Three-dimensional facies architecture and three-dimensional calcite concretion distributions in a tide-influenced delta front, Wall Creek Member, Frontier Formation, Wyoming

Keumsuk Lee, M. Royhan Gani, George A. McMechan, Janok P. Bhattacharya, Stephanie L. Nyman, and Xiaoxian Zeng

ABSTRACT

Ground-penetrating radar (GPR) has been used to image the three-dimensional (3-D) internal structure (and, thus, the 3-D facies architecture) of a top-truncated delta front in the topmost parasequence in the Wall Creek Sandstone Member of the Frontier Formation in Wyoming and to estimate the distribution of low-permeability concretions throughout the 3-D GPR volume.

The interpretation of the 3-D GPR data is based both on correlations with outcrop and on calibration with core data from holes within the survey grid. Two main radar facies (RF) are identified. Radar facies 1 corresponds to tide-influenced mouth bars formed by a unidirectional flow during delta progradation or bidirectional flow during tides, whereas RF2 is correlated with laterally migrating channels developed on previous bar deposits. The delta-front foreset beds dip in the same direction as the dominant paleocurrent indicators. The GPR interpretation is consistent with the outcrop interpretation that, following a regressive period, bars and channels were developed at the Raptor Ridge site before subsequent transgressive ravinement. The individual 3-D deltaic facies architectures were reconstructed from the 3-D GPR volume and indicate that the depositional units are larger than the survey grid.
Cluster analysis of the GPR attributes (instantaneous amplitudes and wave numbers) calibrated with the cores and the outcrop was used to predict the distribution of near-zero permeability concretions throughout the 3-D GPR volume; clusters of predictive attributes were defined and applied separately in the bars and channels. The predicted concretions in the bars and the channels are 14.7 and 10.2% by volume, respectively, which is consistent with those observed in the cores (14.7 and 10.5%, respectively), and their shape and thickness are also generally in consonance with those in the outcrop and cores. The estimated concretions are distributed in an aggregate pattern with irregularly shaped branches within the 3-D GPR volume, indicating that the cementation does not follow a traditional center-to-margin pattern. The concretions and 3-D geological solid model provide cemented flow baffles and a 3-D structural framework for 3-D reservoir modeling, respectively.

INTRODUCTION

Ground-penetrating radar (GPR) has been used for detailed subsurface imaging of deltaic deposits since the early 1990s; however, most studies have focused on modern deltas associated with unconsolidated fluvial deposits (Jol and Smith, 1991; Pepola and Hickin, 2003; Roberts et al., 2003), instead of ancient marine environments exposed in outcrops. Although GPR has revealed high-resolution structural information in fluvial sediment bodies and has been used to build reservoir models (McMechan et al., 1997; Corbeanu et al., 2001; Zeng et al., 2004), few examples document detailed three-dimensional (3-D) delta-front facies architecture (Lee et al., 2005), and there are no studies of 3-D cement distribution. Preserved delta fronts in outcrops are commonly characterized by prograding clinoforms and systematic variations in sedimentary facies (Bhattacharya and Walker, 1992; Snelgrove et al., 1996, 1998).

Calcite cement is a common diagenetic feature in sandstone reservoirs. Pervasive pore-filling calcites can be found in spheroidal, elongate, tabular, or irregular forms (McBride, 1996). Calcite-cemented sandstone can occur over a range of burial depths, depending on the supply of the cementing materials. For example, calcite cement zones are characteristic within the Middle Jurassic delta-front sandstones in the North Sea (Walderhaug and Bjorkum, 1992). Because concretions fill up the pore spaces as their volume expands (Dutton et al., 2002), the permeability and porosity distributions in sandstone reservoirs may be significantly affected (Hassouta et al., 1999). This has been demonstrated by two-dimensional (2-D) reservoir simulations (Dutton et al., 2002; White et al., 2003).

Because three-dimensional models of concretion-bearing sandstone reservoirs are derived from the limited information available from outcrop and borehole sedimentology, fluid behavior is difficult to predict accurately. Although boreholes can provide statistically defined 3-D information, uncertainty remains in interwell interpolation. In contrast, GPR can provide detailed 3-D structural
information within the sandstone reservoirs and also provide estimates of permeability and porosity through calibration with core measurements.

The distribution of obstacles to fluid flow in a reservoir may be extracted from GPR data by analyzing GPR attributes (Lemke and Mankowski, 2000). Corbeanu et al. (2002) and Hammon et al. (2002) estimated the spatial distribution of mudstone flow baffles and barriers in fluvial deposits by calibrating the GPR attributes to the borehole measurements via cluster analysis. This technique is also applicable to deltaic sandstone reservoirs to provide a 3-D image of the diagenetic features (cements), as demonstrated below.

This study has two objectives. The first is to image the internal structure of a top-truncated lowstand delta front from 3-D GPR data acquired at the Raptor Ridge reservoir analog site in Wyoming; this allows for the 3-D visualization of the deltaic sedimentary bodies. The second objective is to estimate the distribution of low-permeability cements that are flow baffles, by calibrating GPR attributes (instantaneous amplitudes and wave numbers), with core permeability measurements. The resulting models are suitable for input to fluid-flow simulation (Tang, 2005).

