An introduction to ground penetrating radar (GPR) in sediments

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Introduction

In sedimentary geology, ground penetrating radar (GPR) is used primarily for stratigraphic studies where near-continuous, high-resolution profiles aid in determining: (1) stratigraphic architecture, (2) sand-body geometry, and (3) correlation and quantification of sedimentary structures. In the past, to investigate lateral continuity and variability of sediments, we had to infer the correlation between boreholes, outcrops or shallow trenches. Nowadays, with suitable ground conditions (sediment with high resistivity, e.g. sands and gravels), we can collect GPR profiles that show the subsurface stratigraphy. In addition, 3-D GPR can provide much greater appreciation of sand-body geometry and architecture. GPR is, however, not a universal panacea; in some cases, ground truth is still required because lithological determination is by no means unequivocal, therefore borehole or outcrop data may be required to corroborate the results of a GPR survey. Indeed, the latest GPR survey data, including 3-D depth migration, required both boreholes and outcrop data to generate a 3-D velocity model (e.g. Corbeanu *et al.* 2001). In addition, fine-grained sediments (low resistivity) and areas with saline groundwaters cause rapid attenuation of the radar signal, leading to poor signal penetration.

This book begins with an introductory paper (Jol & Bristow 2003) aimed at those with little or no experience of GPR and including the basics of data collection, processing and interpretation. The book is then divided into sections on sedimentary environments, including aeolian and coastal, fluvial and alluvial fan, glacial, and lakes; ancient sediments (reservoir analogues); tectonics; and engineering and environmental applications. The final section looks at various aspects of GPR methodology. The chapters all provide case studies from a range of sedimentary environments in Europe, North America and South Africa. This introductory paper attempts to place the papers in this volume in context with the literature and to highlight some areas for further investigation in the future; it is not intended to be an exhaustive literature review.

In compiling the volume we asked authors to follow a few conventions, including the use of: (1) GPR profiles or GPR images instead of radargrams; (2) the term 'reflection(s)' when describing GPR profiles (reflectors are the subsurface interfaces where reflections are generated); and (3) objective stratigraphic terminology to describe the reflection patterns (oblique, continuous) when initially interpreting a GPR profile – once completed, more interpretative terminology can be used, keeping the interpretation separate from the description.

GPR in sediments

In the late 1980s and early 1990s a series of papers showed the potential of GPR as a tool for imaging the shallow subsurface. Papers by Jol and Smith (1991, 1992*a*, *b*) and Smith and Jol (1992*a*, *b*), clearly demonstrated the potential of GPR, with outstanding profiles within lacustrine deltaic environments. Around the same time, important papers by Davis and Annan (1989), Beres and Haeni (1991) and Gawthorpe *et al.* (1993) laid down the procedures for GPR surveys and interpretation. These were followed by tests of the penetration and resolution of GPR in sediments (Jol 1995; Smith & Jol 1995*a*). Early GPR surveys were often tied to outcrop observations or trenched sections in order to verify the results of the geophysics (e.g. Smith & Jol 1992*a*; Huggenberger 1993; Bristow 1994; Bristow *et al.* 1996). While early comparisons between GPR profiles and outcrop sections were largely qualitative, more recent outcrop analysis has been more quantitative, aiming to determine the causes of GPR reflections (van Dam & Schlager 2000) and constrain velocity pro-

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files for 3-D depth migration and improved interpretation (Corbeanu *et al.* 2001).

Aeolian and coastal environments

The high resistivity of aeolian sands gives good GPR penetration (>10 m), and the large sedimentary structures within dune sands can be clearly imaged on GPR profiles (Harari 1996; Bristow *et al.* 1996, 2000*a*, *b*; Jol *et al.* 1998), making them suitable targets for GPR surveys. GPR profiles image cross-stratification and bounding surfaces in dunes, revealing their internal structure and relative chronology. In this volume, two papers, Botha *et al.* (2003) and Havholm *et al.* (2003), describe parabolic dunes. In comparison with other GPR surveys of aeolian sediments, the depth of penetration in the Lauder Sandhills described by Havholm *et al.* (2003) is rather limited: less than 5 m. This is attributed to signal attenuation by pedogenic silts, clays, and carbonate and iron oxides. Botha *et al.* (2003) use a combination of GPR and optical dating methods to investigate dune activity on the Maputaland coastal dunes in South Africa. Establishing the chronology of dune development is an important step toward understanding the forcing mechanisms (Bailey *et al.* 2001; Clemmensen *et al.* 2001) and this area of study is likely to expand.

