MAPPING HIGH RESISTIVITY BURIED CHANNEL DEPOSITS WITH AIRBORNE ELECTROMAGNETIC SURVEYS AND OTHER METHODS

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Abstract

Aggregate deposits in the shale-dominated plains of northeast British Columbia (NEBC) are in short supply yet the demand for gravel is continually increasing due to the construction of all-season petroleum development roads in the region. Gravels deposits close to surface with minimal overburden are preferred but such deposits are relatively rare in NEBC. Many gravels are completely buried and techniques commonly used for identifying surface features, such as geomorphological mapping, are ineffective for locating these blind deposits. Due to these difficulties, new subsurface investigation and geophysical techniques are being tested and used. Airborne, high resolution, electromagnetic (EM) surveys are particularly successful because of the high resistivity contrasts between sands and gravels and underlying shale and overlying clay-rich glacial sediments. For example, a helicopter-borne RESOLVE multi-frequency EM survey, flown over a gravel deposit underlying 1 to 5 m of clay rich till, shows relatively high resistivity values (*e.g.* >60 ohm-m) in the gravels and low resistivity values (*e.g.* <15 ohm-m) in the till. The sands and gravels occur along a gentle southeasterly slope with no obvious geomorphic indications of their presence. In the inferred core of the paleochannel deposit, the sands and gravels are at least 5 m thick. The EM survey was flown with 100 m line spacing over the deposit and 200 m spacing over a larger area (42 km^2). The flat, till covered, deposit, which was originally detected only in seismic shot hole logs, was mapped remarkably well with the high frequency (115 kHz) data, which best reflects the shallow geology. Follow-up field studies show that the depths of the deposit appear to be less than the EM data suggests, but the overall shape and location of the deposit is well represented, as is the presence and geometry of the till cap over the gravels.

Mapping of buried Quaternary channels also has recently become of interest in NEBC because of their shallow gas potential and because of hazards associated with buried channels such as artesian water and pressurized gas blow-outs. In this paper we report on geophysical and remote sensing techniques we are using to map both shallow buried channels and deeper paleo-valleys.

Introduction

In this paper we provide the results of geological ground-truthing of airborne electromagnetic data collected over a buried paleochannel deposit in northeast British Columbia (Kotcho East deposit; Figure 1). Sands and gravels within the buried deposits are differentiated from the surrounding clay-rich till and shale bedrock by their high resistivity. We also present results on the use of gamma logs in conventional oil and gas wells to map paleochannels on a regional basis.

The study area occurs within the Boreal Plains of northeast British Columbia (NEBC), an area of low relief dominated by nearly flat-lying sedimentary rocks, mainly marine shales of the Lower Cretaceous Shaftsbury Formation and sandstones of the Upper Cretaceous Dunvegan Formation. The surficial geology of the area is dominated by clay-rich tills, glaciolacustrine sediments, and thick organic deposits. Glaciofluvial sands and gravels are rare at the surface resulting in a high demand and the need to identify buried deposits for road construction and other purposes. The Quaternary geology of the study area was recently summarized by Levson *et al.* (2004, 2005).

The study of buried paleochannel deposits has several economic applications in NEBC and surrounding areas. These include: identification of aggregate resources for petroleum development road (PDR) construction, provision of a stratigraphic framework for the Quaternary/Tertiary gas exploration play, and the identification of areas of thick Quaternary deposits and permafrost for engineering purposes. Recent well blow-outs and serious drilling problems associated with shallow gas and artesian aquifers have further highlighted the importance of paleochannel mapping in the region. Related data, such as drift thickness information, also have applications in estimating drilling costs (*e.g.* casing depths), as well as in improving design of seismic surveys and interpretation of geophysical data.

