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Abstract: Ground-penetrating-radar surveys were conducted on relict channel bars of the Meander River spillway north of High Level, Alberta. Advanced data processing (migration) was used to enhance the quality of ground-penetrating-radar images from the channel-bar deposits. These improvements aided subsequent data interpretation that was achieved through application of the principles of radar stratigraphy. Four radar facies and one radar package are described, representing vertical and downstream accretion elements of the channel-bar complexes. Vertical-accretion deposits formed from the deposition of gravelly bedload sheets are the most common strata. Cut-and-fill elements are relatively uncommon in the bar stratigraphy, suggesting relatively stable channels during bar development.

Résumé : Des levés au géoradar ont été exécutés sur des barres de chenal reliques du déversoir de la rivière Meander au nord de High Level (Alberta). Un traitement poussé des données (migration) a été appliqué afin d'améliorer la qualité des images des dépôts de barre de chenal acquises au géoradar. Ces améliorations ont facilité l'ultérieure interprétation des données fondée sur les principes de la stratigraphie radar. On décrit quatre faciès radar et un assemblage radar représentant des éléments d'accrétion suivant la verticale et vers l'aval des complexes de barre de chenal. Les dépôts d'accrétion suivant la verticale formés par dépôt de nappes graveleuses de la charge de fond constituent les strates les plus communes. Les petites structures de creusement-comblement sont relativement rares dans la stratigraphie des barres, ce qui suggère que les chenaux étaient relativement stables pendant la formation des barres.

INTRODUCTION

The sedimentology and stratigraphy of relict, high-energy fluvial deposits provide invaluable records of paleoenvironmental conditions in northern Alberta (cf. Smith and Fisher, 1993; Fisher et al., 1995). In particular, these deposits contribute to the understanding of former ice-sheet dynamics, sedimentary processes, and the characteristics of deglaciation. Whereas considerable research has been done on the high-energy fluvial sediments of the large Clearwater River–lower Athabasca River spillway channel in northeastern Alberta (Fisher, 1993; Smith and Fisher, 1993; Fisher and Smith, 1993; Fisher et al., 1995), little is known about similar deposits in northwestern Alberta, apart from those reported in aggregate resource assessments (e.g. Smith et al., 2005).

In this study, ground-penetrating radar (GPR) is applied to evaluate the sedimentology and stratigraphy of relict channel bars along a meltwater spillway formed from the breach and rapid drainage of glacial Lake Peace, north of High Level, Alberta. Ground-penetrating radar is a noninvasive geophysical technique based on the propagation and reflection of high-frequency electromagnetic (radar) waves. The principles behind GPR are well documented in the geological literature (Davis and Annan, 1989; Reynolds, 1997; Jol and Bristow, 2003). Digital GPR systems enable rapid acquisition of continuous, high-resolution data regarding the stratigraphy and internal structure of unconsolidated, sand-and-gravel-dominated sedimentary deposits.

Despite the obvious potential of GPR, the number of studies applying this technique to map the sedimentology and stratigraphy of relict, high-energy glaciofluvial deposits is limited (notable exceptions include Fisher et al. (1995), Jol et al. (1998), and McCuaig and Ricketts (2004)). Important sedimentological information, however, has been obtained from GPR data collected in fluvial environments (Gawthorpe et al., 1993; Best et al., 2003; Lunt and Bridge, 2004; Lunt et al., 2004; Wooldridge and Hickin, 2005; among others). This has been achieved despite a lack of advanced data processing such as migration. Migration is routinely applied in the processing of seismic-reflection data in order to remove effects caused by the curvature of the wavefront. Migrated seismic or radar profiles give a clearer and more realistic image of the form and orientation of the subsurface (Neal, 2004). Despite these advantages, migration is not routinely applied to radar data used in sedimentological studies (e.g. Fisher et al., 1995; Ekes and Hickin, 2001; Cassidy et al., 2003; McCuaig and Ricketts, 2004; Wooldridge and Hickin, 2005).

In light of the above statements, the aims of this paper are to assess the effects of migration on the interpretation of GPR profiles from a relict, high-energy fluvial deposit; and map sedimentary structures in the relict channel bars and thereby infer the geomorphological development of these landforms.

STUDY AREA

The study area is north of High Level, Alberta, along the Meander River (NTS 84 K and 84 N). The sites chosen for the GPR surveys include a pit located at the abandoned Meander River airstrip, currently being mined by Knelsen Sand and Gravel Ltd., and a pit north of the hamlet of Meander River, operated by Dechant Construction Ltd. (Fig. 1). The pits are located on relict channel bars. Several abandoned channels occur on the east side of the bars. The modern Meander River flows within a 500 m wide, slightly sinuous, spillway channel, referred to as the Meander River spillway (Mathews, 1980). At the confluence of the Meander and Hay rivers, the Hay River is captured by the Meander River spillway and flows north to Great Slave Lake in the Northwest Territories.