Despite the proximity of the sea, and large volumes of conductive, saline water, GPR can work extremely well in coastal sediments if there is a freshwater aquifer. Leatherman (1987) reviewed potential applications for GPR in coastal sediments, while Neal and Roberts (2000) provide a good review of subsequent progress. GPR studies of spits and barrier beaches (Jol *et al.* 1996*a*; Van Heteren *et al.* 1996, 1998; Smith *et al.* 1999) and a prograding foreland (Neal & Roberts 2000) show good resolution of large-scale sedimentary structures from prograding shorefaces. Møller and Anthony (2003) use a combination of radar stratigraphy and radar facies to investigate the structure and stratigraphy of a Holocene barrier beach in Denmark. O'Neal and Dunn (2003) take a sequence-stratigraphic approach to the interpretation of GPR profiles. They use GPR to delineate three unconformity- bounded highstand units within the Quaternary Cape May Formation. The GPR profiles were also used to locate boreholes and pick sample locations for optically stimulated luminescence (OSL) dating. The structure and stratigraphy of coarse-gravel barrier-spit deposits from Lake Bonneville are described in Smith *et al.* (2003). They demonstrate the effectiveness of GPR in interpreting depositional sequences in coastal sediments, although associated fine-grained sediments, such as salt-marsh deposits, lead to high attenuation.

The use of GPR to define stratigraphy in coastal sediments, to identify stratigraphic horizons such as the transgressive ravinement surfaces identified by O'Neal and Dunn (2003), to develop a relative chronology, and to aid in picking sampling points for geochronological dating is predicted to increase in the future.

Fluvial and alluvial fan environments

There have probably been more GPR studies of river deposits than any other sedimentary environment because of the widespread distribution of river deposits, their ease of access and their importance as shallow aquifers. The variable style of fluvial systems, the heterolithic character of fluvial sediments, their large-scale depositional forms, such as point bars, combined with fresh water, make river deposits particularly suitable for investigation by GPR. The resulting studies have led to significant GPR papers, including those by Beres and Haeni (1991), Gawthorpe *et al.* (1993), Huggenberger (1993) and Beres *et al.* (1995). Woodward *et al.* (2003) use examples of GPR profiles from the South Saskatchewan, a sand-bed braided river in Canada, to illustrate data collection and processing. The ability of GPR to image and characterize the geometry and facies of fluvial sediments in both 2-D and 3-D has proved important for hydrogeologists (Beres & Haeni 1991; Huggenberger *et al.* 1994; Beres *et al.* 1995). The characterization of alluvial aquifers for hydrogeological studies using GPR will continue, as will GPR investigations of fluvial sediments to provide information on fluvial stratigraphy and sedimentary architecture (Heinz & Aigner 2003). Heinz and Aigner (2003) use 3-D GPR surveys to identify the geometry and stacking patterns of three architectural styles in outwash gravels.

In this volume, there are two papers that use GPR profiles to describe and interpret alluvial fan deposits. Ekes and Friel (2003) suggest that GPR can be used to assess the evolution of an alluvial fan sequence and, in conjunction with geochronological data, the return frequency of the formative processes, in their case debris flows and floods. This information is useful in understanding alluvial fan evolution and hazard assessment, although they report some difficulty in distinguishing between debris flow and sheetflood facies on the GPR profiles. Roberts *et al.* (2003) describe radar facies within Holocene fan-delta deposits in Canada and use radar facies to identify beach deposits within the fan delta. They suggest that the preservation of beach deposits within the delta sequence is indicative of a macrotidal setting, while accommodation space, water depth and sediment supply are important in determining fan-delta architecture.

