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Electrical resistivity ground imaging (ERGI): a new tool for mapping the lithology and geometry of channel-belts and valley-fills

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ABSTRACT

Efforts to map the lithology and geometry of sand and gravel channel-belts and valley-fills are limited by an inability to easily obtain information about the shallow subsurface. Until recently, boreholes were the only method available to obtain this information; however, borehole programmes are costly, time consuming and always leave in doubt the stratigraphic connection between and beyond the boreholes. Although standard shallow geophysical techniques such as ground-penetrating radar (GPR) and shallow seismic can rapidly obtain subsurface data with high horizontal resolution, they only function well under select conditions. Electrical resistivity ground imaging (ERGI) is a recently developed shallow geophysical technique that rapidly produces high-resolution profiles of the shallow subsurface under most field conditions. ERGI uses measurements of the ground's resistance to an electrical current to develop a two-dimensional model of the shallow subsurface (<200 m) called an ERGI profile. ERGI measurements work equally well in resistive sediments ('clean' sand and gravel) and in conductive sediments (silt and clay). This paper tests the effectiveness of ERGI in mapping the lithology and geometry of buried fluvial deposits. ERGI surveys are presented from two channel-fills and two valley-fills. ERGI profiles are compared with lithostratigraphic profiles from borehole logs, sediment cores, wireline logs or GPR. Depth, width and lithology of sand and gravel channel-fills and adjacent sediments can be accurately detected and delineated from the ERGI profiles, even when buried beneath 1–20 m of silt/clay.

Keywords Channel-belts, channel-fills, electrical resistivity, fluvial sediments, shallow geophysics, valley-fills.

INTRODUCTION

Geomorphologists, sedimentologists, stratigraphers, surficial geologists and Quaternary researchers map the lithology and geometry of sand and gravel channel and valley-fills because these deposits are often: (1) economically significant groundwater and hydrocarbon reservoirs; (2) sources of economic placer deposits (e.g. gold, tin, diamonds); (3) sources of construction aggregate; and (4) modern analogues of ancient deposits (invaluable to exploration geologists and reservoir engineers) (Miall, 1996). Previously, researchers relied on drill core, trenches and sediment exposures to map subsurface lithologies and their geometries. Although drill core accurately represents vertical facies changes and stratigraphy in a single dimension, lateral facies changes are not available without extensive

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coring programmes. Recently, shallow geophysical methods, such as ground-penetrating radar (GPR), have been used as an alternative to coring to obtain vertical and horizontal sedimentological information about the shallow subsurface quickly and economically (<200 m).

Although GPR can quickly and economically obtain such information about the shallow subsurface, it is limited to 'clean' sand and gravel exposed at the surface and is unable to detect channel-fills or valley-fills beneath even thin layers (>1 cm) of silt or clay (Moorman, 1990; Reynolds, 1997). New tools are required that can image channel-fills and valley-fills under a wider variety of conditions. Electrical resistivity ground imaging (ERGI) may be one such tool. Although ERGI has found limited application in sedimentology, stratigraphy, Quaternary studies and geomorphology, it has been more widely used in geohydrology and environmental consulting, where it is commonly referred to as electrical resistivity tomography (ERT; e.g. Maillol *et al.*, 1999; Daily & Ramirez, 2000; El-Behiry & Hanafy, 2000). The term ERGI is used in this paper, rather than ERT, because measurements used here are from the ground surface, whereas ERT commonly involves measurements from borehole to borehole or from borehole to surface.

The objective here is to demonstrate that ERGI can quickly and economically obtain vertical and horizontal sedimentological information about the shallow subsurface under most conditions. This paper assesses ERGI's ability to map the geometry and lithology of sand and gravel channel-fills and valley-fills, even when buried in silt and clay.

Four different fluvial settings were selected for field experiments: (1) an anastomosing river channel-fill in the upper Columbia River, British Columbia, Canada; (2) a buried Holocene channel-fill and underlying Pleistocene braid-plain succession in the Rhine–Meuse delta, The Netherlands; (3) a late Pleistocene valley-fill near Yorkton, Saskatchewan, Canada; and (4) a Quaternary braid-plain (valley-fill) of the Yukon River, in the Yukon Flats of central Alaska, USA (Fig. 1).