GEOLOGICAL SETTING

The study area is located between the Powder River and Wind River basins in Wyoming (Figure 1) and contains deltaic environments influenced by rivers, waves, and tides (Bhattacharya and Willis, 2001). During the Late Cretaceous, sediments were transported eastward from the topographic highs of the Sevier orogenic belt into the western margin of the Western Interior seaway, forming the Frontier Formation (Barlow and Haun, 1966; Dyman et al., 1994). The Wall Creek sediments form the uppermost member of the Frontier Formation. They were deposited into a foreland basin and were eroded significantly during subsequent transgression (Bhattacharya and Willis, 2001). Continuous, north-south–oriented, Wall Creek outcrops are well exposed in a series of sandstone cliffs along the Frontier outcrop belt (Figure 1). Winn (1991) interpreted the sandstone bodies as storm-dominated offshore shelf deposits; however, a recent study suggests that the formation contains top-truncated deltas (Bhattacharya and Willis, 2001; Lee et al., 2005). The Wall Creek Sandstone Member is interpreted to consist of several delta lobes, indicated by different sandstone bodies (in parasequences PS 1 to PS 6 from oldest to youngest, Figure 2) (Howell et al., 2003). The exposed topmost parasequence (PS 6) at Raptor Ridge, near the southern end of the Frontier outcrop belt, was chosen for this study.

The Raptor Ridge site contains a mixed-influenced delta lobe capped by a transgressive ravinement surface (Gani, 2005). The site provides favorable conditions for a GPR survey; it has near-planar
surface topography that is cut by a northwest-southeast–oriented valley (Figure 1). The Raptor Ridge vicinity contains exposed sedimentary columns of the outcrop showing the six parasequences; only the topmost deltaic sand body (PS 6) can be clearly seen along the cliff face (Figures 3–5). Parasequence 6 is interpreted as a top-eroded lowstand delta front (Gani, 2005). In the delta-front sandstone, calcite cements commonly show a reddish color in the cliff face (Figures 3, 4).

**DATABASE**

The database for this study consists of a 3-D GPR data volume, outcrop sedimentology conducted on a 300-m (1000-ft)-long cliff face, 10 cores drilled behind the cliff to a depth of 11 m (36 ft), digital cliff face photos, and the present-day topography. The GPR data are integrated with the geologic data for calibration and interpretation. The 3-D data used here (Figure 5) were...
Figure 2. Stratigraphic section along the Frontier outcrop belt containing six parasequences. The Raptor Ridge site lies in the topmost parasequence (PS 6) near the southern end of the section AB. Modified from Howell et al. (2003).

Figure 3. Photomosaic of the cliff face in the depositional dip direction (a) and its bedding diagram (b) showing the alternation of southward-dipping dinoforms of the distributary mouth bars separated by laterally migrating channels. See Figure 5 for location. In (a), concretions are the reddish areas within the bar and channel sandstones.
collected in the context of a larger project, which also includes two larger 2-D grids. The 2-D data provide some constraints at the edges of the 3-D grid and help to interpret the radar facies within a larger scale framework. Detailed analysis of the 2-D data will be presented elsewhere.

The GPR reflection data were collected at the Raptor Ridge site in the summer of 2002 using a Pulse-EKKO IV system (manufactured by Sensors & Software, Inc.). The 3-D GPR data were acquired on a rectangular survey grid of 30 × 80 m (98 × 262 ft) (Figures 1, 5). The 3-D volume had 1-m (3.3-ft) GPR line spacing and 0.25-m (0.82-ft) trace spacing along each line; the lines run approximately parallel to the paleocurrent direction (Figure 5). A common-offset geometry with 3 m (9.8 ft) transmitter-to-receiver spacing was used to obtain the GPR data, at a frequency of 50 MHz. The time window and sampling interval were set at 300 and 0.8 ns, respectively, and traces were stacked 128 times at each survey point to improve the signal-to-noise.

Figure 4. Photomosaic of the cliff face in the depositional strike direction (a) and bedding diagram (b) showing the alternation of subhorizontal bedsets of the distributary mouth bars separated by laterally migrating channels. See Figure 5 for location. In (a), concretions are the reddish areas within the bar and channel sandstones.

Figure 5. Detailed map of the Raptor Ridge site showing the locations of the sedimentary cores, the photomosaics, and the 3-D survey grid. Paleocurrent direction measurements conducted on the topmost parasequence are indicated in the circle. See Figure 1 for location.
Topographic data collected with a global positioning system (GPS) with accuracy of approximately 0.03 m (0.098 ft) were used to define the datum for depth migration of the GPR data.

Detailed outcrop analysis of the exposed cliff face was done in 2002 and included mapping of facies, shales, cements, bedding and bounding surfaces, paleocurrent directions, and traditional vertical logged sections combined with high-resolution digital photomosaics (Gani, 2005). Clinoform surfaces traced along the outcrop allow correlations of the sedimentary facies and structures with the 3-D GPR data.

Ten cores (Figure 5) were drilled to provide independent sedimentologic information (including concretions) away from the cliff faces and unweathered samples of the entire section for permeability and porosity measurements and thin sections. Two of the cores (cores 8 [10.9 m (35.7 ft) depth] and 9 [10.7 m (35.1 ft) depth]) in the 3-D GPR volume are used for depth control for processing and interpretation of the 3-D GPR data. These two cores are also used for calibration of the GPR attributes to predict the concretion distribution. The other eight cores are used to constrain analysis of a 2-D GPR grid (which is not presented here).