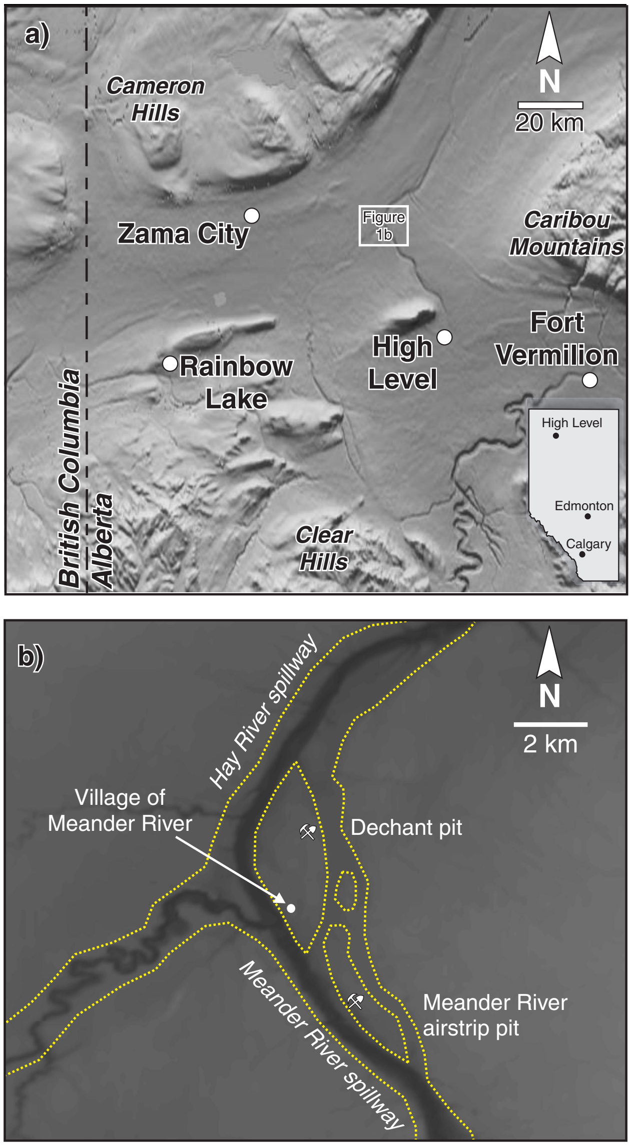

Figure 1. a) Location of study area north of High Level, Alberta. **b)** Locations of study sites (denoted by shovel and pick-axe symbol) with spillways, channels, and bars outlined in yellow.

This relict spillway channel is associated with the breach and rapid northward drainage of glacial Lake Peace (Mathews, 1980; Smith et al., 2005), as the Laurentide Ice Sheet margin retreated eastward from Mount Watt, about 11.5–11 ka BP (Lemmen et al., 1994; Dyke, 2004).

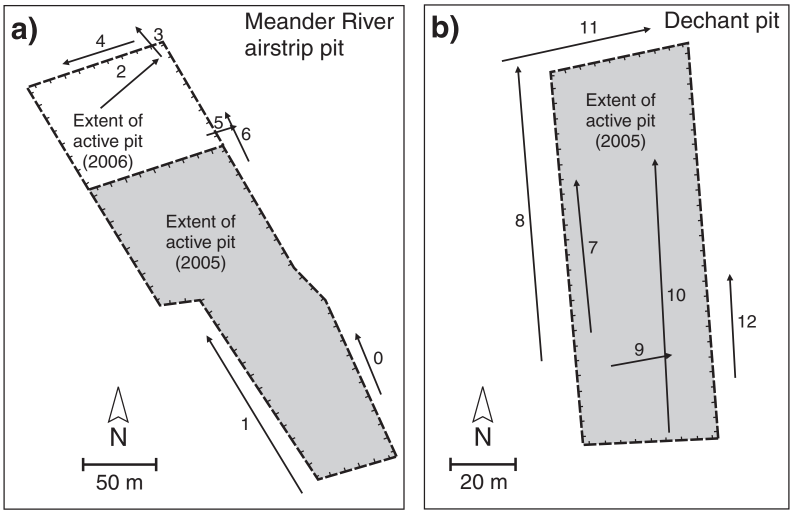

Figure 2. a) Locations of GPR profiles at each pit. **b)** The arrows denote orientation of each profile. Ground-penetrating-radar lines are numbered 0 to 12.