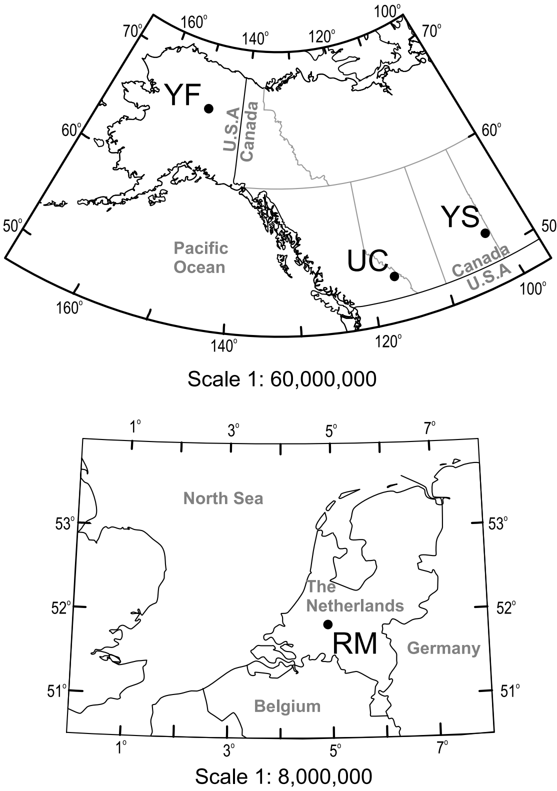

Fig. 1. Location of the four study sites in North America and Europe. UC, Upper Columbia River Beavertail channel-fill. RM, Rhine–Meuse delta Schoonrewoerd channel-belt and underlying braid-plain. YS, Yorkton, Saskatchewan valley-fill. YF, Yukon Flats braid-plain.

METHODS

ERGI involves introducing an electrical current into the ground with two electrodes and measuring the voltage drop across the surface of the ground with two other electrodes. Because electrical flow disperses throughout the ground, these surface measurements provide information about the electrical character of materials below the earth's surface. The primary control on the depth of investigation for a measurement is the distance between the electrodes. ERGI profiles are produced by modelling the data from a series of measurements with different depths and locations along a survey line (Reynolds, 1997).

ERGI is a recent evolution of an old technique. DC-Resistivity (direct current resistivity), the precursor to ERGI, requires manually moving the four electrodes for each measurement and using curve matching to interpret the data (Ward, 1990; Milsom, 1996; El-Hussain *et al.*, 2000). ERGI has evolved from significant improvements to data collection and interpretation. New computer-controlled multielectrode systems automatically collect large quantities of data without needing to move the electrodes (Griffiths *et al.*, 1990). New software uses two-dimensional finite difference or finite element inversion routines to produce two-dimensional models of the subsurface called ERGI profiles (Edwards, 1977; Beard *et al.*, 1996; Loke & Barker, 1996). Lastly, high-speed computers allow for rapid data processing and manipulation (e.g. topographic corrections; Tong & Yang, 1990). These improvements make data collection and processing quick, simple and inexpensive. They also make interpretation relatively straightforward and reliable (Loke, 2000a,b).

Although ERGI theory and methodology are amply explained elsewhere (Telford *et al.*, 1990; Ward, 1990; Reynolds, 1997; Loke, 2000a,b), two points should be addressed. First, the arrangement of the four electrodes used to make an individual resistivity measurement affects the measurement's depth of investigation, vertical and horizontal resolution and sensitivity to noise. Reynolds (1997) provided an excellent description of the strengths and weaknesses of the three commonly used electrode arrangements (arrays) for ERGI (Wenner, Schlumberger and dipole–dipole arrays). ERGI surveys can be conducted without fully understanding the differences between the electrode arrays and, for most ERGI surveys conducted for sedimentological studies, the differences between arrays can be treated as negligible.

