3-D FACIES ARCHITECTURE AND CALCITE CONCRETION DISTRIBUTIONS IN A TIDE-INFLUENCED DELTA FRONT, WALL CREEK MEMBER, FRONTIER FORMATION, WYOMING

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ABSTRACT

Ground Penetrating Radar (GPR) has been used to image the 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 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 GPR data is based both on correlations with outcrop and on calibration with core data from holes within the survey grid. From the 3-D GPR volume, two main radar facies (RF) are identified between a regressive (lower) boundary and a transgressive erosional (upper) boundary. RF1 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 the pro-delta muddy layer or 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, nine bodies
consisting of three facies architectural elements 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 wavenumbers) calibrated with the sediment cores and the outcrop was used to predict the distribution of near-zero permeability baffles throughout the 3-D GPR volume; criteria were defined and applied separately in the bars and channels. The predicted concretions in the bars and the channels are 14.8% and 10.7% by volume, respectively, which is consistent with those observed in the sediment cores (14.70% and 10.54%, respectively). The estimated concretions are distributed in an aggregate pattern with irregularly oriented branches within the 3-D GPR volume, indicating that the cementation does not follow a traditional center-to-margin pattern. The concretions are integrated into a 3-D digital geological solid model to provide a 3-D structural framework for 3-D reservoir modeling.

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), rather than on 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; Corbeau et al., 2001; Zeng et al., 2004), few examples document detailed 3-D delta front facies architecture (Lee et al., 2005). Delta fronts are characterized by prograding cliniforms 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). Since 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 2-D reservoir simulations (Dutton et al., 2002; White et al., 2003).

Three-dimensional reservoir modelers have difficulty in predicting fluid behavior within concretion-bearing sandstone reservoirs from the limited information available from outcrop and borehole sedimentology. Although boreholes can provide statistically defined 3-D information, uncertainty remains in interwell interpolation. Therefore, a technology such as GPR is needed to provide detailed 3-D structural information within the reservoirs. GPR can image high-resolution internal structures of a sandstone reservoir 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, allowing for the 3-D visualization of the deltaic sedimentary bodies. The second is to estimate the distribution of low permeability cements that are flow baffles, by calibrating GPR attributes (instantaneous amplitudes and wavenumbers), with core permeability measurements. The resulting models are suitable for input to fluid flow simulation. Since oil and gas fields are located east of the study area in the Wall...
Creek where it is buried, the results will be applicable to improving production.

**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 forming the top member of the Frontier Formation, 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). The Wall Creek sandstone 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 transgression ravinement surface (Gani and Bhattacharya, 2005). The site provides favorable conditions for a GPR survey; it has a near-planar surface topography that is cut by a NW-SE 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 and 4). PS 6 is interpreted as a top-eroded lowstand delta front (Gani and Bhattacharya, 2005). In the delta-front sandstone, calcite cements commonly show a reddish in color in the cliff face (Figures 3 and 4).
DATABASE

The database for this study consists of a 3-D GPR data volume, outcrop sedimentology conducted on a 300-m-long cliff face, ten cores drilled behind the cliff to a depth of 11 m, 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 collected in the context of a larger project which also includes two 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.

GPR Data

The GPR reflection data were collected at the Raptor Ridge site in the summer of 2002 using a PulseEKKO IV system (manufactured by Sensors & Software, Inc.). The 3-D GPR data were acquired on two rectangular survey grids of 30 m × 80 m and 12 m × 12 m (Figures 1 and 5). The smaller GPR volume was acquired to delineate an individual concretion body embedded in the sandstone, whereas the larger volume was collected to image the depositional features; only the larger volume will be presented in this paper, which focuses on the bar-scale internal architectures and the distribution of concretions. The larger 3-D volume had 1-m GPR line spacing and 0.25 m trace spacing along each line; the lines run approximately parallel to the paleocurrent direction (Figure 5). A common-offset geometry with 3 m 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 ns and 0.8 ns, respectively, and traces were stacked 128 times at each survey point to improve the signal-to-noise ratio. A few common-midpoint gathers were also collected for velocity analysis.