The Meander River airstrip pit, located on the west side of Highway 35 (Fig. 1b), has been mined extensively. The pit is located near the geometric mid-section of an elongate channel bar, which is about 5 km long and 0.7 km wide. The pit walls reveal glaciofluvial sediment that are poorly to moderately sorted, horizontally or irregularly bedded, and contain clast- and matrix-supported units. The lower beds (>3 m depth) tend to be clast-supported gravel and the upper sediments (<3 m depth) are generally matrix supported. Clast size ranges from granule to boulder gravel, with a sand or granule matrix. In the upper matrix-supported sediments, large cobbles to boulder-sized clasts have b-axes in excess of 0.3 m, suggesting entrainment under high flow velocity.

Extraction commenced in 2005 at the Dechant pit, which is about 7 km north of the Meander River airstrip pit (Fig. 1b). The Dechant pit is located on the eastern side of another large channel bar (7 km long and 2 km wide). Unlike the Meander River airstrip pit, the relatively small active area of the Dechant pit (~6000 m^2 in 2005) has not yet reached the base of the glaciofluvial deposit. The pit walls reveal poorly to well sorted glaciofluvial sediment, with horizontal to inclined bedding, which is either clast- or matrix-supported. Similar to Meander River airstrip pit, exposures reveal large cobbles to boulder-sized clasts with b-axes in excess of 0.3 m, although modal grain size is slightly smaller in the northern Dechant pit (Campbell, 2006).

METHODS

Ground-penetrating radar images the subsurface by sending pulses of electromagnetic energy into the ground, recording the strength and traveltime of subsurface reflections. The energy is reflected back from interfaces of materials having different dielectric properties. These differences are usually due to changes in water content, grain size, compaction, and cementation by oxidation and/or leaching. Ground-penetrating radar has been found to be most effective in electrically resistive materials such as sand and gravel, peat, ice, and limestone (Jol and Bristow, 2003).

The GPR surveys were conducted along thirteen transects in the two active gravel pits in 2005 and 2006 (Fig. 2). Twelve transects were surveyed in 2005 (lines 0–3, 5–12) and one was surveyed in 2006 (line 4). The majority of surveys were conducted along transects located outside of the active pits, within 10 m of the pit walls, which allowed for visual correlation between images observed in the GPR profiles and the features exposed in the walls. Three profiles were acquired along the floor of the active pits. New stratigraphy exposed by extraction activities at the Meander River airstrip pit in 2006 prompted an additional transect survey (line 4) along the northwest side. In all GPR surveys, the position of the beginning and end of the transects were determined with a Global Positioning System. Profiles were collected parallel to the meltwater channel with a south to north orientation, and perpendicular to the channel with an east to west orientation. A Sensors and Software Inc. Noggin Plus 250 MHz GPR was used. The reflections are recorded and displayed on a digital video logger (DVL), which provides real-time data quality control in the field. The Noggin system is a bistatic GPR that uses shielded antennas with a fixed spacing of 28 cm. During the surveys, traces were collected every 5 cm with 8 stacks per trace. Based on point-source reflections, a velocity of 0.11 m/ns was used to convert two-way traveltimes into depths for all thirteen profiles. This yielded penetration depths of up to 4 m with a vertical resolution of about 0.3 m.

Processing of the data involved standard techniques, including line stretching to account for slight inaccuracies in the trace spacing, low-frequency noise removal, filtering, automatic gain control (AGC) to enhance reflector amplitude at depth, and trace-to-trace averaging to remove horizontal distortions caused by the undulating surface. The data were migrated following the method of Stolt (1978) in order to adjust dipping reflections to an improved horizontal and vertical position. Migration removes structural distortions associated with undulating reflections and diffraction patterns. Migration parameters include velocity in metres per second, a spatial offset in metres, and a scaling factor. Values used in this study are 0.115 m/s, 0.3 m, and 0.5, respectively.

The GPR profiles were interpreted following radar stratigraphic principles. This involves the identification of reflection terminations or boundaries (Jol and Smith, 1991; Gawthorpe et al., 1993) to qualitatively classify different reflection patterns. The methodology follows that of Neal (2004) in order to identify and describe the main radar facies and radar packages. Radar facies are comprised of sets of reflections with distinctive shape, dip, and continuity that represent the bedding and internal structure of a sedimentary deposit. Radar packages are depositional units consisting of genetically related strata that are bounded on the top and bottom by radar or bounding surfaces. A qualitative scheme (i.e. high-, moderate-, and low-angle) was used to describe the relative dip of reflections since it is not known whether migration produced one-to-one correlation between dips of radar reflections and sedimentary deposits.