Second, ERGI profiles should be 'ground-truthed' by qualitative comparison with alternative forms of subsurface information (e.g. drill core, electric logs, GPR, shallow seismic, exposures) whenever possible (Loke, 2000a). Ground-truthing is necessary, as the resistivity of sediments is altered by the quantity and chemistry of pore space moisture. Although tables of typical resistivity values for sedimentary materials have been published based on laboratory studies (e.g. Reynolds, 1997), these values are not necessarily useful for interpreting field data. Preliminary ERGI interpretation for sedimentological studies in natural settings should be based on the relationship between grain size and resistivity. Under any particular set of moisture conditions, gravel always has a higher resistivity than sand. Similarly, sand has a higher resistivity than silt, and silt has a higher resistivity than clay.

To date, no paper outlines ERGI field procedures. The field procedures described here were developed through extensive field testing (Baines, 2001). The multielectrode ERT system is set up with the electrodes placed at regular intervals along a survey line. The distance between the electrodes is called the electrode spacing. Electrical contact with the ground is achieved by connecting each electrode to a stainless steel stake driven ≈20 cm into the ground. Depth of investigation for the survey is slightly less than one-fifth of the total length of the survey line (Barker, 1989; Ward, 1990). Resolution is equal to approximately one-half of the electrode spacing (e.g. if the electrodes are 5 m apart, the resolution will be ≈2·5 m; Baines, 2001). Depth and resolution show an inverse relationship dependent on the electrode spacing and the total number of electrodes. For example, 56 electrodes spaced 12 m apart measured using a Wenner electrode array will produce a 110-m-deep profile with 6 m resolution. Conversely, 56 electrodes spaced 2 m apart measured using a Wenner electrode array will produce an 18-m-deep profile with 1 m resolution. Often, the depth/resolution compromise results in a survey line shorter than the region of interest. 'Roll-along' techniques (as described by Loke, 2000a) can extend a survey to any length (kilometres long if necessary), but do not alter the depth of investigation.

Resistivity data are collected with a 56-electrode AGI Sting/Swift resistivity system (Figs 2 and 3). The AGI system uses 'smart electrode' switches moulded directly into the multielectrode cables. A command file on the Sting selects

Fig. 2. Photograph showing a close-up of the Sting/Swift resistivity system. The Sting (on the right) is the resistivity meter and data logger. The Swift (on the left) is the switching system that connects to the multiple electrode cables and allows the Sting to select which four of the 56 or more electrodes to use for each resistivity measurement. In the centre is the 12 V motorcycle battery that provides electricity for the measurements.

Fig. 3. Photograph of the Sting/Swift resistivity system showing the layout of the electrodes along a survey line at Fort Yukon, Yukon Flats, Alaska, USA. Note the GPR survey being conducted in the background.

which of the 'smart electrodes' to use for each measurement. Resistivity data are processed in the field using RES2DINV (Loke, 2000b) on a laptop computer (with a Pentium II processor) to generate ERGI profiles. Most ERGI surveys without roll-alongs take <4 h for equipment handling and data collection. Data processing typically takes 1–2 min.

RESULTS

For the sake of brevity, the field sites are discussed separately, including a description of each site along with its lithology and geometry, followed by the ERGI profile for that site and its interpretation.

Beavertail channel-fill, British Columbia, Canada

The Beavertail channel-fill (Fig. 4) is a partially abandoned anabranch of an anastomosing reach of the upper Columbia River in the Rocky Mountain Trench of British Columbia, Canada. The channel-fill is located mid-valley, 6 km northwest of the hamlet of Harrogate. The Columbia River only flows through the channel during flood discharge, usually from 1 June to 30 July. This cross-section is at the same location as channel 4 in Makaske's (1998) Columbia River Valley cross-profile. Four vibrocores indicate that the sand-filled channel varies between 6 and 7 m thick. The topography suggests that the channel is 45 m wide. The channel-fill is encased in clayey silt except for a 14-m-wide span of exposed sand in the bed of the remnant channel.

The ERGI profile at this site (2 m spacing, Wenner array) almost duplicates the lithology and geometry of the channel-fill as interpreted from vibrocores. In the ERGI profile, the channel-fill has a thickness between 6 and 7 m and an interpreted width of 46 m. Although vibrocores provide excellent vertical resolution (direct measurement of core barrel penetration), ERGI provides better two-dimensional information with excellent lateral resolution (≈1 m). At this site, the lateral geometry of the channel-fill was easily inferred from topography; usually, interpretation is only as reliable as the distance between boreholes.