GROUND-PENETRATING RADAR DATA PROCESSING

Preprocessing of the 3-D GPR data (Table 1) is similar to that described by Lee et al. (2005). The average trace amplitude (Figure 6a), determined over a user-specified time and trace window after air and direct wave removal, shows northwest- to southeast-trending linear anomalies (parallel to the survey lines), which are acquisition artifacts (Brown, 2004; Cordsen, 2004) caused by antenna coupling changes from line to line. These undesired amplitude artifacts were effectively reduced by performing amplitude balancing (Figure 6) by scaling average absolute amplitude of each survey line to the same reference level.

Prestack Kirchhoff depth migration (Epili and McMechan, 1996) was performed on the GPR data with a 3-D migration velocity model obtained by matching GPR reflection depths with the corresponding boundaries in the cores. The migration code was modified to analytically compute the traveltimes instead of ray tracing, by assuming locally constant velocity, resulting in a significant reduction of the computation time (Lee et al., 2005). The migration used the topographic surface as the datum and, thus, needs no elevation statics. The grid increments in the migrated volume are 0.1 m (0.33 ft) in the depth and in in-line directions and 0.2 m (0.66 ft) in the crossline direction. An automatic gain control (AGC) with a 0.5-m AGC window is applied to the migrated profiles to compensate for attenuation to make the deeper parts of the images more visible for interpretation (Table 1). For the concretion calibration, the migrated GPR volume is used with no AGC because instantaneous amplitudes are used.

GROUND-PENETRATING RADAR DATA ANALYSIS AND INTERPRETATIONS

This article follows the facies architectural model suggested by Gani (2005) based on an outcrop study at Raptor Ridge. The model consists mainly of five basic facies-architectural elements: prodelta fines, frontal splay, tidally modulated deposit, channel, and bar accretion. Their corresponding sedimentary facies are facies 1–5, respectively in Figure 7 and are bounded by five orders of bounding surfaces (zero to fourth order from lowest to highest), which are defined on the principle of superposition and crosscutting relationships (Gani, 2005).

For a more confident interpretation, the outcrop and two cores (8 and 9) were directly compared with the GPR data to establish radar facies type and boundaries (Figures 8, 9; Table 2). The radar facies were recognized from the GPR volume to map facies architectures, and then the depositional setting was inferred from the corresponding radar facies, correlated to core and outcrop data, which are associated with the depositional setting. However, the inherent resolution limitation (a quarter wavelength) allows 50 MHz GPR to detect no lower than third-order surfaces.

The third-order bounding surfaces bind channels and sets of most of the subordinate surfaces downlapping and/or onlapping onto the third-order surfaces (Figure 3). The top transgressive marine ravinement surface TES (Figure 3) is fourth order, truncates lower order surfaces, and erodes delta-plain deposits; it is a regionally traceable surface strewn with granules and pebbles. The GPR penetration was limited in most places from 10 to 12 m (33 to 39 ft) depth, which is the depth to the top of the prodelta mud deposits that highly attenuate the GPR waves.
Table 1. Ground-Penetrating Radar Data-Processing Steps Applied to the GPR Volume

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dewowng</td>
<td>The low-frequency capacitive background is eliminated from each trace caused by coupling between the antennas and the ground surface.</td>
<td><img src="image1.png" alt="Example Image" /></td>
</tr>
<tr>
<td>Time-zero alignment</td>
<td>Each trace is shifted so that all the direct arrivals (the air waves) line up.</td>
<td><img src="image2.png" alt="Example Image" /></td>
</tr>
<tr>
<td>Trace editing</td>
<td>Data traces, or parts of traces, that contain high-energy noise are replaced with the average of the good traces to either side.</td>
<td><img src="image3.png" alt="Example Image" /></td>
</tr>
<tr>
<td>Air and direct wave removal</td>
<td>By subtracting the average trace over the air-wave time window from each GPR trace, the higher energy of air and direct waves can be removed.</td>
<td><img src="image4.png" alt="Example Image" /></td>
</tr>
<tr>
<td>Depth migration</td>
<td>Prestack Kirchhoff migration was performed on the GPR data with a 3-D migration velocity model.</td>
<td><img src="image5.png" alt="Example Image" /></td>
</tr>
<tr>
<td>Autogain control (AGC)</td>
<td>AGC is applied after migration to make the deeper parts of the structure more visible.</td>
<td><img src="image6.png" alt="Example Image" /></td>
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</tbody>
</table>
Ground-Penetrating Radar Facies Analysis

Radar facies were identified using reflection amplitude, continuity, and configuration. The radar facies were compared with the sediment textures in the cores and were correlated with the facies architectures seen in the outcrop. The calibration and correlation provide the crucial information to correctly identify the depositional features, which produce the radar reflections, and to confirm the identity of the sedimentary structures detected in the subsurface.