During data acquisition, the console triggers the transmitter antenna to emit an elec-
trical wave into the subsurface. The energy is detected by a receiver antenna after being reflected from subsurface sedimentological features. The received signals are sent back to the console for digitization; they are then saved on a hard disk in a PC, which also displays the data in real time for quality control (cf. Davis and Annan, 1989).

Outcrop Sedimentology

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

Core 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 (#8 [10.9 m depth] and #9 [10.7 m depth]) within 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. The other 8 cores are used to constrain analysis of a 2-D GPR grid (which is not presented here).

GPS Topography

A topographic survey was performed by a global positioning system (GPS) to establish the absolute 3-D positions of all the data types, and topographic variations within a single coordinate system. The GPS topographic data were collected with a real-time kinematic (RTK) survey with a Leica GS500 at an interval of 2 m or less, depending on
the topographic features encountered. The horizontal error in the GPS topographic data was ±0.01-0.02 m. The vertical error is ±0.02-0.03 m.

GPR DATA PROCESSING

Preprocessing of the 3-D GPR data (Table 1) includes ’dewowing’, adjustment of time-zero, trace editing and elimination of air/direct waves which are caused by the high dielectric contrast between air and soil. The direct ground and air waves traveling between the GPR antennas may hide shallow reflections; these strong direct signals can be removed by subtracting the average amplitude, over the corresponding time window, from each GPR trace. The average amplitude level is determined over a user-specified time and trace window.

The average trace amplitude, after air/direct wave removal (Figure 6a), shows north-west to south-east trending linear anomalies (parallel to the survey lines) which are acquisition footprint artifacts (Cordsen, 2004; Brown, 2004) caused by antenna coupling changes from line to line. These undesired amplitude artifacts were effectively reduced by performing an amplitude balancing of the GPR traces in the 3-D data volume (Figure 6b).

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 travel times instead of ray-tracing, resulting in a significant reduction of the computation time. The migration used the topographic surface as the datum and so needs no elevation statics. An auto-gain control (AGC) is applied to the migrated profiles to compensate for attenuation to make the deeper parts of the images more visible for interpretation (Table 1). The GPR data, after the migration, are reformatted and imported into a commercial seismic interpretation software package. For the concretion calibration, the migrated GPR volume is used with no AGC, as instantaneous amplitudes are used.
This paper follows the facies architectural model suggested by Gani and Bhattacharya (2005) based on the outcrop study of the Raptor Ridge. The model consists of six basic facies-architectural elements: prodelta fines, frontal splay, storm sheet, tidally modulated deposit, channel and bar accretion. Their corresponding sedimentary facies are Facies 1 to 6, respectively in Figure 7 and are bounded by five orders of bounding surfaces (zero-to fourth-order). The fourth-order surfaces include regressive (RES) and transgressive erosional surfaces (TES). The top marine ravinement surface TES truncates lower order surfaces and erodes delta plain deposits; it is a regionally traceable surface strewn with granules and pebbles. The RES is the lowest boundary of the Raptor Ridge sandstones; it erodes pre-existing pro-delta sediments. The inherent resolution limitation (a quarter wavelength) allows 50 MHz GPR to detect no lower than third-order surfaces. Thus, the discussion of 3-D architectural elements will be limited to three (tidally modulated, channel, and bar accretion).

**GPR Facies Analysis**

Radar facies representing depositional environments were interpreted using reflection amplitude, continuity and configuration (Gawthorpe et al., 1993). For a more confident interpretation, we also integrate the sediment texture and architectures seen in the outcrop and the two sediment cores (#8 and #9). The calibration and correlation provide the crucial information to correctly identify the features which produce the radar reflections and to confirm the identity of the sedimentary structures detected in the subsurface. The GPR penetration was limited in most places from 10 m to 12 m depth, which is the depth to the top of the pro-delta mud deposits that are highly attenuating of the GPR waves.

Two distinct radar facies (RF1 and RF2) are recognized in this study (Table 2). RF1 is characterized by moderate-to-high amplitude and continuity reflections. The correspond-
ing radar facies shows ~E-W striking, repetitive, wide, subparallel reflection patterns on constant depth slices (Figure 8a). RF1 is subdivided into two subordinate radar facies, RF1a and RF1b.