Schoonrewoerd channel-belt and underlying braid-plain, The Netherlands

The Schoonrewoerd channel-belt (Fig. 5) is a buried delta distributary channel in the Holocene Rhine–Meuse delta, The Netherlands (Makaske, 1998; Berendsen & Stouthamer, 2000). Underlying the Holocene delta is a thick (>70 m), vast (at least 60 km wide by 120 km long), uniform Pleistocene sand and gravel braid-plain that outcrops at the surface in the east and is 22 m deep in the west (Berendsen & Stouthamer, 2001). The channel-fill survey site is located 30 km east of Rotterdam and 1 km south of the town of Molenaarsgraaf. Twenty hand cores (gouge and 'Van der Staay') along a 400-m survey line indicate that the sand-filled channel is ≈65 m wide by 8·5 m thick. It is located 1·5 m below the ground surface and 2 m above the Pleistocene braid-plain, which itself is 12 m below the ground surface. The channel-fill is encased in clay and peat with sandy clay levee 'wings'

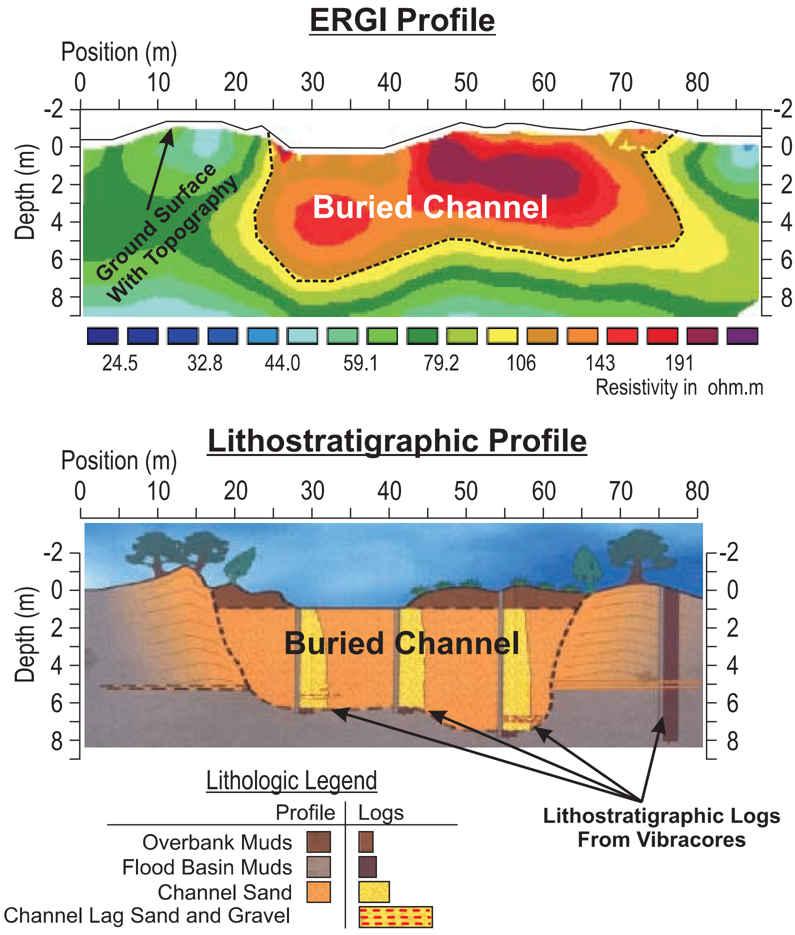

Fig. 4. Comparison of a portion of an ERGI profile with a lithostratigraphic profile based on vibrocores. Although both images show the sand-filled Beavertail channel in the anastomosing reach of the upper Columbia River, 6 km north-west of Harrogate, British Columbia, Canada, the ERGI survey line is located 50 m downstream from the vibrocore survey line. Data acquisition time for ERGI was 2 h and, for the four vibrocores, logging and drafting took 14 h.

(Schoonrewoerd cross-section 8, 'Molenaarsgraaf I' of Makaske, 1998).