Two radar facies (RF1 and RF2) are recognized in this study (Table 2), although the tide influence and diagenetic features prevent discernment between them in some places within the GPR volume. RF1 is characterized by moderate- to high-amplitude and continuity reflections both in the dip and strike directions. The corresponding radar facies show approximately east-west–striking, repetitive, wide, subparallel reflection patterns on planar slices (i.e., Figure 10a). RF1 is subdivided into two subordinate radar facies (RF1a and RF1b) in the dip direction, although being similar to each other in the strike direction (Table 2).

RF1a consists of oblique reflection configurations with in-situ dip angles of about 5°, which is consistent with that of the third-order bounding surfaces of bars (and, thus, is consistent with prograding delta-front foreset beds; Lee et al., 2005). RF1b is characterized by low-angle (1–2°), subhorizontal, landward-dipping reflectors, with occasional steps. Because of difficulty identifying the corresponding sedimentary facies, RF1b can be interpreted to represent two different depositional facies of the delta-front bars (upstream accretion and/or tidal modulation of the mouth bars), unless otherwise constrained by other evidence (Jol and Bristow, 2003). These two facies can both produce landward-dipping bedding geometry, but the depositional environments are different. Although the landward migrations of the delta-front bars are observed in a river-dominated delta (van Heerden and Roberts, 1988), tidally modulated bars can be found in tide-influenced river deltas (Willis et al., 1999). Tidal sand bars are also commonly associated with herringbone cross-bedding. Siegenthaler (1982) showed herringbone cross-bedding surfaces with less than 1 m (3.3 ft) vertical separation, between which are the foreset beds.

Figure 6. Amplitude balancing removes the linear stripes indicated by arrows in (a) that are artifacts of the data acquisition. Each panel is a view, from above, of the survey grid, and the amplitude plotted as each survey location is the average absolute amplitude of the trace at that location. (a) is before balancing and (b) is after.
of tidal sand bars. The ebb-flood–induced surfaces are subhorizontal or seaward dipping, but they are still lower angle than the foreset beds. Similar features were observed in the sandstone outcrop at Raptor Ridge (Gani, 2005). Thus, RF1b would be more reasonably interpreted as the internal architecture of tidal sand bars.

RF2 is characterized by short, complex, low- to high-amplitude, and continuity reflections both in the dip and strike direction profiles; oblique and sigmoidal accretion
Figure 8. A northwest-southeast–trending, dip-oriented GPR profile through cores 8 and 9, illustrating the correlation of borehole lithofacies to GPR facies: (a) uninterpreted radar line; (b) interpreted radar line. The rectangular box (5 × 10 m; 16 × 33 ft) in (b) represents dip-view radar facies shown in Table 2; the thick solid line in the box indicates the corresponding strike-view radar facies. SDR = seaward-dipping reflection; LDR = landward-dipping reflection; and GU1 to GU3d are GPR units, as described in the text. See Figures 5 and 12 for location and detailed lithofacies, respectively.
events that downlap the U-shaped reflection are observed in the strike direction, suggesting a channel migration (Table 2). Because of mud clasts and accretionary features in the channel facies, the corresponding GPR reflection configurations are irregularly oriented, mottled, or chaotic on planar slices (i.e., Figure 10b).

**Ground-Penetrating Radar Boundaries and Ground-Penetrating Radar Architectural Elements**

The core-calibrated GPR bounding surfaces and associated GPR units (GUs) are identified within the 3-D volume and are well correlated with the outcrop

<table>
<thead>
<tr>
<th>GPR Facies</th>
<th>Characteristics</th>
<th>Dip Direction Example</th>
<th>Strike Direction Example</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF1a</td>
<td>Moderate- to high-amplitude and continuity reflections with low-angle (1-2°), landward-dipping dinoforms in dip direction; subhorizontal or parallel reflections in strike direction</td>
<td><img src="image" alt="5 m" /></td>
<td><img src="image" alt="5 m" /></td>
<td>Forested beds of mouth bars at a delta front, formed during a delta progradation</td>
</tr>
<tr>
<td>RF1b</td>
<td>Moderate- to high-amplitude and continuity reflections with low-angle (1-2°), landward-dipping dinoforms in dip direction; subhorizontal or parallel reflections in strike direction</td>
<td><img src="image" alt="5 m" /></td>
<td><img src="image" alt="5 m" /></td>
<td>Tidal modulation of mouth bars at a delta front, formed during tides</td>
</tr>
<tr>
<td>RF2</td>
<td>Short, complex, irregular, low- to high-amplitude continuity reflections from multiple, irregularly oriented reflection of varying lengths in both dip and strike directions; troughs lapped by slightly oblique or sigmoidal reflections in strike direction</td>
<td><img src="image" alt="5 m" /></td>
<td><img src="image" alt="5 m" /></td>
<td>Lateralized distributary channels and associated channel fill</td>
</tr>
</tbody>
</table>

* The inverted triangles represent tie points. See Figure 8 for the locations of these radar facies type sections.
interpretation (Figures 3, 4). The GPR boundaries are traceable through the whole 3-D GPR volume (Figures 11, 12), suggesting that the interbar boundaries are substantially longer than the survey grid. The GPR units are referred to as GU1 to GU3, respectively, from oldest to youngest. To reconstruct the individual 3-D facies architectures, the (picked) horizon interpretations were imported into Gocad. Figure 12 shows both the shapes of the erosional surfaces and the 3-D geometry of the bodies; to the best of our knowledge, this is the first time that delta-front facies architectures can be readily seen at the submeter scale in 3-D.