RF1a consists of oblique, prograding reflection configurations at a (current, in situ) angle of about 5°, indicative of dipping delta-front foreset beds (Lee et al., 2005). The seaward dipping radar facies corresponds to a bar growth element. RF1b is characterized by (occasionally stepwise) low-angle (1-2°), subhorizontal, landward dipping reflectors. Facies RF1b can be interpreted to represent two different depositional facies of the delta-front bars [unless otherwise constrained by other evidence (Jol and Bristow, 2003)]: upstream accretion and/or tidal modulation of the mouth bars. These two facies can both produce landward-dipping bedding geometry but the depositional environments are different. While 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 crossbedding. Siegenthaler (1982) showed that herringbone crossbedding surfaces with less than a meter interval, separate the foreset beds of the 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 outcrop of the Raptor sandstones (Gani and Bhattacharya, 2005). Thus, RF1b would be more reasonably interpreted as the internal architecture of tidal sand bars.

RF2 (Table 2) is characterized by short, complex, irregular, low-to-high amplitude and continuity reflections, indicative of mud and sand beds (Beres and Haeni, 1991; van Heteren et al., 1998). The corresponding reflection configurations are irregularly oriented, mottled, or chaotic on depth slices (Figure 8b). RF2 is interpreted as laterally migrating channels with mud clasts developed on the pre-existing prodelta or on older bar deposits.
GPR Architectural Elements

Four GPR bounding surfaces (GBSs) were identified by tying stratigraphic boundaries from the cores to the GPR volume data (Figure 9). The GPR units (GUs) between these GPR boundaries are well correlated with the sedimentary records in the outcrop. The GPR boundaries and the GPR units are referred to as GBS1 to GBS4 and GU1 to GU3, respectively, from oldest to youngest. To generate the individual 3-D architectural units, the lithostratigraphic horizons picked within the GPR units were imported into GOCAD for 3-D visualization.

GPR Boundaries

The GPR boundaries are traceable through the whole 3-D volume (Figure 9) suggesting the interbar boundaries are substantially longer than the survey grid. Each GBS corresponds to a third- or fourth-order bounding surface. GBS1 correlates with a fourth-order surface (the RES), and is the most undulatory surface (with up to approximately 1.5 m of local relief). GBS2 and GBS3 correspond to third-order bounding surfaces between bar and channel facies. GBS2 exhibits similarity in relief to GBS1 whereas GBS3 is a planar-to-low relief surface. GBS4 correlates with a fourth-order surface (the TES) and is the uppermost surface that is seen throughout most of the GPR volume.

GPR Units and 3-D Facies Architecture

The three 3-D architectural elements (tidally modulated, channel and bar accretion) were extracted from the 3-D GPR volume. GU1, GU2, GU3 are composed of 1, 4 and 4 elements, respectively (Figure 10). GU1 is the lowest GPR unit but its radar facies is not clearly defined because of limited radar resolution. GU1 is bounded by GBS1 and GBS2 at its base and top, respectively. The thickness of unit GU1 ranges 0.5 m to 1.5 m, showing three east-west trending troughs. The structural lows are approximately parallel to the
strike, and perpendicular to the depositional dip. The southernmost trough contains a north-south oriented, scoop-shaped depression narrowing to the south.

GU1 is interpreted to represent an eroded composite bar with distal bar-growth elements (Figure 11) accumulated on a pre-existing mud layer; therefore, the unit probably is composed of RF1a. The structural depressions are interpreted to be formed by subsequent migrating channels; thus, the top boundary of GU1 is an erosional basal surface which is traceable through the 3-D GPR volume.

GU2 consists of four-stacked bodies (GU2a to GU2d, Figures 9 and 10) which are characterized by RF2. The thickness of GU2 ranges from 3.5 m to 5 m. Only portions of the four bodies are present within the 3-D GPR volume, so that their lateral dimensions are uncertain. GU2 is interpreted as channel-fill deposits accumulated by a series of channelizing events (channel elements) forming a four-storey channel succession. Each storey is separated by scour surfaces within the channel succession. Stratigraphically, the channel complex can start with either (or both) GU2a and GU2b. After initial erosion of the channels, they were filled with transported sands. These two lower channels may be a single channel unit depending on the extent of the next scouring event (the base of GU2c). The thicknesses of GU2c and GU2d compared with GU2a and GU2b suggest that the two upper channels were active in a relatively higher-energy condition. The scour and deposition events followed successively until the top channel fill (GU2d) formed a boundary between channel and bar-growth elements.