The ERGI profile at this site (2 m spacing, Wenner array) closely matches the lithology and geometry of the channel-fill as interpreted from the cores. The ERGI profile also detects the basal Pleistocene braid-plain. The profile does not show the left side of the channel-fill because a water-filled ditch and adjacent road prevented further data collection. In the ERGI profile, the channel-fill is 9 m thick by 68 m wide, and the braid-plain is 12 m below the surface. Again, there is remarkable correspondence between the ERGI profile and the interpreted lithology and geometry of the Schoonrewoerd channel-fill. It is important to note that, at this site, the ERGI data were collected and processed in <10% of the time taken for coring.

Yorkton valley-fill, Saskatchewan, Canada

The late Pleistocene Yorkton valley-fill is a sand and gravel valley-fill incised into shale bedrock (Fig. 6). The valley-fill is located ≈5 km east of the town of Yorkton, Saskatchewan. A 5- to 15-m-thick glacial till sheet overlies the entire area. Spontaneous potential (SP) and resistance (R) wireline logs acquired from a borehole near the centre of the valley-fill indicate 5 m of glacial till and 50 m of sand and gravel overlying bedrock (Bauman & Nimeck, 2000).

The ERGI profile at this site (15 m spacing, Wenner array) agrees with the lithology and stratigraphy of the valley-fill as interpreted from the wireline logs, while also providing information about the width and cross-sectional geometry of the valley-fill. In the ERGI profile, the valley-fill is 58 m thick by 265 m wide and is noticeably asymmetrical. Because of the 15 m electrode spacing and resultant 7·5 m resolution, the ERGI profile cannot effectively represent the thin (5 m) till sheet. At this site, ERGI provides the full two-dimensional geometry of the fill. With further work at this or any other survey site, additional profiles could provide a full three-dimensional reconstruction.