3-D Facies Architecture Descriptions

GU1 is the thinnest GPR unit (0.5–1.5 m; 1.6–4.9 ft) and forms a single architectural element, extending throughout the 3-D volume (Figure 12). GU1 is characterized by seaward- and landward-dipping reflections in RF1 (Figure 8), but the reflections are weak, with low continuity because of the presence of the interbedded mud deposits as well as the inherent GPR resolution limitations. The top of GU1 forms three east-west-trending troughs that are overlain by GU2.

GU2 is composed of four elements (GU2a to GU2d in Figure 12), and the thickness of its elements increases upward, ranging from 3.5 to 5 m (11.5 to 16.4 ft). The subunits are characterized by RF2 and are vertically stacked through about 5 m (16.4 ft). The top surface of the stacked radar unit is relatively flat throughout the GPR volume.

GU3 also consists of four elements (GU3a to GU3d in Figure 12) and is characterized by RF1; the three subunits (GU3a to GU3c) are composed of seaward-dipping reflections (RF1a), whereas the top subunit (GU3d) contains a mixture of RF1a and RF1b in which each radar facies is locally lapping against the other; a gradational transition occurs between them, both vertically and laterally. Thus, it is difficult to delineate individual elements from the GPR boundaries (i.e., onlap, downlap, and toplap).

Figure 10. Slices showing clipped amplitude variations on planes at about (a) 3 m (10 ft) and (b) 8 m (26 ft) depth below, and parallel to, the topographic surface ([a] is in the bars, and [b] is in the channels). The bar facies (RF1 in [a]) shows east-west-trending, banded, high amplitudes with spotted patterns interpreted as tidal modulation. The channel facies (RF2 in [b]) exhibits irregularly oriented, mottled, or chaotic patterns caused by mud clasts and accretionary events.
Interpretations

GU1 is interpreted as distal delta-front bar deposits (Figure 13) consisting of facies 2 and 3 (Figure 7), which is consistent with the outcrop interpretation (Figures 3, 4). The coexistence of seaward- and landward-dipping reflections (Figure 8) suggests that the distal mouth bars are slightly tidally modulated at the delta front. The trough structures of GU1 are the result of lateral erosion by the overlying GPR unit (GU2).

GU2 is interpreted as channel-fill deposits (Figure 13), as a result of intermittent fluvial flood events (Gani, 2005), as seen in the outcrop (facies 4 in Figure 7). The stacked radar units represent the product of an accumulation by a high-energy series of channelizing events, each separated by scour surfaces. The scour and deposition events repeat until the top channel fill formed a boundary between the channel and the overlying bar-growth elements (GU3).

GU3 is interpreted as progressively tidally modulated, proximal river-mouth bars at the delta front (facies 5 in Figure 7) because it contains a higher sand:mud ratio than the distal bars (GU1) (Figure 13); the top delta-front body corresponds to the bar deposits overlain by the channels in the outcrop (Figure 9). The mixed bar

Figure 11. Three-dimensional perspective view of the migrated GPR volume (a) and its 3-D solid geological model (b) showing distributary-bar deposits separated by laterally migrating channels. A vertically separated view of the solid model is shown in Figure 10. The uppermost ravinement surface (the TES) is not shown, because the plot starts slightly deeper.
facies suggest a change in depositional environment from a river-dominated to a tide-influenced river delta. The single radar-facies architectures (GU3a to GU3c) represent dominantly prograding river-mouth bars deposited by a unidirectional flow (i.e., a river flow or an ebb tide current). The presence of mixed radar facies in the subunit (GU3d) is indicative of highly tide-influenced mouth-bar deposits, whose internal structures may be highly modified by migrations of dunes and bars during bipolar tides (Willis, 2005).

In summary, distal delta-front mouth bars with relatively small tide influence were deposited on a prodeltaic layer at the Raptor Ridge site, consisting of very fine-grained frontal splay deposits with mudstone rip-up

Figure 12. A vertically separated version of the 3-D GPR interpreted volume in Figure 9 showing nine facies architectural elements within the GPR units.
clasts (GU1, Figure 12), and they were subsequently eroded by laterally migrating channels (GU2) that are interpreted to be river-flood-induced deposits. The four-stacked channel deposits are capped by more proximal, increasingly tidally modulated, mouth-bar deposits (GU3) that were dominant until subsequent transgressive ravinement eroded the top of GU3. The lower (GU1) and upper (GU3) bar sediments were deposited in the paleoflow direction. The delta-front development is consistent with the outcrop analysis by Gani (2005).

**OBSERVED DISTRIBUTION OF CALCITE CONCRETIONS**

**Calcite Concretions in Cliff Face and Cores**

Calcite cementation is a major diagenetic event at Raptor Ridge and is confined to the middle of the deltaic sand body (Figures 3, 4). Cemented concretions were mapped along a 100-m (330-ft)-long outcrop in both the dip and strike directions (Figures 3, 4). The cement
is patchy, forming elongate, tabular concretions within the host sandstone. The pattern of the calcite cement is typical of that in sandstones (Walderhaug and Bjorkum, 1992; McBride, 1996; Klein et al., 1999; Dutton et al., 2000). The concretions are apparently more abundant, more rounded, and larger in the channels than in the bars. The larger concretions in both bars and channels possibly contain multiple nucleation centers (Dutton et al., 2002). The concretions in general do not always follow the stratigraphic geometries; they terminate within a bed or cut across bedding surfaces.