Glacial environments

GPR has been used to investigate coarser-grained glacial and glaciofluvial deposits in Europe, Canada and the USA (Ulriksen 1982; Sutinen 1992; Beres *et al.* 1995; Fisher *et al.* 1995; Jol *et al.* 1996*c*). In this volume, fluvioglacial outwash of the 1996 Jokulhlaup deposits at Skeiðarársandur in Iceland are described by Cassidy *et al.* 2003). They combine GPR profiles with outcrop observations and published descriptions to interpret the depositional chronology. They recognize three distinct areas of deposition (icewall canyon, proximal outwash fan, distal outwash fan) and four stages of deposition (early rising stage, rising/peak stage, waning stage and post-flood stage). They suggest future applications of their model in bedrock fluvial systems and alluvial-fan feeder systems. Degenhardt *et al.* (2003) use GPR to investigate the structure of a rock glacier; layers within the glacier are interpreted as flow lobes, indicating that the glacier is a composite feature.

Bakker and van der Meer (2003) show GPR profiles through a glaciotectonic push moraine in the Netherlands. The profiles show imbricate thrusts in the proximal area passing into a fold-and-thrust belt, with the fold wavelength increasing in the distal area. They use this as evidence for deformation during one glaciotectonic event. The good penetration (up to 45 m) and continuity of reflections is attributed to the nature of the deformed sediments, which are largely fluvioglacial outwash gravels. Tills with a high clay matrix content are likely to have a much higher attenuation, reducing the depth of penetration. Leopold and Völkel (2003) use GPR to help resolve a stratigraphic problem in Late Pleistocene to Early Holocene slope deposits that are locally covered by peat. Their GPR profiles show a variety of reflection patterns within the peat and good examples of onlapping relationships at the base of the peat.

Lakes

Freshwater lakes are resistive and can therefore be penetrated by GPR where radar can be used for sub-bottom profiling and to investigate water depth and the thickness and extent of sediments (Haeni 1996; Moorman & Michel 1997). Hunter *et al.* (2003*b*) made a GPR survey of a reservoir when it was frozen over in winter, which improved access and the speed of data collection. They use GPR to assess recent sediment deposition in the reservoir and the thickness of sediment above bedrock. Sediment accumulation rates are calculated from comparison with earlier bathymetric surveys. The sediment thickness data are used to constrain potential dredging depths while the sediment accumulation rates are used to evaluate sediment trap design.

Lake deltas have been studied by Jol and Smith (1991) and by Smith and Jol (1992*a*, *b*, 1997), where large-scale foresets in coarse-grained sediments provide exceptionally good sites for GPR. In this volume, Smith *et al.* (2003) describe the internal structure of coarse-grained barrier and spit deposits that formed in Lake Bonneville, while large-scale foresets from a Lake Bonneville delta provide the test site for an evaluation of reflection characteristics from repetitive layers (Kruse & Jol 2003).

Ancient sediments: reservoir analogues

GPR datasets (2-D and 3-D) collected from outcrops are used as analogues for hydrocarbon reservoirs. This data can also be used to provide both qualitative and quantitative data for petroleum and hydrogeology reservoir modelling (Thompson *et al.* 1995; Jol *et al.* 1996*b*; Corbeanu *et al.* 2001). In Pringle *et al.* (2003*a*), outcrop sedimentary and topographic data are combined with GPR to produce a 3-D model of turbidite channel deposits. The aims of the study are to complement conventional outcrop data and improve the data available for hydrocarbon-reservoir modelling and the results include a quantitative 3-D volumetric model suitable for hydrocarbon-reservoir modelling. Pringle *et al.* (2003*b*) use vertical radar profiles (VRP) to provide time-depth calibration for radar profiles, which improves correlation of reflection events with observed lithological horizons in sedimentary rocks. They include examples from Ordovician and Carboniferous turbidite sequences and Tertiary fluvial sandstones, with impressive resolution at 65 m depth in the Carboniferous rocks.

The literature on GPR in carbonates appears to be rather sparse, with carbonate sedimentologists lagging behind their clastic colleagues in applying GPR to limestones or carbonate sediments. There is clearly a practical problem with operating GPR in many modern carbonate environments because of the attenuation caused by saline waters. However, limestone is highly resistive and should have good potential based on several studies that have been undertaken (Pratt & Miall 1993; Liner & Liner 1995; Sigurdsson & Overgaard 1998; Dagallier *et al.* 2000). Pedley *et al.* (2000) and Pedley and Hill (2003) show that GPR can be used to investigate tufas with different lithologies, giving distinct radar reflections. Pedley and Hill (2003) use this information to investigate paludal tufas, and discriminate between line-sourced tufas and point-sourced mound tufa deposits. In addition to characterizing carbonate deposits, GPR should be used for void detection in limestones and could be used to investigate caverns and sink holes in karst terrain.