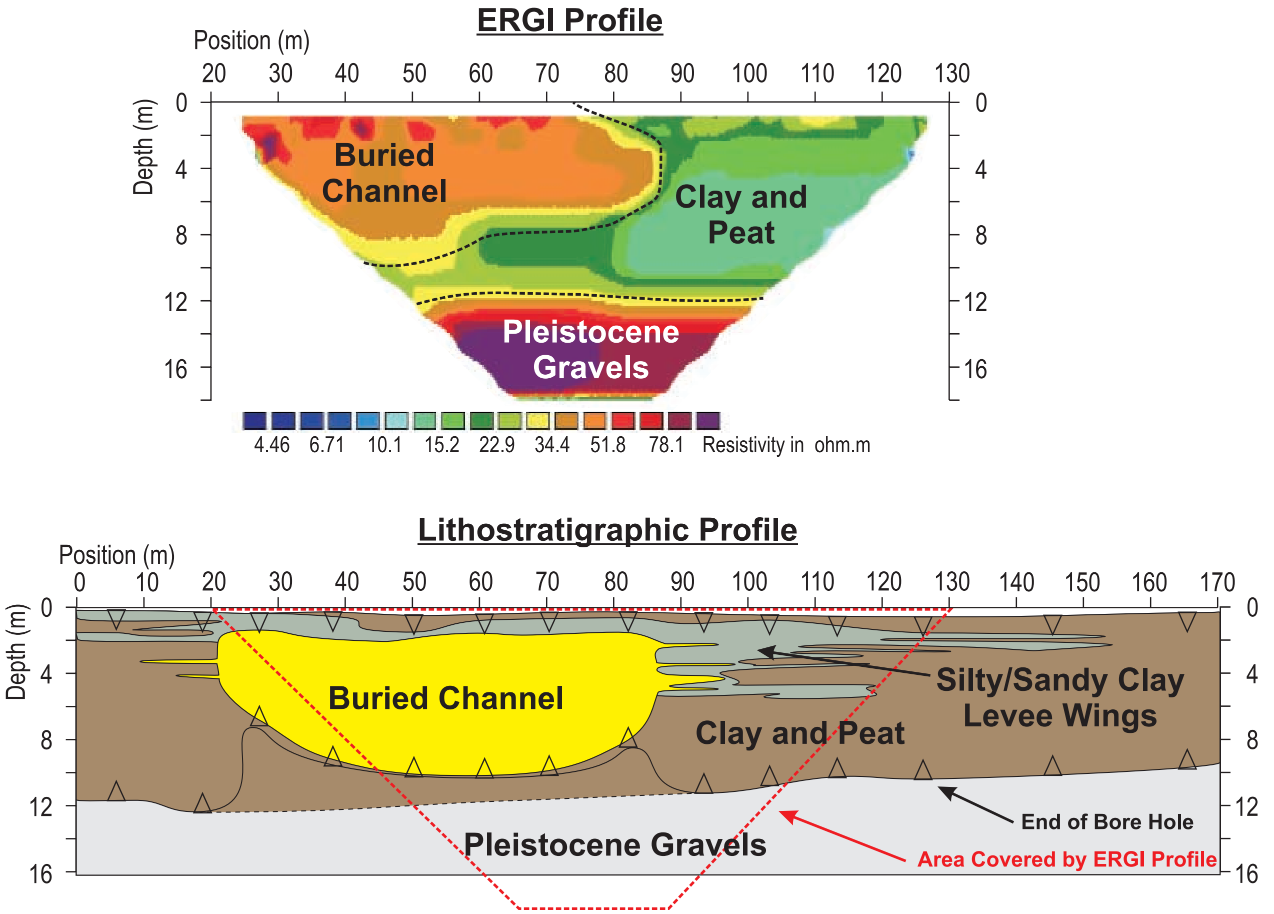

Fig. 5. Comparison of an ERGI profile with a lithostratigraphic profile based on core data. Both images show the Schoonrewoerd channel-fill and underlying Pleistocene braid-plain, Rhine–Meuse delta, 30 km east of Rotterdam, The Netherlands. Data acquisition time for ERGI was 1·25 h; the 14 hand cores took roughly 40 h.

Yukon Flats braid-plain, Alaska, USA

The Quaternary gravel braid-plain of the Yukon River (Fig. 7) in east central Alaska is over 150 km wide by 300 km long (Clement, 1999). The braid-plain near the village of Fort Yukon, where the US Geological Survey drilled a 390-m borehole in 1994 was examined. A GPR (12·5 MHz antennae) profile obtained for this study agrees with the lithostratigraphic log and indicates 30 m of gravel overlying a thick lacustrine or anastomosing river basin fill.

The ERGI profile (12 m spacing, Schlumberger array), on the same survey line as the GPR, closely matches the lithology and thickness of the gravel sheet as interpreted from the GPR profile and lithostratigraphic log. In the ERGI profile, the gravel braid-plain is 30 m thick. This shows how GPR can provide corroborative data for ERGI. This is the only site investigated where GPR provided useful data, because there were no silt or clay sediments at or near the surface.

DISCUSSION

ERGI has many advantages over other methods of obtaining sedimentological information about the shallow subsurface. The most important is its ability to map accurately the geometry of sand and gravel deposits buried by silt or clay. No other geophysical technique can achieve this level of accuracy with so little effort. Borehole data are extremely expensive, time-consuming, invasive and cannot easily approach ERGI's horizontal resolution. However, borehole data can significantly assist ERGI interpretation. Combined borehole and ERGI campaigns require very few boreholes and take advantage of the strengths of each technique to locate lateral facies changes at buried channel margins precisely while accurately determining the thickness and lithology of the fill sediments.

Another advantage of ERGI over other methods of obtaining sedimentological information about the shallow subsurface is how 'user-friendly'