Differences in concretion sizes exist between the outcrop and the cores. The thickness of the concretions in the cliff face ranges from 0.2 to 1.7 m (0.66 to 5.57 ft), and they attain a maximum length of about 10 m (33 ft); the thicknesses in the cores range from 0.02 to 1.22 m (0.065 to 4.00 ft). These two types of measurements also show inconsistency in their average occurrence of concretions. In the outcrop, the bars contain less cement (5.5% in area) than the channel deposits (9.7% in area); in contrast, in the cores, cement is more abundant in the bar facies (14.7% in volume) than in the channel facies (10.5% in volume). For the prediction of concretions by calibration of GPR attributes, we use the outcrop values as constraints in size and shape because the distance between individual one-dimensional cores are longer than the maximum length of the concretions; otherwise, the prediction will result in overestimation of the concretion dimensions (i.e., size and shape). The distributed cores, however, are probably better constraints in estimating the percent volume of the concretions because they provide broader spatial sampling. The differences in concretion fractions between the cliff face and the cores may be affected by weathering; neither are truly 3-D.

**Petrophysical Analysis**

The Raptor Ridge sandstones that contain the calcite-cemented concretions are feldspathic litharenites to lithic arkoses with an average composition of quartz (51%), feldspar (21%), and rock fragments (28%). The cemented regions have no distinct difference in grain composition from the rest of the sandstone. Concretions in the outcrop are entirely cemented by calcite (with minor chlorite and kaolinite). The grain texture of the cemented concretions is upper fine grained, moderately sorted, and subangular to subrounded (Figure 14).

![Image](image_url)

**Figure 14.** Thin-section photomicrographs of (a) uncemented and (b) cemented sandstones (see Figure 13 for sample depths). The uncemented sandstone (a) shows 0.0% concretion, permeability = 270.8 md, and porosity = 21.33%. The cemented sandstone (b) shows 24.0% concretion, permeability = 8.2 md, and porosity = 0.0%.

The main components of the concretions are a low-magnesium, ferrous calcite.

Permeability profiles were constructed from Hassler cell measurements on the cores (e.g., Figure 13) for constructing a 3-D permeability distribution for input to flow modeling. The permeability in the bars is 325 ± 176 md; the permeability in the channels is 234 ± 149 md. The concretions have much lower permeability, which is locally superimposed on the higher permeability backgrounds in the bars and channels.

The permeability of the cemented sandstones ranges from 0.01 to 0.1 md (e.g., Figure 13). The mouth-bar sands show porosity ranging from less than 10 to 32% (Figure 14a), but near-zero porosity when calcite cements fill the intergranular pores (Figure 14b). The petrophysical relationships observed in the cores and thin sections suggest that the sharply bounded concretions...
can be good GPR reflectors because porosity contrasts are associated with changes in electrical properties (Davis and Annan, 1989).

**ESTIMATED DISTRIBUTION OF CALCITE CONCRETIONS**

Predicting the occurrence and distribution of concretions in the sandstone reservoirs is an important factor in predicting porosity and permeability. We use two GPR attributes (instantaneous amplitude and instantaneous wave number) to separate the concretions from the other background lithologies (i.e., sandstone) within the 3-D GPR volume between the TES and the mud layer. For the estimation, cores 8 and 9 were used to define the depths, thicknesses, and boundary sharpness of the concretions.

**Ground-Penetrating Radar Attribute Analysis**

The procedure consists of five steps (see Corbeau et al., 2002; Hammon et al., 2002, for discussion): (1) GPR traces in the vicinity of each hole are extracted; (2) correlation of these traces with the lithology of the cores is used to identify depth windows for reflections corresponding to concretions; (3) two GPR attributes, instantaneous amplitude (IA) and instantaneous wave number (IW) (which is the instantaneous spatial frequency), are crossplotted to quantify the behaviors of the concretions relative to the background sediments (Figure 15); (4) IA and IW are calibrated by identifying clusters corresponding to the concretions (separately for the bars and the channels); and (5) the criteria are applied to estimate the distribution of the concretions throughout the GPR volume. The most important step is the calibration.

![Crossplots of the GPR attributes on which the criteria for the concretions were built. The boxes in (a) indicate the criteria that are defined and applied separately to the bar and the channel parts of the GPR data volume. The black dashed lines in (a) are second-order polynomial trends of the concretions. The concretions are superimposed on the background data points (b). The thin dashed line in (b) represents a separation between the bar and channel facies. C1W8 = top concretion in core 8; C1W9 = top concretion in core 9; C2W8 = middle concretion in core 8; C3W8 = lowest concretion in core 8; C2W9 = middle concretion in core 9. See Figure 16 for location of the real and predicted concretions at the cores.](image)
Figure 15a shows the IA-IW trajectories of the five main concretions identified in cores 8 and 9. The reflection associated with each individual concretion has its maximum amplitude at approximately 50 MHz (the nominal dominant frequency of the GPR data) and then has a well-defined trend of progressively lower amplitude toward the higher frequencies (see the dashed black lines). The most salient prediction of each concretion is the group of points at the 50-MHz end of its trajectory, where it is flattened, and at higher amplitude. This subset of points also has minimal overlaps with the (more evenly distributed) background points (Figure 15b).