RESULTS AND INTERPRETATIONS

Migration

Migration resulted in a number of enhancements to the reflection profiles. For example, the unmigrated radar-reflection profile in Figure 3a shows a series of near-horizontal, laterally discontinuous, subparallel reflections extending to depths of up to 3 m. Migration of this profile (Fig. 3b) resulted in maintenance of the nearhorizontal attitude of the reflections, but with an increase in their continuity; and the collapse of diffractions, giving increased clarity to the image and revealing previously obscured primary reflections. Small diffractions in the unmigrated profile are believed to have been generated by small boulders (b-axes in excess of 0.3 m) in the upper part of the deposit acting as isolated reflection points.

A second example of the effects of migration is shown in Figures 3c and 3d. The unmigrated profile shows a complex arrangement of subhorizontal and dipping reflections and diffractions (Fig. 3c). Migration of the profile (Fig. 3d) resulted in the collapse of small diffractions and enhanced the clarity and continuity of reflections, revealing a more realistic image of the subsurface. In particular, migration improved the nature and position of a slightly undulating, subhorizontal reflection at 70 ns. The latter forms the base of the profile and is associated with a perched groundwater table. In this case, the perched groundwater table occurs above the gravel-till contact because the till has a high fines content (approximately 27% sand, 47% silt, and 26% clay). Migration also resulted in an increase of primary reflection continuity, a change in position (horizontal and vertical), and an increase in the dip of reflections.

Reflection characteristics and interpretations

Interpreted GPR profiles from each site are shown in Figures 4 and 5. Four radar facies were recognized in the channel-bar deposits on the basis of reflection configuration and continuity. One radar package was identified on the basis of the geometry of bounding surfaces. The various radar facies and radar package are interpreted to represent accretion elements of the channel-bar complexes. The GPR profiles show significant signal loss within 4 m of the surface. The groundwater table above the till was clearly resolved in three profiles located along the base of the Dechant pit (Fig. 5). It is noted that many profiles contain a reflectionpoor zone extending from the surface to approximately 1 m depth. The authors speculate that this zone corresponds to compaction from heavy mining equipment operating at the pits; therefore, this zone is not ascribed to a separate facies.

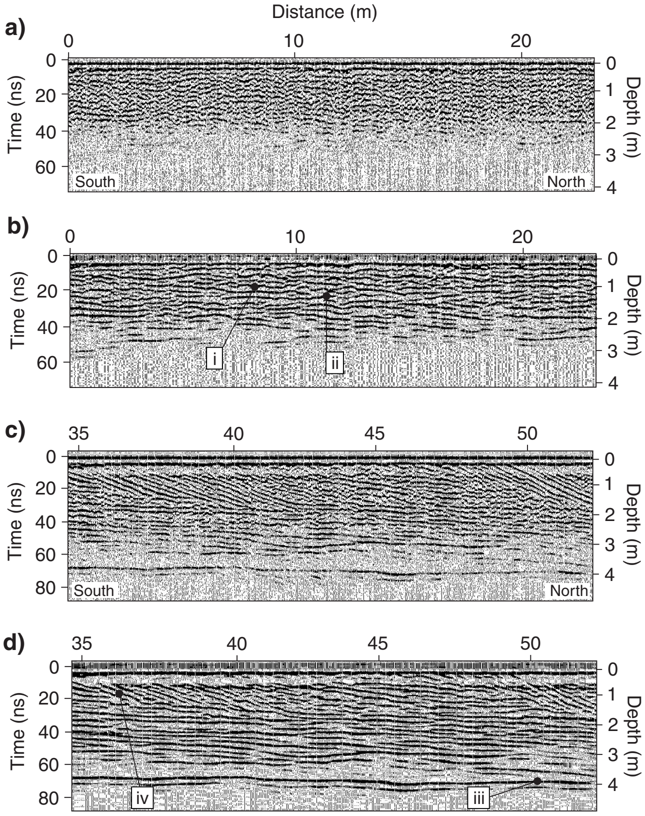

Figure 3. Examples of **a), c)** unmigrated and **b), d)** migrated radar profiles. Note the effect of migration: i, improved reflection continuity; ii, collapse of diffractions; iii, increased reflection amplitude; and iv, a change in reflection dip angle.