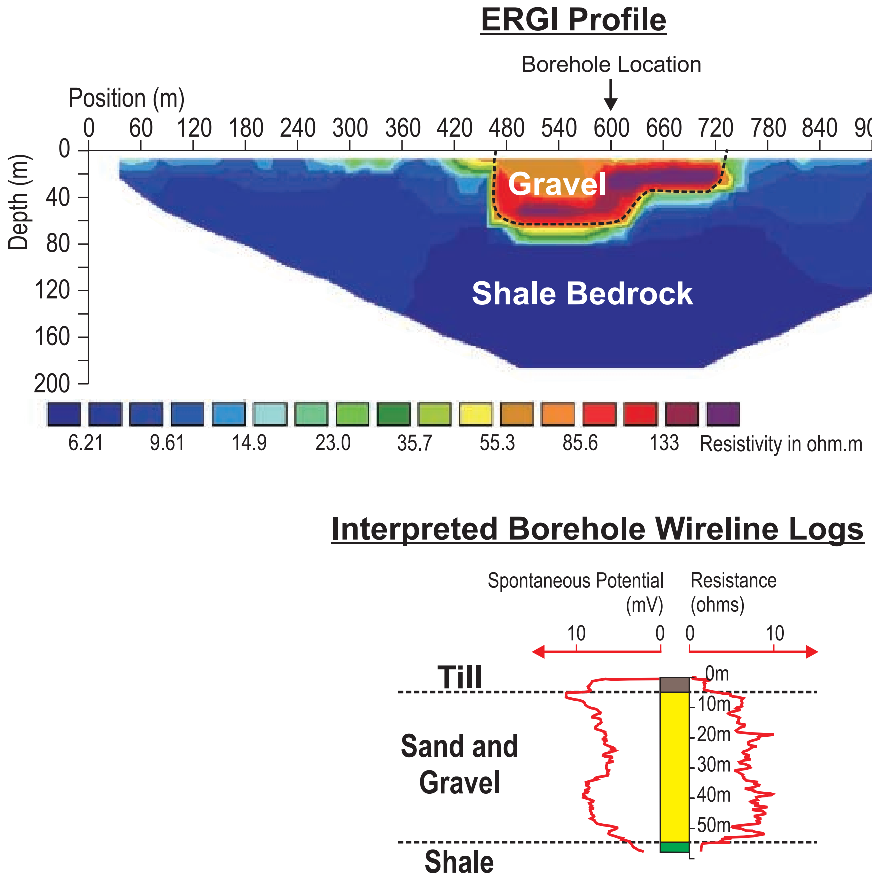

Fig. 6. An ERGI profile showing ≈58 m of gravel above shale bedrock in a late-Pleistocene valley-fill near Yorkton, Saskatchewan, Canada. Wireline log data from a borehole at meter 600 indicates that the valley-fill is 55 m thick.

ERGI is in the field. It is fast, cost-effective, non-invasive and robust. ERGI data acquisition requires between one-fifth and one-tenth of the time spent drilling shallow boreholes to investigate a site. ERGI's speed, combined with the quality and quantity of the information produced, make it a very cost-effective geophysical technique. Its non-invasive qualities mean that there are no explosives, noise, ground disturbance or waste. ERGI is environmentally friendly and is permitted in parks, wildlife reserves and urban areas. Because ERGI is not subject to anthropogenic interference from such features as overhead wires or fences, there are no geophysical constraints against working within urban areas (e.g. Wisén *et al.*, 2000).

Although there are many advantages to ERGI, there are several limitations. Dry or frozen ground is difficult to image with ERGI. Both conditions lead to extremely high contact resistance and erroneous measurements. Accurate data collection in frozen ground is possible if the electrode stakes penetrate through the frozen layer into unfrozen sediments. Accurate data collection is possible in dry ground by wetting the ground around the electrode stakes with salt water. Another challenge arises because ERGI is a two-dimensional method that may misrepresent complex three-dimensional fluvial architecture (Reynolds, 1997; Loke, 2000a) by producing 'fuzzy' edged features. The simplest way to avoid three-dimensional effects is to orient surveys perpendicular to channels rather than diagonally. If the orientation of a buried channel-fill is unknown, several ERGI profiles may be required to determine its alignment. A final consideration is safety for bystanders, wildlife or livestock. Although ERGI uses sufficiently low electrical current that there is little risk of death or serious injury, contact with a 'live' electrode is not advisable.

