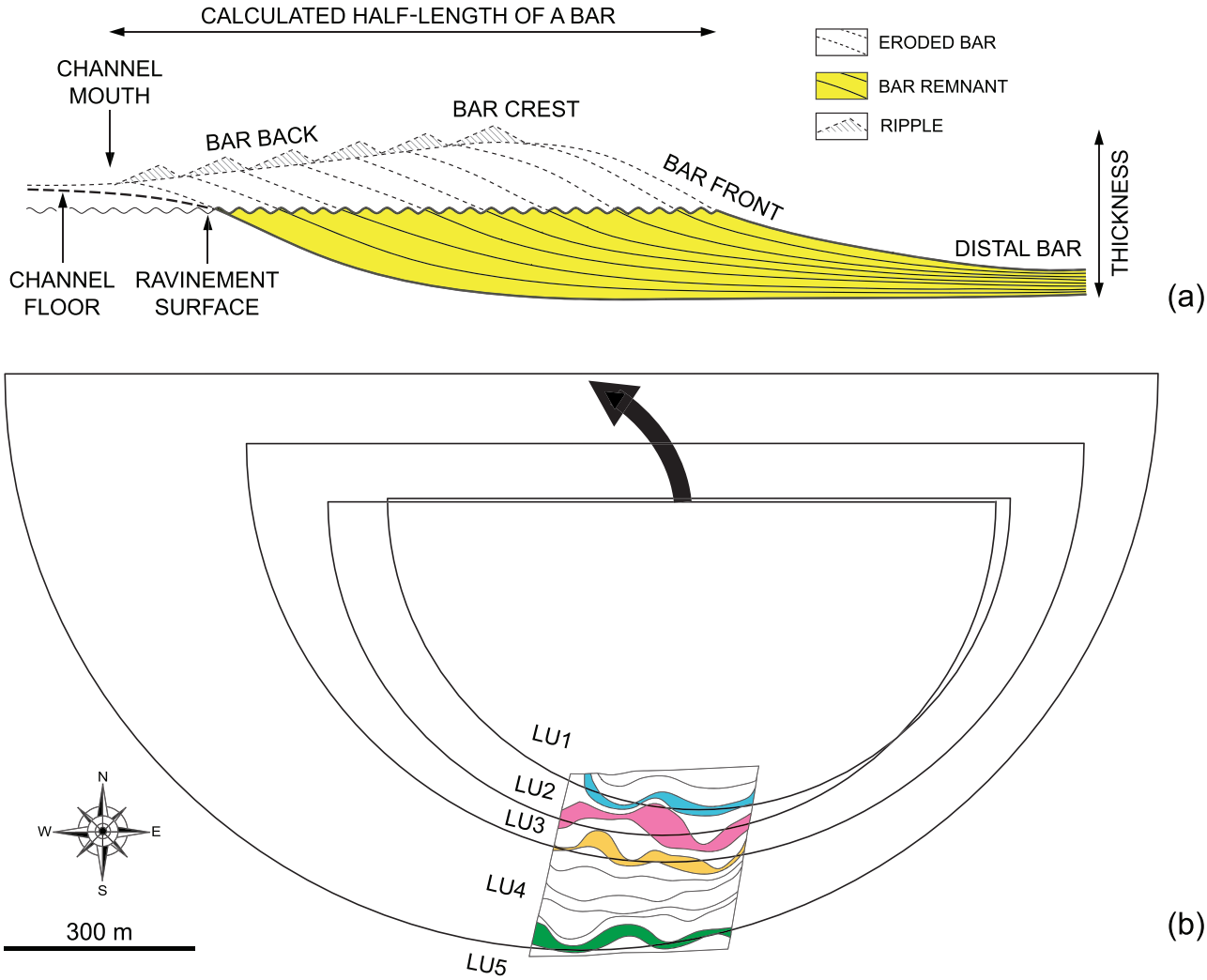


Figure 11. A schematic cross section of (a) a bar showing the radius and thickness and (b) a 3-D GPR reconstruction used to measure the radius from the channel mouth to bar front. Each semicircle represents the inferred area covered by each bar. As the bar deposits were growing steadily basinward, they were apparently accreting landward as well, as indicated by the heavy arrow.

lateral lithological variance. However, a similar geometry is observed in the outcrop and the GPR data in both the strike and dip directions. The dip lines are characterized by top-truncated, low-angle, southerly dipping reflectors, whereas the strike lines are characterized by very low-angle, parallel, wavy reflectors.