Mapping Large Paleo-valleys in NEBC – Land Use Applications

The relatively subdued topography of NEBC does not reflect the irregular, buried bedrock surface. In many areas, deeply incised paleo-valleys are masked entirely by thick accumulations of Quaternary sediments. These valleys developed in pre-glacial time and subsequently were filled with a succession of sediment associated with advance and recession of the Laurentide Ice Sheet (LIS). Pre-glacial and advance-phase glaciofluvial sands and gravels are typically overlain by glaciolacustrine silts and clays deposited in proglacial lakes dammed by the LIS. By the last glacial maximum the LIS overrode the lakes and their sediments and deposited a thick blanket of till. When the LIS retreated, proglacial lakes again formed.

Identifying and mapping of these paleo-valleys has become important in NEBC for a number of reasons including shallow gas exploration, drilling safety, potable groundwater protection, and seismic processing and interpretation. Quaternary-hosted gas was discovered in northwestern Alberta in 1988 and was brought into production in 1993 (Clare, 1988; Canadian Discovery Digest, 2001). The gas was discovered in glaciofluvial sand and gravel reservoirs with clay-rich glaciolacustrine and diamicton cap rock. Reservoirs are typically small, but some are economic. Well 6-13-112-24W5 had a cumulative production of 35.7 bcf gas between May 2000 and August 2005. The geological setting in British Columbia is comparable to that of northwestern Alberta, suggesting there is potential for similar gas plays in BC.

Thick inhomogeneous Quaternary sediments have proven to be a safety concern for oil and gas, as well as water well drilling. For example, in 2005 a water drilled to <200 m on the Etsho Plateau intersected gas. A blow-out did not occur but the gas flow was significant enough to tie the well into the pipeline system and produce the gas. Numerous other examples of incidents involving gas and over pressurized aquifer blow-outs have been reported in drilling records in BC and Alberta (*e.g.* Clare, 1988; British Columbia Oil and Gas Commission, 2005; Well a-94-L/94-I-9, WA 15130; Well d-46-F/94-I-15, WA 17119). These incidents have cost the oil and gas industry millions of dollars in lost time, abandonment of wells, and destruction of equipment as well as injuries and at least one fatality in the last year. Blow-out preventers are not commonly used when drilling surface casing or water wells. If drillers are aware of the potential for intersecting gas or water, blow-out preventers can be used to mitigate dangerous situations.

As noted above, groundwater aquifers are abundant in northeast BC and are often associated with the sand and gravel beds within the valley-fill. Protecting these sources of potable water for urban and agricultural use is a concern in areas of competing land use, particularly where oil and gas drilling activity and urbanization may compromise the quality of groundwater. Identifying aquifer distribution through subsurface stratigraphy ensures that decisions such as casing depth, drilling fluid management, and water resource allocation are optimized. For example, British Columbia legislation requires casing