Assuming that the five concretions in Figure 15a are characteristic of those throughout the volume (in terms of thickness and degree of cementation, which determine the reflection amplitudes), it is sufficient to use the boxes in Figure 15a as the criteria for identifying concretions. It is not necessary to use the higher frequency tails in the criteria because all the concretions produce reflections with higher amplitudes at frequency near 50 MHz (so none will be missed in the predictions), and the possibility of overprediction will be minimized (Figure 16). The tails do not add any new information because they are redundant with the clusters at approximately 50 MHz.

Figure 15b shows the IA-IW point distributions for the concretions and the background points in both the bars and the channels. The sloping dashed line gives an almost complete separation between the bar and channel background values (the “o” and “+” locations, respectively). This also shows that it is very difficult to separate concretions from the backgrounds if the IW windows described above were not used, but it is straightforward if they are.

**Distribution of Predicted Concretions**

A reasonable match exists between the predicted bodies and the corresponding concretions in the cores (Figure 16); concretions that are only lightly cemented
and/or are thinner than the GPR resolution are not expected to be detected. Reliability of predictions is higher in the bars because there is little overlap between the cemented and uncemented sandstones (Figure 15b). Overlap leads to prediction of concretions where there are none; conversely, concretion data points that lie outside the selected concretion bounds lead to non-prediction of concretions where there are some. Thus, the observed and predicted concretions at the core locations (Figure 16) match well if we simply count the number of predicted concretions, but not so well if the concretion width and locations are considered in detail. The separation of cemented and uncemented regions in the IA-IW plane (Figure 15b) in the channels is not as good as the bars, so there is a higher uncertainty associated with the corresponding individual predictions (although the volume percent is forced to be accurate via the calibration to the cores).

The 180 and 100 largest predicted concretions, in the bar and channel facies, respectively, are incorporated into the 3-D geological solid model (Figure 17). These numbers of predicted bodies were chosen by matching the predicted volume percentage of concretions (14.7% and 10.2% in the bars and channels, respectively) with the observed volumes (14.7% and 10.5%, respectively). This is further supported by two independent observations: first, the predicted distributions of concretions confined to the middle of the two-facies model (Figure 17) are very similar, and second, both of these sets of predicted concretions have a lower bound in volume of about 130 model grid points (0.26 m$^3$; 9.2 ft$^3$), which are also (fortuitously) approximately the lower bound of resolution of the GPR data. Any smaller concretions that are present would have no detectable influence on fluid flow through the model, so not being able to detect them has no net detrimental effect.

Figure 18 contains two additional types of displays to provide more complete information on the 3-D concretion distribution and geometry. Figure 18a and b show the predicted concretion distributions on the same two planar slices on which the amplitudes are shown in Figure 10 (in the bars and channels, respectively). The bar concretions (Figure 18a) consist of roughly east-west–trending linear features on the planes and approximately follow the larger amplitudes on the same plane (Figure 10a). The channel concretions show much more heterogenous distributions of positions and shapes, as do the corresponding amplitudes (Figure 10b).

Figure 18c and d contain views, from above, of the shapes and thicknesses of a few representative predicted concretions in (1) the bars and (2) the channels. The bar and channel concretion bodies attain maximum thicknesses of 1.0 and 1.4 m (3.3 and 4.6 ft), respectively (Figure 18c, d), which are consistent with the observed thicknesses both in the cores and the outcrops. In the bars, the predicted concretions have relatively uniform
Figure 18. Slices showing the predicted concretions (a) in the bars on a plane at about 3 m (10 ft) depth below and parallel to the topographic surface and (b) in the channels on a plane at about 8 m (26 ft) below and parallel to the topographic surface. Transparent views of five representative (the 2nd, 4th, 6th, 8th, and 20th largest) concretions lying (c) in the bars and (d) in the channels. The slices in (a) and (b) are at the same locations as those in Figure 10.
thickness and tend to be elongated in the strike (east-west) direction. In the channels, the predicted concretions are more equidimensional, with more rapid variation in thickness. These differences are consistent with the expected spatial variations in porosity and permeability in the bar and channel facies (and, thus, the concretion-filling patterns). It is clear, from comparing Figure 18a and b with Figure 18c and d, that 2-D exposures (whether model slices or outcrop) underestimate the size, and have almost no information on the shape, of 3-D concretions.

The modeled concretions appear to be aggregately distributed in the bar and channel facies (Figure 18). This distribution pattern is typical of calcite concretions in shallow-marine sandstones (Bjorkum and Walderhaug, 1990a). The geometry and spatial distribution of predicted concretions are consistent with a detailed study of diagenesis at the Raptor Ridge. The growth patterns of the Raptor Ridge concretions do not always follow the traditional concentric center-to-margin pattern; they typically show a complicated aggregate pattern related to the direction of fluid flow. Similar results were found in the McBride et al. (2003) study of concretions in the Ferron, Frontier, and Second Frontier sandstone units of Utah and Wyoming.