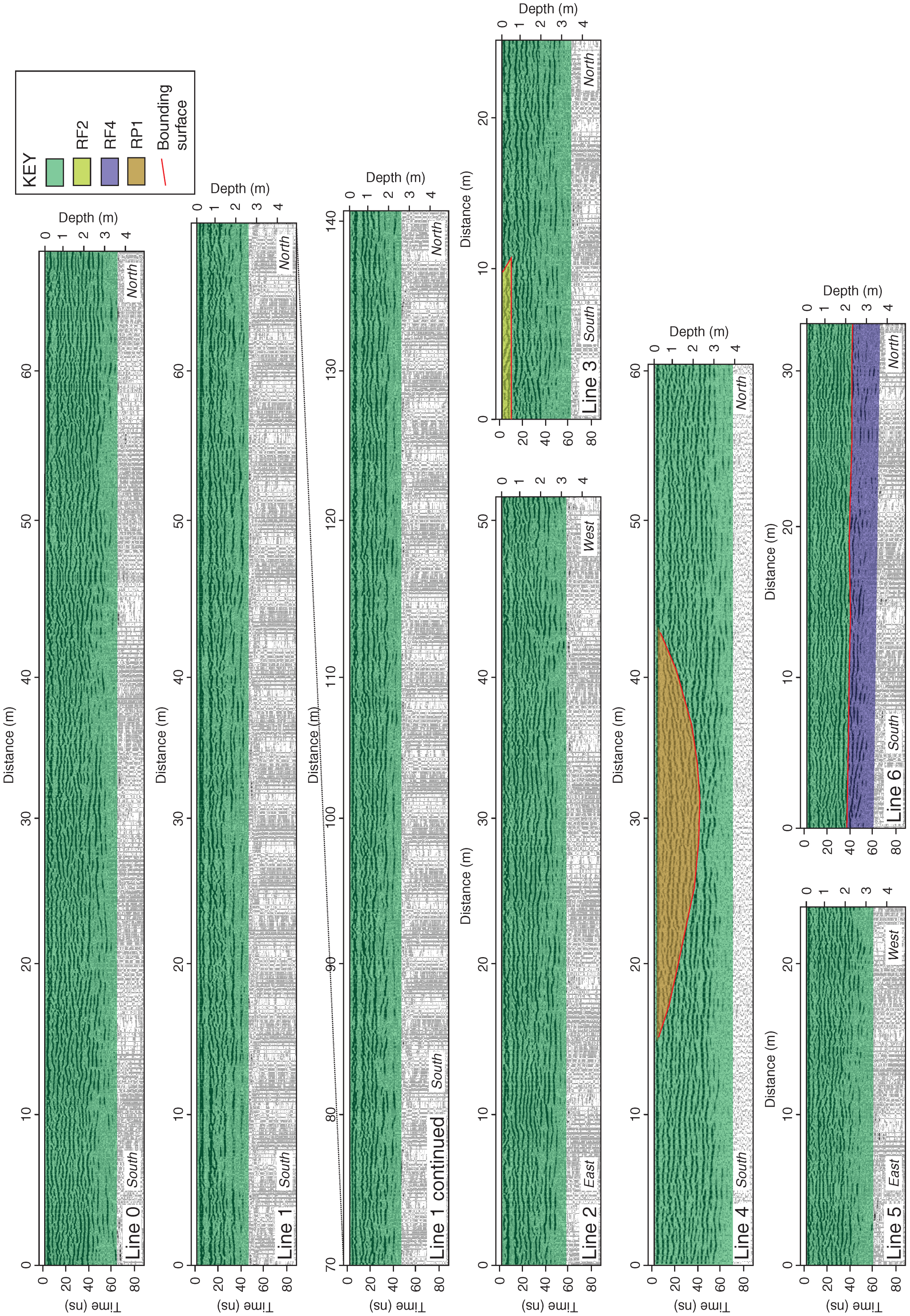

Figure 4. Ground-penetrating radar-profiles from the Meander River airstrip pit (*see* Fig. 2 for location and orientation of profiles). The radar facies (RF) and radar package (RP) are identified by different colours according to the key.