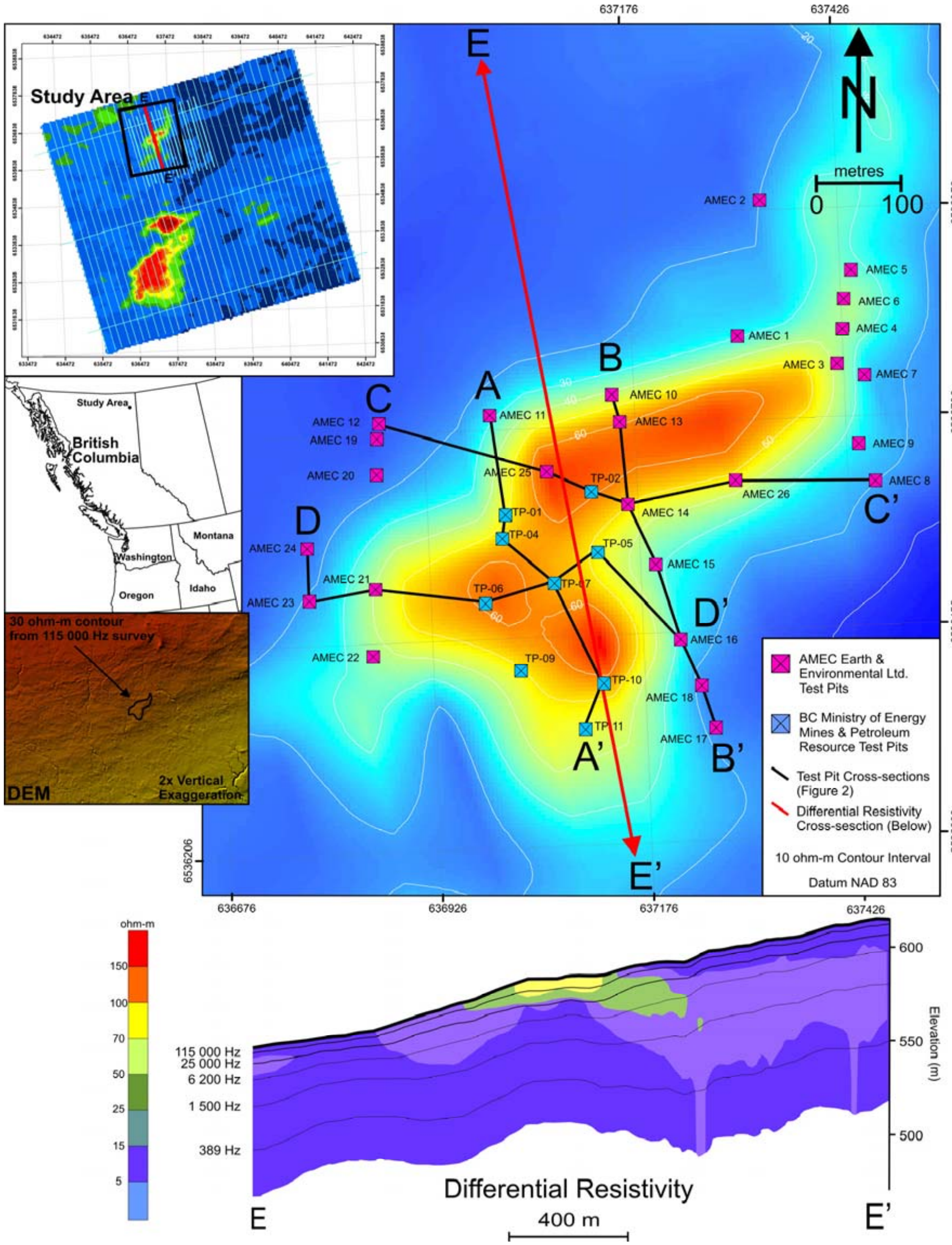

Figure 1: Results of a high resolution, electromagnetic survey in northeast BC (only 115 kHz map shown). Warm (red and yellow) and cold (blue) colors indicate higher and lower resistivity values, respectively. The entire survey (upper left) was flown with 200 m line spacing and covered 42 km^2 (boxed area shows the location of the more detailed survey with a 100 m line spacing). Low relief and gentle slopes in the study area are shown in the DEM (left). The pseudo-section (bottom) shows the apparent differential resistivity along line E-E'. See Figure 2 for test-pit and cross-section details. The locations of test pits are not exact.

to be set below all strata expected for drinking water and at least 25 m into a competent horizon to prevent blow-outs (*Petroleum and Natural Gas Act, 1998*). Providing information on drift thickness helps ensure that casing is set into an appropriate substrate (generally competent bedrock), rather than unconsolidated drift, protecting aquifers from possible drilling fluid contamination.

Thick packages of unconsolidated material at surface have consequences for the seismic industry. These packages tend to have slow seismic wave velocities relative to consolidated rock. As a result, deeper reflections are distorted by slow wave propagation and can introduce erroneous interpretations. Processing can mitigate these distortions if the depth and geometry of the paleo-valley, and therefore the slow velocity zones, are determined.