CONCLUSIONS AND IMPLICATIONS

ERGI profiles accurately portray lithology, stratigraphy and geometry of buried sand and gravel

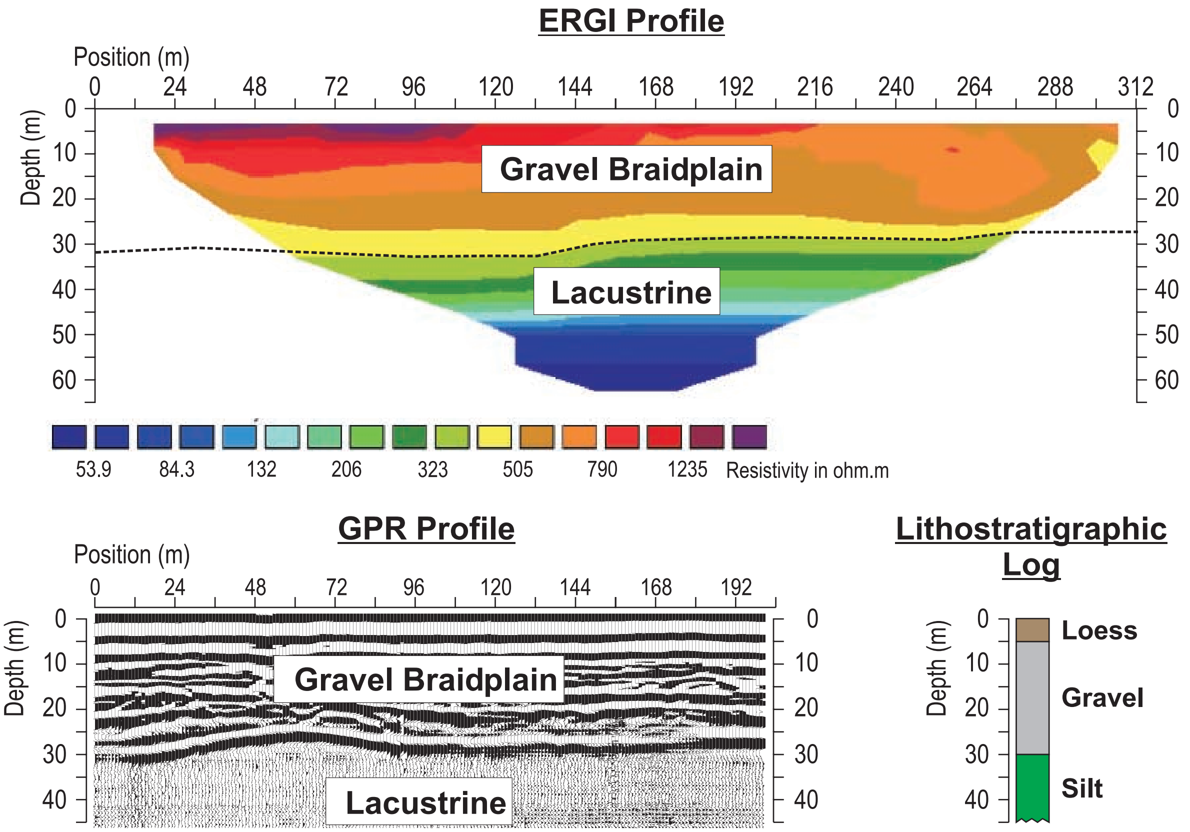

Fig. 7. Comparison of an ERGI profile with a ground-penetrating radar (GPR) profile and a borehole lithostratigraphic log. The images all show ≈30 m of fluvial gravel in the Yukon River braid-plain, Yukon Flats, Alaska, USA. The borehole was obtained 3 km from the active channel-belt and shows 5 m of loess overlying the gravel.

fluvial deposits. Variations in the modelled resistivity values represent different lithologies. Geometries of homogeneous deposits are represented by zones of similar resistivity values. For example, sand channel-fills buried in mud appear as channel-shaped high-resistivity anomalies. Our field data confirm that such anomalies correctly represent the lithology and geometry of the 'real world'.

These field experiments indicate that ERGI is a remarkable geophysical tool. It detects complex lithofacies changes and maps geometries. It functions equally well in conductive sediments (silt–clay, organic, brackish or saline) and in resistive sediments (sand or gravel). This means that ERGI can detect and delineate resistive bodies buried in conductive sediments. It is anticipated that ERGI will prove to be a highly useful, and possibly indispensable, tool for investigating fluvial and other depositional successions.

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