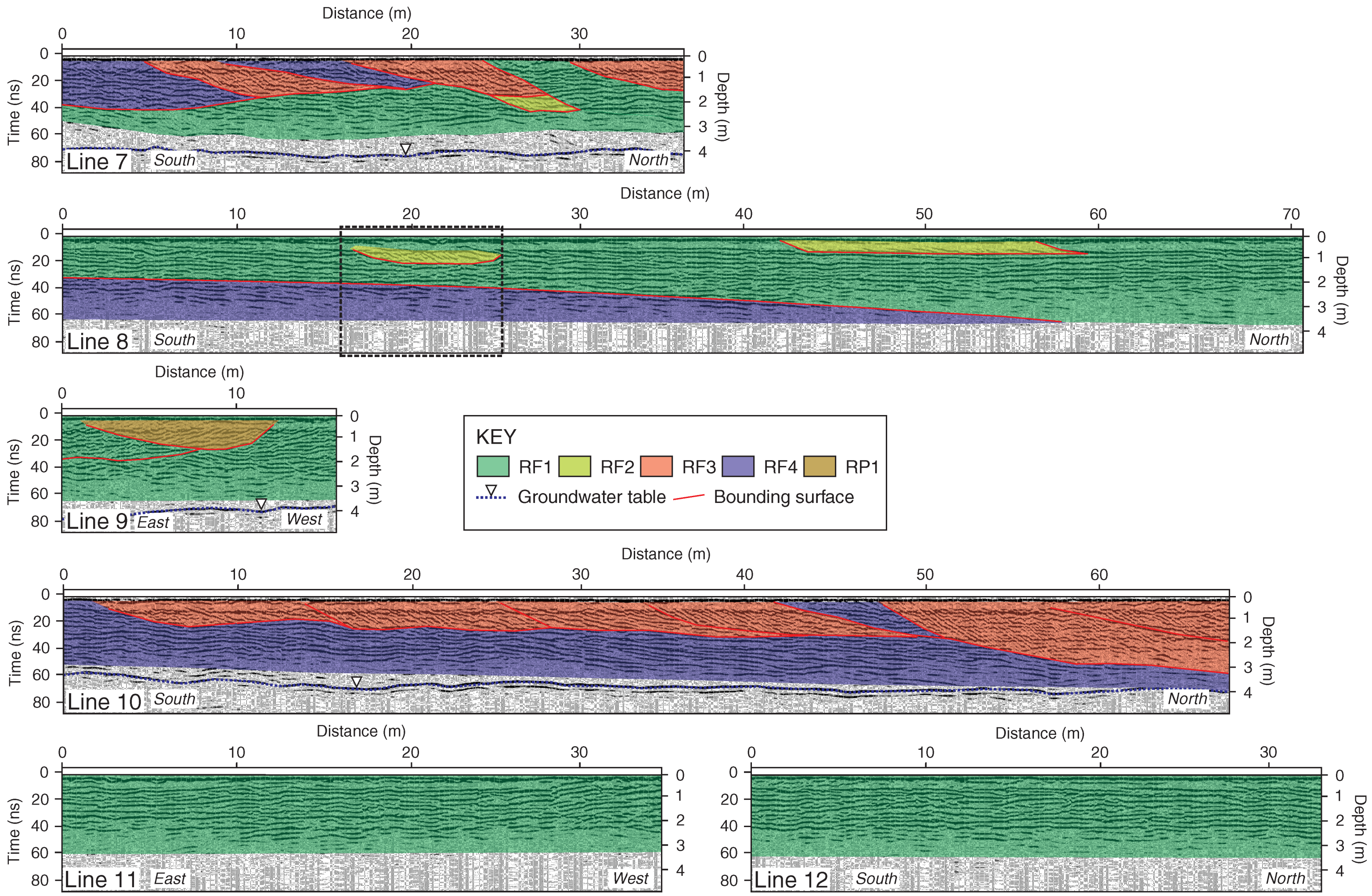

Figure 5. Ground-penetrating-radar profiles from the Dechant pit (*see* Fig. 2 for location and orientation of profiles). The radar facies (RF) and radar package (RP) are identified by different colours according to the key. Outlined area in line 8 corresponds to Figure 6.

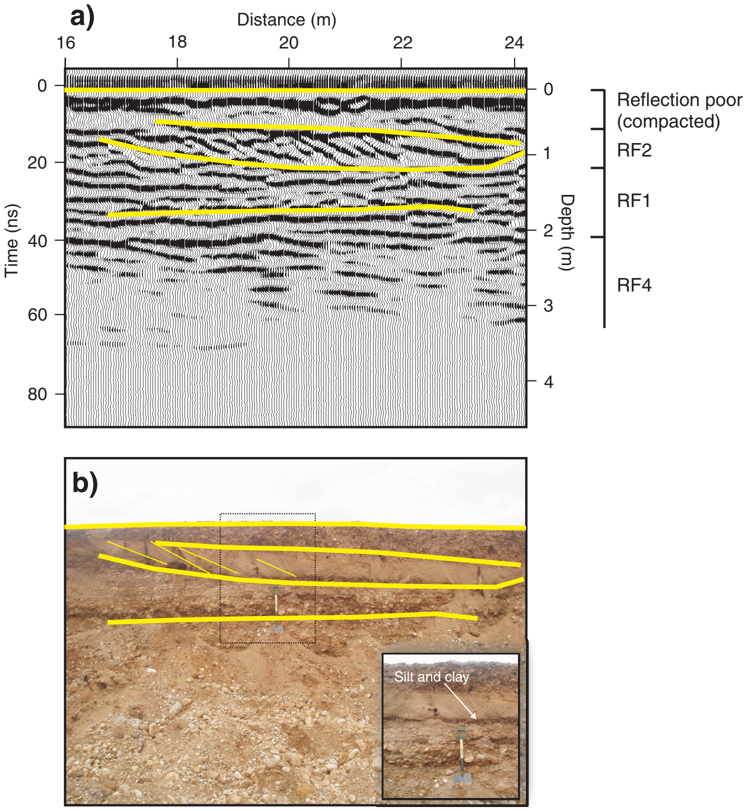

Figure 6. a) Section of GPR profile from line 8 (location given in Fig. 5) and **b)** corresponding sedimentary features (Dechant pit). Inset photograph in Figure 6b (location given by outline) shows silt and clay along lower bounding surface. Shovel in centre of inset photograph (1.1 m long) for scale.