High Resolution Airborne Electromagnetics

High resolution, electromagnetic (EM) surveys have been found to be an effective method for mapping buried paleochannel deposits in NEBC. For example, the Kotcho East deposit is a completely buried sand and gravel feature that includes at least three distinct lobes (Figure 1, upper left). The granular materials are buried by one to five meters of clay-rich diamicton, interpreted to be till, and thin silt (Levson *et al*., 2004). The deposit was first identified from seismic shot hole data and the northernmost lobe was immediately investigated with a test pitting program (Dewer and Polysou, 2003). An airborne EM survey was subsequently flown over the region to test the utility of the method for mapping buried sands and gravels (Best *et al*., 2004). The helicopter-borne RESOLVE multi-frequency EM system was used (Cain, 2004). The system measures five frequencies (0.4, 1.5, 6.4, 25 and 115 kHz) providing a range in effective depth of exploration. The survey was flown with 100 m line spacing over the northern lobe and 200 m spacing over a larger area (25 km^2). The three lobes of the deposit were clearly identified by the high frequency (115 kHz) EM data (Figure 1). Gravels in the region have high resistivity values (often >100 ohm-m) and show a marked contrast with the adjacent fine-grained glacial sediments which exhibit low resistivity values (*e.g.* 5-15 ohm-m). This contrast in electromagnetic properties allows for relatively high resolution mapping using airborne EM. Results of test pitting programs conducted in the area to ground truth the EM mapping are shown in Figure 2.

All of the goals of the pilot EM survey were achieved including an attempt to evaluate the utility of the method for mapping shallow gravel deposits, to trace the extent of the Kotcho East gravel deposit beyond the field tested boundaries of the northern lobe and to identify any new gravel targets in the region. The southern two areas are much larger than the northern lobe and were the focus of reconnaissance ground investigations that later also confirmed the presence of sand and gravel deposits there (Levson *et al*., 2004). The northern lobe of the deposit is characterized by crudely stratified, poorly sorted, large cobble to boulder-sized gravels interbedded with well stratified, moderately well sorted, sands and pebble gravels (Figure 3). Sharp contrasts in grain size and sorting from bed to bed probably reflect sudden changes in flow energy. Low angle, large-scale, trough cross-bedding, cut-and-fill structures, and large clast clusters reflect strongly channelized flows (Levson *et al*., 2005). The gravels are sharply overlain by a clay-rich till containing both local clasts and distally derived (Canadian Shield) erratics.

The geometry of the Kotcho East deposit could not be determined from aerial photographic interpretation of geomorphic data due to the subdued relief created by the till blanket. However, apparent resistivity sections constructed from the EM data (*e.g.* E-E' on Figure 1) show a convex-upward profile at the top, with the overlying till thickening away from the approximately north-east trending axis of the deposit. For comparison, a series of cross-sections through the deposit constructed from test-pit data are provided in Figure 2. The locations of the sections and test-pits used are shown on