GU3 is the uppermost GPR unit and consists of four bodies (GU3a to GU3d, Figure 10). The bodies are characterized by RF1a except for GU3d which is a mixture of RF1a and RF1b. GU3 corresponds to proximal delta-front bar facies developed on the channel fills (Figure 11). The bar facies consists of two types of deposition. GU3a, GU3b and GU3c are interpreted to represent less tide-influenced mouth bars deposited by a unidirectional flow (i.e., river flow and ebb tide current) because their seaward dipping foresets (RF1a) are consistent through the 3-D GPR volume, allowing us to define the 3-D deltaic architectures. The sand bars are all larger than the 3-D survey grid. GU3d is interpreted as highly tide-
influenced mouth-bar deposits. Because of the complex GPR reflection patterns, it is difficult to identify distinct contacts (i.e., onlap, downlap and toplap) between the two types of mouth bars. Within GU3d, each radar facies is occasionally lapping the other, but a gradational transition dominantly occurs between them, both vertically and laterally. GU3d is a compound facies body containing the tidal mouth bars whose internal structures are highly modified by migrations of dunes and bars during bipolar tides (Willis, 2005).

After the lateral migration of the channel, the three sand bars were deposited at a tide-influenced river-delta front, followed by (or concurrently with) highly tide-influenced sand bar deposits during the high and low tides. The tidally modified deposits were dominant until subsequent transgression ravinement eroded the top of the deltaic deposit.

**OBSERVED DISTRIBUTION OF CALCITE CONCRETIONS**

**Calcite Concretions in Cliff Face and Sediment Cores**

Calcite cementation is a major diagenetic event at Raptor Ridge (Nyman et al., 2005). Cemented concretions were mapped along a 100-m-long outcrop in both the dip and strike directions (Figures 3 and 4). The cement is patchy, forming elongate, tabular concretions within the host sandstone. The pattern of the calcite cement is typical in sandstones (Walderhaug and Bjokum, 1992; McBride et al., 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.

There are differences in concretion sizes between the outcrop and the cores. The thickness of the concretions in the cliff face ranges from 0.2 m to 1.7 m, and they attain a maximum length of ~10 m; the thicknesses in the cores range from 0.02 m to 1.22 m.
These two types of measurement also show inconsistency in their average occurrence of concretions. In the outcrop, the channels contain less cements (5.5% in area) than the bar 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 1-D 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 sparsely distributed cores, however, are probably better constraints in estimating the percent volume of the concretions because they provide broader spatial sampling.

Petrophysical Analysis

The Raptor Ridge sandstones that contains the calcite-cemented concretions are feldspathic litharenites to lithic arkoses with an average composition of quartz (51%), feldspar (21%) and rock fragments (28%) (Nyman et al., 2005). 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 sub-angular to sub-rounded (Figure 12). The main components of the concretions are a low-magnesium, ferrous calcite.

The cemented sanstones exhibit very low permeability (0.01 md to 0.1 md) in both horizontal and vertical directions, as determined from Hassler cell measurements on the sediment cores (Figure 11). The mouth-bar sands show porosity ranging from less than 10% to 32% (Figure 12a) but near-zero porosity when calcite cements fill the intergranular pores (Figure 12b). 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).
3-D distribution of concretions is estimated by GPR attribute analysis in the following section.