Radar facies 1 (RF1): subhorizontal, discontinuous to moderately continuous, subparallel reflections

Radar facies 1 is the predominant facies (~90%) of the Meander River pits (Fig. 4, 5). It is characterized by stacked (1–4 m thick), subhorizontal, discontinuous to moderately continuous (2–20 m long), subparallel reflections. The reflection configuration is the same in both flow-parallel (e.g. Fig. 4, line 0; Fig. 5, line 8) and flow-normal (e.g. Fig. 4, line 2; Fig. 5, line 11) GPR profiles. Some of the reflections in this facies show a variety of subtle convexities and concavities that may be an effect of the slightly undulating ground surface over which the surveys were run.

Radar facies 1 is interpreted as vertical accretion deposits derived from bedload sheets deposited over bar surfaces. The subparallel nature of RF1 is probably due to the discontinuous nature of bedload deposition (Ashmore, 1991). Sheets are commonly preserved on bar-top surfaces because during falling stages, as discharge drops below the threshold of motion for coarse gravel, flows are not competent to rework the sediment, stranding the sheets on bar tops (Wooldridge and Hickin, 2005). Radar facies 1 dominates the stratigraphy in the upper 4 m at the Meander River airstrip pit because it likely represents the dominant process of deposition in the late stages of bar development along this segment of the Meander River spillway.

Radar facies 2 (RF2): small-scale (0.5–1.0 m), planar, steeply inclined reflections

Radar facies 2 is characterized by small-scale (0.5–1.0 m long), roughly parallel, planar, steeply inclined reflections. This facies is found in small packages (10–20 m long) that are bounded above and below by RF1, and is more commonly found in the upper few metres of the profiles. The underlying walls of the Dechant pit expose a package of sandy gravel with high-angle, north-dipping foresets overlain and underlain by RF1 (Fig. 6). The lower bounding surface of the sandy gravel package contains silt and clay, suggesting deposition in standing water.

Reflections defining the RF2 are interpreted as bedding derived from sandy gravel, bedload sheets deposited over bar surfaces during washover events. The dipping cross-strata are interpreted as a washover-delta deposit, based on comparison with similar deposits from sandy washover deltas examined by Schwartz (1982). These deposits may have developed in secondary channels or scour pools that incised the bar; therefore, the cross-strata may show a range of dip directions. The example in Figure 6 shows a thin (1 m thick) unit of RF 2 bounded above and below by matrix-supported gravel units of RF1. The smaller grain size of RF2 suggests deposition during low stages.

Radar facies 3 (RF3): medium-scale (1.0–3.0 m), planar, steeply inclined reflections

Radar facies 3 is characterized by medium-scale (1.0–3.0 m long), roughly parallel, planar, steeply inclined reflections. The facies is typically found in packages that are bounded by moderate- and high-angle bounding surfaces. In all occurrences, the facies overlies either RF1 or RF4. In some instances, RF3 shows a gradual thickening to the north (Fig. 5, line 10).

Radar facies 3 is interpreted as bar-margin slipface deposits associated with bedload sheets avalanching and passing over bar margins into deeper water at high-stage flows. Similar bar deposits have been imaged with GPR by Wooldridge and Hickin (2005). These deposits are typically oriented to the north. Wooldridge and Hickin (2005) speculated that changes in flow competency during bar formation causes the angle of this facies to vary, such that moderate- and high-angle bounding surfaces separate different sets of bar-margin slipface deposits.

Radar facies 4 (RF4): low-angle, moderately continuous, subparallel reflections

Radar facies 4 is characterized by low-angle, offlapping, moderately continuous, subparallel reflections (1–3 m thick, 5–15 m long) that dip northward. The facies is most common in profiles collected along the base of the Dechant pit and is overlain by RF3.

Radar facies 4 is interpreted as downstream- and lateral-accretion deposits in which bedload sheets are deposited on the downstream (Fig. 5, line 10) and lateral (Fig. 4, line 6) margins of bars. This facies documents the migration of bedload sheets over bar tops or along channel floors onto bar margins, causing barforms to aggrade and translate laterally and downstream. The moderately continuous and subparallel reflections suggest that sediment deposition is influenced by mean flow conditions depositing extensive sheet-like strata.

Radar package 1 (RP1): curved, concave-up reflections

Radar package 1 is characterized by a basal, curved, concave-up reflection that truncates adjacent reflections and is filled with a mix of subhorizontal and/or steeply inclined reflections. The package is 10–30 m long, about 1–3 m thick, with concave-up edges that dip gently into the centre of the form. Only two examples of RP1 were found (Fig. 4, line 4; Fig. 5, line 9).