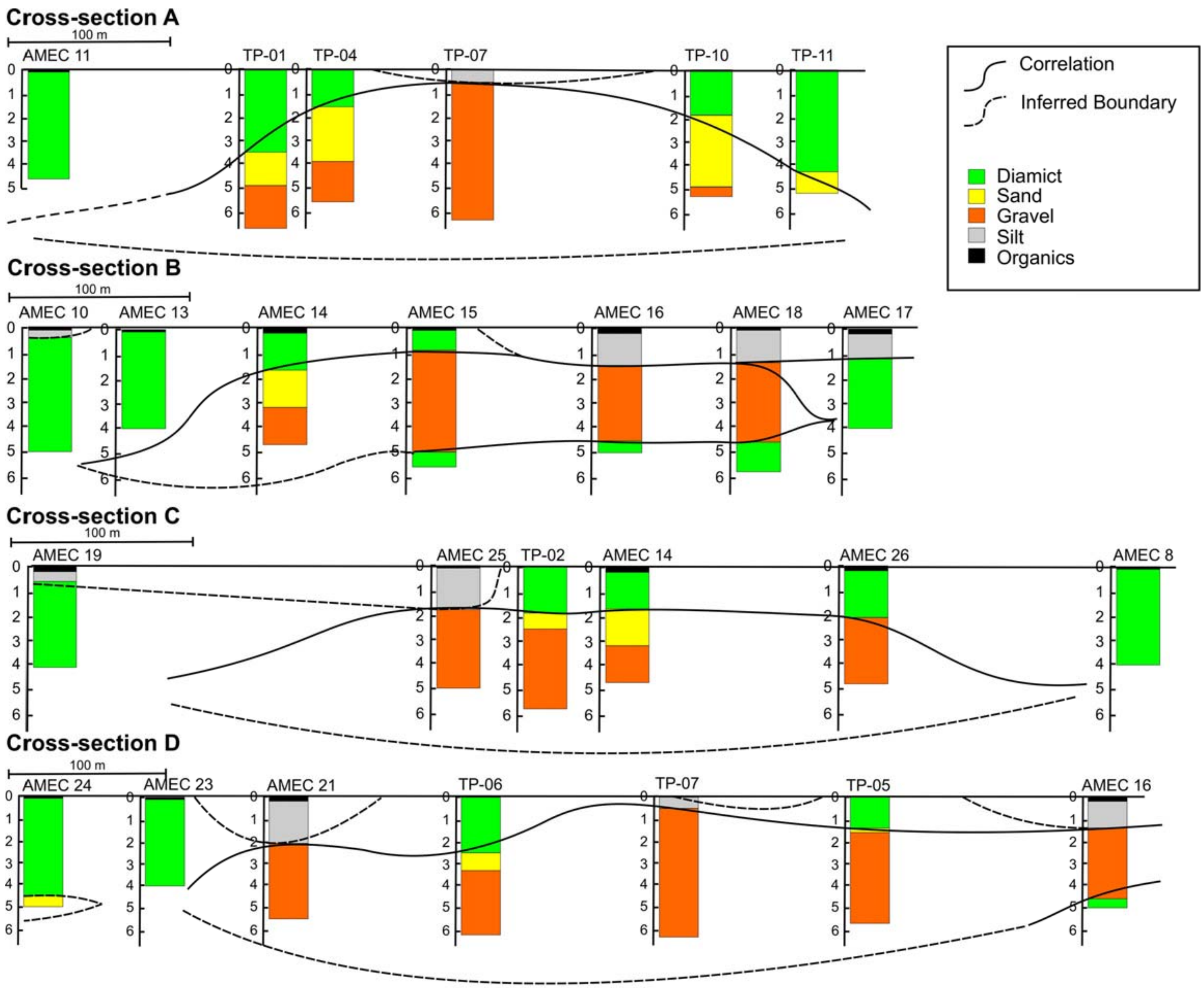

Figure 2. Test pitting by AMEC Earth and Environmental limited and the British Columbia Ministry of Energy and Mines and Petroleum Resources confirmed the presence of sand and gravel below clay rich till and silt. Several cross-sections are presented showing the general shape of the sand and gravel body within the finer sediments. See figure 1 for cross-section location.

Figure 1. The convex-upward profile is apparent on all the cross-sections but is most clearly seen on section A-A' which is perpendicular to the main axis of the deposit. This geometry is consistent with a subglacial channel origin as postulated by Levson *et al.* (2005). The top of the deposit is nearly flat in places along its axis (*e.g.* see center of Section C-C', Figure 2) but on the margins the top clearly drops off and the overlying till thickens rapidly (*e.g.* at either end of section C-C' the till is more than 4 m thick). This locally flat surface is confirmed by a nearly horizontal till/gravel contact exposed in a mine excavation that trends generally parallel to the deposit axis in the vicinity of section C-C' (Figure 3). This geometry is expected for flow parallel sections oriented along the axis of the paleochannel. The lower contact of the deposit varies from strongly convex upward (*i.e.* trough-shaped) to undulatory.