Tectonics

GPR has been used for imaging faults in the subsurface with varying degrees of success (Bilham & Seeber 1995; Smith & Jol 1995*b*). Reiss *et al.* (2003) describe faulted alluvial and colluvial sediments in northeastern Spain, southern Spain and Sicily. They show that normal faults can be mapped using GPR and suggest that GPR should be used as a pretrenching tool in palaeoseismic investigations. In addition, they suggest that quantitative evaluation of high-resolution GPR profiles could be used to trace fault segments along strike, assess changes in displacement along faults and possibly to balance sections. It is clear that, given appropriate lithologies, GPR surveys in both 2-D and 3-D should see increased applications in fault analysis and the reconstruction of faulting history, including the manner and size of fault displacements and their relative chronology.

Engineering and environmental applications

GPR is probably most widely used in environmental and engineering field applications, ranging from the detection of reinforcing rods in concrete to water leaks and contamination (see Reynolds 1997 and references therein). In this volume, Hendrickx *et al.* (2003) present a study with a different application in landmine detection. They test GPR performance in wet and dry conditions and illustrate some of the problems associated with using GPR to detect non-metallic landmines. Hunter *et al.* (2003*a*) test the ability of GPR to detect hydrocarbon contamination in permafrost areas. They show that bulk electrical properties (velocity and attenuation) vary systematically between frozen and unfrozen materials. They also show that, where petroleum contamination is pervasive, there is a decrease in attenuation.

GPR methodology

As the use of GPR in the sediments field matures, more technical studies in GPR methodology are being pursued. For example, van Dam *et al.* (2003) make a detailed assessment of the factors that produce reflections in sediments, in particular the thin layers of cross-stratification which are beneath the normally expected scale of resolution ($\lambda/4$). Using synthetic radar traces and impedance models of thin layers, van Dam *et al.* (2003) show that reflections from subcentimetre-scale structures are composites of interfering signals and that there are 'tuning effects' which can occur, giving reflections that vary with radar frequency. This paper follows earlier investigations of the influence of iron oxides (van Dam *et al.* 2002*a*), organics (van Dam *et al.* 2002*b*) and sediment character (van Dam & Schlager, 2000). They conclude that changes in water content associated with small-scale textural changes in sediments are responsible for the changes in dielectric properties that produce radar reflections. Kruse and Jol (2003) use observed relative amplitudes of GPR reflections from dipping delta foreset beds to constrain the permittivity contrasts associated with layers of sediments. They also investigate the difference between thick and thin beds. They show that finite-difference time-domain (FDTD) modelling of GPR data can help to constrain the variability and scaling of electromagnetic properties. Lutz *et al.* (2003) show that GPR data collected with the antennae parallel and perpendicular can be combined to improve the quality of a GPR profile. They advocate the use of a quadripole survey with two transmitters and two receivers. Further field and laboratory studies of GPR in sediments and the effects of changes in material properties are likely to follow. The use of synthetic GPR profiles to model the signal response is likely to increase and help constrain GPR profile interpretation in the future.

Conclusions

The application of GPR in sediments is expanding rapidly because GPR provides high-resolution images of the shallow subsurface that cannot be derived by any other non-destructive method. The use of GPR has gone beyond characterizing environments by reflection patterns and radar facies and is moving into a more quantitative assessment of sand-body geometry and architecture. GPR has great potential in the selection of borehole locations and picking sample points for geotechnical, stratigraphic and geochronological studies. The use of GPR in imaging shallow stratigraphy should lead to significant advances in Quaternary stratigraphy, geohazards research, the hydrogeology of shallow aquifers and contamination. This volume includes some innovative applications of GPR in sediments, including vertical radar profiles, borehole radar and imaging sedimentary fill beneath a frozen lake. The use of GPR to tackle specific and sometimes longstanding stratigraphic problems is likely to increase, as is the use of true 3-D GPR surveys. Further work is required to constrain the identification of buried objects and subsurface lithology.

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