Radar package 1 is interpreted as scour and/or secondary channel fills (i.e. cut-and-fill elements) bounded by erosional concave-up channel edges (Fig. 5, line 9). The continuous, high-amplitude bounding reflections are erosional scours that have truncated the adjacent strata. The scours and/or secondary channels are filled by sediments that show changes in dip angle, which is a consequence of the unsteady process of material avalanching into these depressions. The infrequent occurrence of RP1 at both pits suggests that secondary channels or scours were either relatively uncommon or rarely preserved in the stratigraphy. This package only occurs in the upper portion of RF1.

DISCUSSION AND CONCLUSIONS

Ground-penetrating radar can provide unique perspectives into the stratigraphy and internal sedimentary structure of unconsolidated, sand-and-gravel-dominated, sedimentary deposits; however, the data-processing steps can significantly influence the output and sedimentological interpretation of GPR profiles (Woodward et al., 2003). Although there are many common approaches to data processing (Jol and Bristow, 2003), a literature review reveals that migration (a form of data processing) is not routinely applied to GPR data gathered in high-energy fluvial deposits (e.g. Fisher et al., 1995; Ekes and Hickin, 2001; Cassidy et al., 2003; McCuaig and Ricketts, 2004; Wooldridge and Hickin, 2005). This study demonstrates that migration can significantly improve the quality and clarity of reflections in radar data derived from such deposits, thereby contributing to more realistic sedimentological and geomorphological interpretations. Migration restores dipping reflections to an improved horizontal and vertical position, it removes diffractions associated with point reflectors or complex undulating reflectors, and it also removes geometric distortions imparted on undulating reflections. Particularly in situations where the principles of radar stratigraphy are applied, migration contributes significantly to the overall interpretation of radar facies, surfaces, and packages. One important drawback of migration, however, is that it often removes diffractions, which can be useful for identifying large boulders in the deposit, thereby contributing to the sedimentological and geomorphological interpretation of the former depositional setting. Thus, in some cases, it may be useful to investigate deposits with a combination of migrated and unmigrated GPR data.

The principles of radar stratigraphy were successfully used to interpret the radar reflection profiles acquired in gravel pits along the Meander River spillway. The GPR profiles reveal a variety of radar facies that represent vertical and downstream accretion elements of the channel-bar complexes. The most common radar facies (RF1) is characterized by subhorizontal, discontinuous to moderately continuous, subparallel reflections. This reflection configuration is interpreted as vertical accretion deposits derived from bedload sheets deposited over bar surfaces. Lunt et al. (2004) and Wooldridge and Hickin (2005) have imaged similar deposits with GPR in modern deposits of gravel-bed rivers. Many deposits of ancient and modern braiding rivers also exhibit horizontal, parallel strata, indicating the important contribution of bedload sheets to bar development (Smith, 1974; Hein and Walker, 1977; Ramos and Sopena, 1983).

Based on the GPR data collected in the Meander River gravel pits, it appears that the stratigraphy generally lacks cut-and-fill elements (also confirmed by observations of pit-wall exposures), which suggests that the channels and bar surfaces were relatively stable during bar development. This contrasts with most gravelly braid-river deposits where frequent bar migration and flow bifurication form numerous channels and scours, which are preserved as channel fills in the sedimentary record (Ashmore, 1991; Heinz and Aigner, 2003; Lunt and Bridge, 2004). Accordingly, the relict channel bars along the Meander River spillway appear to have sedimentary structures more commonly associated with wandering river deposits (Wooldridge and Hickin, 2005) than braid-river deposits (Lunt and Bridge, 2004). The former generally lack significant cut-and-fill elements owing to the stability of channels.

An important contribution of GPR in sedimentological studies is its ability to discriminate grain-size variations within a deposit. Such information is useful for identifying changes in flow hydraulics and sediment supply conditions. Fisher et al. (1995) demonstrated the application of GPR for discriminating facies boundaries in catastrophic flood deposits near Fort McMurray, Alberta, where the range of grain sizes is large. In Newfoundland and Labrador, McCuaig and Ricketts (2004) used GPR to identify the presence or absence of large boulders in glaciofluvial deposits, but were unable to discriminate between sand and gravel. According to the GPR profiles collected in this study, there is no clear discrimination of grain-size variation in the few examples where pit wall exposures were correlated to GPR data (e.g. Fig. 6). Thus, similar to results by McCuaig and Ricketts (2004), the GPR profiles do not provide a means of clearly discriminating between mixed sand and gravel deposits. Thus, backhoe test pits are still needed to provide information of grain-size variations within the deposits.

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