**ESTIMATED DISTRIBUTION OF CALCITE CONCRETIONS**

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

**GPR Attribute Analysis**

The procedure consists of five steps (Figure 13): (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 a depth window for reflections corresponding to the concretions; (3) two GPR attributes, instantaneous amplitude (IA) and instantaneous wavenumber (IW) are plotted to quantify the behaviors of the concretions relative to the background sediments (Figure 14); (4) IA and IW ranges corresponding to the concretions in the GPR data are defined; (5) the criteria are applied to the GPR data volume to estimate the distribution of the concretions. The most important step is to identify the clusters (in the IA versus IW plane) that correspond to the known concretions in the cores and to use this calibration to estimate the concretion distribution throughout the 3-D GPR data volume. Four concretion clusters can be identified in the bars (Figure 14a), but the concretion data in the channels consist of only one identifiable cluster, superimposed or a random distribution (Figure 14b). For the purpose of concretion prediction in the channels, only the single cluster was used (Figure 14b).
Distribution of Predicted Concretions

There is a reasonable match between the predicted bodies and the corresponding concretions in the cores (Figure 15); 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 as there is little overlap between the cemented and uncemented sandstones (Figure 14a). 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 holes (Figure 15) 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 channels is very poor in the IA-IW plane (Figure 14b), so there is a high uncertainty associated with the corresponding individual predictions (although the volume percent is forced to be accurate via the calibration to the cores).

The 100 largest concretions in both the bar and channel facies are incorporated into a geological solid model (Figure 16a). The concretions occupy 14.8% of the volume of the bars and lie within 1.55 standard deviations of the cluster mean in IA and IW. The concretion distribution in the channels fills 10.7% of the channel volume and lies within 1.0 standard deviations of the cluster mean in IA and IW. These bounds were chosen to match the observed volume percent in the cores; they are not unique. The channels contain larger concretions than the bars do. A larger proportion of the volume of the concretions is contained in the larger concretions in the channels than the bars (Figure 17). The 19 largest concretions in the channels make up 80% of the total concretion volume; in the bars, it is the 39 largest concretions (Figure 17). The predicted concretions will be used as low permeability baffles in subsequent fluid flow simulations.

The overall predicted concretion pattern is fairly consistent with that observed in the cross-sections of the outcrop. The modeled concretions appears to be aggregately dis-
tributed in the bar and channel facies (Figure 16a). This distribution pattern is typical of calcite concretions in shallow marine sandstones (Bjorkum and Walderhaug, 1990). The estimated individual concretions indicate that each body has a growth pattern with no preferential orientation in both bar (Figure 16b) and channel (Figure 16c) facies. The geometry and spatial distribution is consistent with a detailed study of diagenesis at the Raptor Ridge (Nyman et al., 2005), suggesting that the concretions nucleate from carbonaceous mud clasts, but their growths do not always follow the traditional concentric center-to-margin pattern, resulting in a complicated aggregate pattern with irregularly oriented branches (McBride et al., 2003).

**SUMMARY**

GPR has been used to image the detailed internal structures of a top-truncated delta front in the topmost parasequence of the Wall Creek 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 m × 80 m 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 sediment cores within the grid. From the 3-D GPR data, GPR boundaries and 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 (GU) including nine facies architectural units.

3-D 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 (approximately perpendicular to the paleocurrent direction), proximal sand bars are deposited on the channel fills. The uppermost GPR unit (GU3) starts with N-S elongated mouth bars formed by unidirectional flow. The prograding sand bars coexist with tidally modulated bar deposits produced by bidirectional flows during high and low tides. The mixed 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 wavenumbers). Criteria for separation of cemented and non-cemented 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 14.8% of the bar volume and 10.7% of the channel volume. The overall estimated concretion pattern matches reasonably with that observed in the cliff face. The predicted spatial geometries suggest that 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 can be used as a framework for subsequent reservoir fluid flow modeling.

ACKNOWLEDGMENTS

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REFERENCES


### TABLE 1. GPR data processing steps applied to the GPR volume.

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>DESCRIPTION</th>
<th>EXAMPLE</th>
</tr>
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<tbody>
<tr>
<td>DEWOWING</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="Image" /></td>
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<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="Image" /></td>
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<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="Image" /></td>
</tr>
<tr>
<td>AIR/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/direct waves can be removed.</td>
<td><img src="image4.png" alt="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="Image" /></td>
</tr>
<tr>
<td>AUTO GAIN 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="Image" /></td>
</tr>
</tbody>
</table>
TABLE 2. GPR facies recognized in this study, and their geological interpretation.