Although calcite cements are commonly thought to be pervasive permeability barriers (Bjorkum and Walderhaug, 1990b; Walderhaug and Bjorkum, 1992), we find an irregular concretion distribution that would be a baffle to fluid flow. Geochemical analysis suggests that the concretions nucleated from carbonaceous and calcareous mud clasts, which originated from δ¹⁸O-rich, marine pore waters, precipitating from shallow (~100 m; ~330 ft) to deeper (~900 m; ~2952 ft) parts of the delta front, reaching a maximum temperature of approximately 40°C. The major growth of the calcareous concretions occurred between 400- and 800-m (1312- and 2624-ft) depths, filling up the deltaic sandstone volume.

A 3-D reservoir fluid simulation based on geostatistically derived Raptor models (Tang, 2005) concludes that inclusion of the GPR information increases the estimated average of geometrical permeability by 7.04%, resulting in an enhanced sweep efficiency from 0.79 to 0.81, compared to the models based on the core and outcrop data alone.

The lithofacies solid model (Figure 17) is a proxy for the corresponding deterministic permeability volume. From the measurements cited above, we can directly substitute the permeability values into the corresponding part of the solid model; 325 ± 176 md in the bars, 234 ± 149 md in the channels, and 0.01-0.1 md for the concretions. This permeability volume can be input to flow modeling (Tang, 2005). An additional contribution to permeability, which may dominate at large scale, is the near-vertical fracturing that is seen in the outcrop; thus, the permeabilities estimated here for the bars and channels may be considered as lower bounds. These fractures are not imaged by the (nearly vertically propagating) GPR signals and, thus, must be estimated independently. Only the lithologic contribution to permeability has been studied here.

**IMPLICATIONS FOR PETROLEUM PRODUCTION**

The results of this characterization of a delta-front reservoir analog are useful to petroleum geologists and engineers seeking to increase recovery from reservoirs in similar environments (i.e., the North Slope of Alaska, the Gulf of Mexico, and the Rocky Mountains). The 3-D GPR-derived detailed internal geometry within a sandstone body contributes to estimation of reservoir volumes, and the predicted concretions embedded in the GPR stratigraphic model may provide improved production performance prediction via upscaled reservoir models. In particular, the study of the delta-front reservoir model will be immediately applicable to improving production because oil and gas fields are located in the Wall Creek and other Frontier sandstones included in the National Petroleum Reserve (NPR-3) to the east of the study area.

**SUMMARY**

Ground-penetrating radar has been used to image the detailed internal structures of a top-truncated delta front in the topmost parasequence of the Wall Creek Sandstone Member. The Raptor Ridge site was chosen because of its favorable conditions for GPR data acquisition. The GPR reflection data were acquired, together with GPS data, over a grid of 30 x 80 m (100 x 262 ft) at a frequency of 50 MHz in the summer of 2002. The outcrop was mapped and photographed for calibration and correlation. Ten cores were drilled both inside and outside the 3-D survey grid.

The GPR data were processed with the GPS data and interpreted by correlation with bedding surfaces observed in the cliff face and in the two cores within the grid. From the 3-D GPR data, GPR boundaries and associated radar units are recognized. The GPR units
are characterized by two main GPR facies: RF1 and RF2. RF1 is interpreted as tidally reworked mouth-bar deposits, whereas RF2 is interpreted as fluvially dominated laterally migrating channel fills. The deltaic sequence was developed by two main types of depositional episodes (channelization and bar growth). The 3-D GPR interpretation shows that the sequence is composed of three GPR units (GUs) including nine facies architectural elements.

Three-dimensional visualization of the architectural units indicates that the deltaic sequence begins with the sand-bar deposits (GU1) prograding in the same direction as the paleocurrent indicators. The distal delta-front deposits were scoured by the subsequent four channels (GU2). After channel migration, proximal sand bars are deposited on the channel fills. The uppermost GPR unit (GU3) starts with northwest-southeast–elongated mouth bars formed by unidirectional flow. As time went on, the prograding sand bars were progressively more influenced by tidal modulation, producing the bidirectional-flow deposits at the delta front, until the mouth bars were truncated by subsequent transgressive ravinement.

The volume and distribution of calcite cements, the main diagenetic features in the Raptor Ridge sandstones, are estimated by a core-constrained cluster analysis of GPR attributes (instantaneous amplitudes and wave numbers). The GPR-derived criteria (concretion clusters) for separation of cemented and noncemented regions were determined and applied separately to the bars and channels. The predicted concretions in the deltaic sandstone are distributed in a dendritic, aggregate manner and account for 14.7% of the bar volume and 10.2% of the channel volume. The overall estimated concretion pattern matches reasonably with that observed in the cliff face particularly in terms of shape and thickness. The predicted spatial geometries are consistent with the difference in porosity and permeability distributions between the bars and the channels. The formation of the concretions do not always proceed from the centers to the edges. The modeled near-zero permeability baffles are incorporated into a 3-D digital geological solid model, which has been used as a framework for subsequent reservoir fluid-flow modeling by Tang (2005).

REFERENCES CITED