The four main GPR surfaces correspond to the surfaces bounding the compound bedsets of the bars in the outcrop. In each of the five lithological units identified, two different facies are repeated; one is characterized by relatively clean-bedded sandstones, indicating a rapid sedimentation rate, whereas the other is

Table 1. Estimated Depositional Volume of Each Mouth Bar

Lithostratigraphic Unit	Maximum Thickness (m)	Half-Length (m)	Volume (m^3)	Pore Volume (m^3)	Possible Fluid Volume (bbl)
LU1	13.0	492	2.3×10^6	4.6×10^5	2.9×10^6
LU2	10.0	533	2.1×10^6	4.2×10^5	2.6×10^6
LU3	10.4	672	3.5×10^6	6.9×10^5	4.3×10^6
LU4	12.4	921	7.7×10^6	1.5×10^6	9.7×10^6

characterized by poorly stratified bioturbated sandstones, representing a low sediment supply. These seaward-dipping lithological units are interpreted as progradational delta-front bar and interbar facies stacked in the distal delta front. Heterolithic delta-front turbidites are produced by sediment gravity flows.

The Murphy Creek reservoir site shows a complex of distributary mouth bars with variable thickness consistent with the prograding delta lobe. The geometry is in general agreement with the internal structures of a lowstand delta system (Hart and Long, 1996)], which is substantially larger than the study site, with a sediment source to the northwest. As the bar deposits were growing steadily basinward, they were apparently accreted landward as well (Figure 11b).

The minimum bar volumes at each stage of growth were estimated by measuring the length and thickness of the stacked deltaic deposits because complete and accurate information on the top truncation of the Murphy Creek reservoir is not available. The resolution limits inherent in GPR measurements make the seaward extension of the thin, deeper parts uncertain and suggest that the actual volumes of the delta lobe may be substantially larger.

REFERENCES CITED

Ainsworth, R. B., H. Bosscher, and M. J. Newall, 2000, Forward stratigraphic modeling of forced regression: Evidence for the genesis of attached and detached lowstand systems, *in* D. Hunt and R. L. Gawthorpe, eds., Sedimentary responses to forced regressions: Geological Society (London) Special Publication 172, p. 163–176.

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

Barton, M. D., 1997, Application of Cretaceous Interior seaway outcrop investigations to fluvial-deltaic reservoir characterization: Part 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: Gulf Coast Section SEPM Foundation 18th Annual Research Conference, p. 33–40.

Bhattacharya, J. P., and R. G., Walker, 1992, Deltas, *in* R. G. Walker and N. P. James, eds., Facies models: Response to sea level change: St. John's, Newfoundland, Geological Association of Canada, p. 157–177.

Bhattacharya, J. P., and B. J. Willis, 2001, Lowstand deltas in the Frontier Formation, Power River basin, Wyoming: Implications for sequence stratigraphic models: AAPG Bulletin, v. 85, p. 261–294.

Bhattacharya, J. P., B. J. Willis, and C. D. Howell, 2001, Top-truncated, lowstand deltas in the Cretaceous Interior seaway of North America (abs.): AAPG Annual Meeting Program, v. 10, p. A17–A18.

Bhattacharya, J. P., C. D. Howell, F. Marcy, G. A. McMechan, C. Olariu, and X. Zeng, 2002, Facies architecture of an ancient delta front deposit using GPR: Cretaceous Wall Creek Member, Frontier Formation, Wyoming (abs.): AAPG Annual Meeting Program, v. 11, p. A18.

Bjorkum P. A., and O. Walderhaug, 1990, Geometrical arrangement of calcite cementation within shallow marine sandstones: Earth-Science Reviews, v. 29, p. 145–161.

Brown, L. F., and W. L. Fisher, 1980, Seismic stratigraphic interpretation and petroleum exploration: AAPG Continuing Education Course Notes Series 16, p. 25–88.

Cattaneo, A., and R. J. Steel, 2003, Transgressive deposits: A review of their variability: Earth-Science Reviews, v. 62, p. 187–228.

Coleman, J. M., and D. B. Prior, 1980, Deltaic sand bodies: AAPG Short Course Notes Series 15, 171 p.

Dutton, S. P., C. D. White, B. J. Willis, and D. Novakovic, 2002, Calcite cement distribution and its effect on fluid flow in a deltaic sandstone, Frontier Formation, Wyoming: AAPG Bulletin, v. 86, p. 2007–2021.

Dyman, T. S., E. A. Merewether, C. M. Molenaar, W. A. Cobban, J. D. Obradovich, R. J. Weimer, and W. A. Bryant, 1994, Stratigraphic transects for Cretaceous rocks, Rocky Mountains and Great Plains regions, *in* M. V. Caputo, J. A. Peterson, and K. J. Franczyk, eds., Mesozoic systems of the Rocky Mountain region, U.S.A.: Rocky Mountain Section SEPM, p. 365–292.

Epili, D., and G. A. McMechan, 1996, Implementation of 3-D prestack Kirchhoff migration, with application to data from the Ouachita frontal thrust zone: Geophysics, v. 61, no. 5, p. 1400–1411.