<table>
<thead>
<tr>
<th>GPR FACIES</th>
<th>CHARACTERISTICS</th>
<th>EXAMPLE</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF1</td>
<td>Moderate-to-high amplitude and continuity reflections with low-angle (4-5°), seaward dipping clinoforms</td>
<td><img src="https://via.placeholder.com/150" alt="Example RF1a" /></td>
<td>Foreset beds of mouth bars at a delta front, formed during a delta progradation</td>
</tr>
<tr>
<td>RF1a</td>
<td>Moderate-to-high amplitude and continuity reflections with low-angle (1-2°), landward dipping clinoforms</td>
<td><img src="https://via.placeholder.com/150" alt="Example RF1b" /></td>
<td>Tidal modulation of mouth bars at a delta front, formed during tides</td>
</tr>
<tr>
<td>RF1b</td>
<td>Short, complex, irregular, low-to-high amplitude continuity reflections from multiple irregularly oriented reflection of varying lengths</td>
<td><img src="https://via.placeholder.com/150" alt="Example RF2" /></td>
<td>Laterally migrated distributary channels and associated channel fill</td>
</tr>
</tbody>
</table>
FIGURES

FIG. 1. The Raptor Ridge site is located near the west margin of the Powder River basin in east Central Wyoming in the United States. The lower panel shows the topography of the study area [with 20 ft (6.096 m) contour interval], the locations of the GPR survey grid, the boreholes and the photomosaics. Oil and gas fields are from the public domain website http://www.sdvc.uwyo.edu/clearinghouse/mineral.html.

FIG. 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. A-B. After Howell et al. (2003).

FIG. 3. Photomosaic of the cliff face in the depositional dip direction (a) and its bedding diagram (b) showing the alternation of southward dipping clinforms of the distributary mouth bars separated by laterally migrating channels. See Figure 1 for location. In (a), concretions are the reddish areas within the bar and channel sandstones.

FIG. 4. Photomosaic of the cliff face in the depositional strike direction (a) and its bedding diagram (b) showing the alternation of sub-horizontal bedsets of the distributary mouth bars separated by laterally migrating channels. See Figure 1 for location. In (a), concretions are the reddish areas within the bar and channel sandstones.

FIG. 5. Detailed map of the Raptor Ridge site showing the locations of the sedimentary cores and a 3-D survey grid. Paleocurrent direction measurements conducted on the topmost parasequence are indicated in the circle. See Figure 1 for location.

FIG. 6. Amplitude balancing removes the linear stripes in (a) that are artifacts of the data acquisition to produce a smoother distribution (b). The amplitude plotted as each survey location is the average absolute amplitude of trace at that location.
FIG. 7. A representative stratigraphic log showing sedimentary facies of the Raptor Ridge (Gani and Bhattacharya, 2005).

FIG. 8. Depth slice maps showing amplitude variation in the (a) bars and (b) channels.

FIG. 9. 3-D 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 ravine-ment surface (TES) is not shown, as the plot starts slightly deeper.

FIG. 10. A vertically separated 3-D GPR interpreted volume in Figure 9 showing nine facies architectural elements within the GPR units.

FIG. 11. Lithofacies of core #9 and the permeability profile showing a upward coarsening sequence of alternating bar and channel facies. Cemented concretions are indicated by near-zero permeability.

FIG. 12. Thin section photomicrographs of (a) uncedmented and (b) cemented sandstones (see Figure 6 for sample depths). The uncedmented 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%.

FIG. 13. Steps in the GPR attribute analysis for estimation of the distribution of the concretions within the 3-D GPR volume.

FIG. 14. Crossplot of the GPR attributes on which the criteria for the concretions were
built. The criteria were defined and applied separately to the bar (a) and the channel (b) portions of the GPR data volume.

FIG. 15. Correlation between concretions predicted from the 3-D GPR data (the green and yellow features) and those observed in the two cores #8 (a) and #9 (b). All the larger predicted concretions match with real concretions (the red zones) observed in the two cores.

FIG. 16. Predicted concretions incorporated into a geological solid model (a) and a 3-D transparent view of representative three concretions (the second, tenth and twentieth largest) lying in (b) the bars and in (c) the channels. Compare (a) with the cliff face concretion map in Figure 3b.

FIG. 17. Comparision of cumulative volume percentage of concretions in the bars and channels. Concretion bodies are ordered from largest to smallest.
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