Gani, M. R., and J. P. Bhattacharya, 2003, Bed-scale facies architecture of an ancient delta lobe deposit of the Wall Creek Member, Central Wyoming, U.S.A. (abs.): AAPG Annual Meeting Program, v. 12, p. A59.

Hart, B. S., and B. F. Long, 1996, Forced regressions and lowstand deltas: Holocene Canadian example: Journal of Sedimentary Research, v. 66, p. 820–829.

Howell, C. D., and J. P. Bhattacharya, 2001, Scales of facies architecture in top-truncated lowstand delta lobes, Upper Cretaceous Wall Creek Member, Frontier Formation, Powder River basin, Wyoming, U.S.A, *in* D. P. Stilwell, ed., Wyoming gas resources and technology: Casper, Wyoming, Wyoming Geological Association guidebook 2001, p. 208.

Howell, C. D., J. P. Bhattacharya, A. B. Robinson, and W. R Griffin, 2003, Topographically controlled, mixed-influence top-truncated deltas: Turonian Wall Creek Member, Frontier Formation, Powder River basin, Wyoming, U.S.A. (abs.): AAPG Annual Meeting Program, v. 12, p. A81.

Howell, C. D., J. P. Bhattacharya, A. B. Robinson, and W. R. Griffin, 2004, Estimates of sedimentation rates from sediment and faunal interactions within an ancient delta lobe, Wall Creek Member, Frontier Formation, Powder River basin, Wyoming, U.S.A. (abs.): AAPG Annual Meeting Program, v. 13, p. A66.

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. S. Perkins, eds., Shallow marine and nonmarine reservoirs, sequence stratigraphy, reservoir architecture and production characteristics: Gulf Coast Section SEPM Foundation 18th Annual Research Conference, p. 127–138.

McBride, E. F., 1997, How predictable are patterns of calcite cement in sandstones? (abs.): AAPG Annual Convention Program, v. 6, p. A79.

Mitchum Jr., R. M., P. R. Vail, and J. B. Sangree, 1977, Seismic stratigraphy and global changes of sea levels: Part 6. Stratigraphic

interpretation of seismic reflection patterns in depositional sequences, *in* C. E. Payton, ed., Seismic stratigraphy — Applications to hydrocarbon exploration: AAPG Memoir 26, p. 117–133.

Neal, A., N. I. Pontee, and J. Richards, 2002, Internal structure of mixed-sand-and-gravel beach deposits revealed using ground-penetrating radar: Sedimentology, v. 49, p. 789–804.

Nyman, L. S., 2003, Provenance and diagensis of the Cretaceous Wall Creek Sandstone, Frontier Formation, western flanks of the Powder River basin, Wyoming: M.Sc. thesis, University of Texas at Dallas, Dallas, Texas, 107 p.

Reading, H. G., 1996, Sedimentary environments: Processes, facies and stratigraphy: Oxford, Blackwell Scientific Publications, 688 p.

Sadeque, J., and J. P. Bhattacharya, 2004, Top truncated delta in the Western Interior seaway: An example from subsurface analysis of the Turonian Wall Creek Member, Frontier Formation (abs.): AAPG Annual Meeting Program, v. 13, p. A121.

Smith, D. G., and H. M. Jol, 1997, Radar structure of a Gilbert-type delta, Peyto Lake, Banff National Park, Canada: Sedimentary Geology, v. 113, p. 195–209.

Sullivan, M. D., C. I. Macaulay, A. E. Fallick, and R. S. Haszeldine, 1997, Imported quartz cement in aeolian sandstone grew from water of uniform composition but has complex zonation: Terra Nova, v. 9, p. 237–241.

Tye, R. S., J. P. Bhattacharya, J. A. Lorsong, S. T. Sindelar, D. G. Knock, D. D. Puls, and R. A. Levinson, 1999, Geology and stratigraphy of fluvio-deltaic deposits in the Ivishak Formation: Applications for development of Prudhoe Bay field, Alaska: AAPG Bulletin, v. 83, p. 1588–1623.

Tyler, N., 1988, New oil from old fields: Geotimes, v. 33, p. 8–10.

van Dam, R. L., and W. Schlager, 2000, Identifying causes of ground-penetrating radar reflections using time-domain reflectometry and sedimentological analyses: Sedimentology, v. 47, p. 435–449.

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., D. C. J. D. Hoyal, N. L. Adair, T. Sun, R. T. Beaubouef, M. Deffenbaugh, P. A. Dunn, C. Huh, and D. Li, 2003, Energy dissipation and the fundamental shape of siliciclastic sedimentary bodies: AAPG Search and Discovery Article 40081: www.searchanddiscovery.com/documents/vanwagoner01/index.htm (accessed June 5, 2005), 8 p.

Willis, B. J., C. D. White, S. L. Gabel, J. P. Bhattacharya, 1999, Documenting deltaic bedding architecture in outcrop for reservoir simulation (abs.): AAPG Annual Meeting Program, v. 8, p. A151.

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

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