The airborne EM data provides a reasonably accurate representation of the buried gravel deposit in both plan view and cross-section. Although the depths of the deposit appear to be less than the apparent resistivity sections suggest, the overall geometry and location of the deposit is well represented, as is the presence of the till cap over the gravels that thickens towards the margins.

Interestingly, the thickness of the deposit appears to be about 5 m as indicated by several test pits that reached the bottom of the gravels and by mine excavations in the northern lobe that show only about 5 m of sand and gravel overlying clay-till. Best *et al*. (in press) estimated the deposit thickness in this area to be about 20 m based on the resistivity cross-sections but they noted that apparent resistivity is an approximate measure of the average resistivity of the earth to a depth equal to the skin depth. Thus, the over estimation of the deposit thickness on the resistivity cross-sections probably is a result of high resistivity values in a layer of coarse sands and gravels that is relatively thin compared to the thickness of the computed skin depth.

The success of this method enabled the British Columbia Ministry of Energy, Mines and Petroleum Resources to provide other agencies with information regarding the basic geometry and depth of the deposit as well as the expected thickness of overburden. This information was used for land tenure and permitting decisions and allowed for well informed assessments when the tenure was assigned to different parties.

Other Geophysical Techniques

Numerous geophysical methods have been used to identify and map Quaternary age paleo-valleys including seismic (Huuse and Lykke-Andersen, 2000; Gabriel *et al*., 2003; Jørgensen *et al.* 2003a; Jørgensen *et al*. 2003b; Kluiving, *et al*., 2003; Praeg, 2003; Sandersen and Jørgensen, 2003), airborne electromagnetics (EM) (Napier, 2003; Best *et al*., in press), transient EM (Danielsen, *et al*., 2003; Jørgensen *et al*., 2003a; Jørgensen *et al*., 2003b; Sandersen and Jørgensen, 2003), ground penetrating radar (Hickin, 2003), gravity (Gabriel *et al*., 2003) and magnetics (Davis *et al*., 2004; Parker Gay, 2004). In this study, borehole geophysics and proprietary regional airborne EM are the principle methods used to map the bedrock topography and near surface stratigraphy. This data is augmented by slow velocity zone maps, seismic shot hole records, and water well records to confirm picks and lithology. The contact of Quaternary drift and the underlying bedrock (usually shale) is determined from a suite of logs including: gamma, induction, and density (Figure 4). As oil and gas well casing typically is set below the bedrock contact, logs that can 'see through' casing are the most valuable. In uncased wells or wells where the top of the bedrock occurs below casing, density and induction wells are helpful. Contacts are mapped and the point data are modeled and corrected for geological interpretation, generating a bedrock surface (*c.f.* Pawlowicz, 2005; Hickin and Kerr, 2005). These maps provide both the depth to bedrock and drift thickness.

Figure 3: Exposure of coarse gravels under till at the Kotcho East deposit. Note the sharp, horizontal, lower contact of the till and the wide range in clast size in the gravels.

Modeled surfaces show deep, linear depressions that are interpreted to be paleo-valleys now filled with Quaternary sediments. Variability of the valley-fill sediments can be assessed using logs that can penetrate the casing. For example, the cross-section in Figure 4 shows a buried depression that extends more than 170 m below the surface and incises into the Shaftesbury shale. Logs show numerous gamma lows within the valley-fill material that are interpreted to be sediment with lower clay content (*e.g.* glaciofluvial beds or sandy diamicton) relative to the rest of the fill sediments (*e.g.*, clay-rich till or glaciolacustrine silt and clay). Correlation of the coarse beds between wells is difficult as it is unlikely that these sediments, associated with subglacial deposition, extend more than several hundred meters. Wells may be several kilometers apart. Consequently, the coarse beds are treated as isolated occurrences, although there is the possibility of some hydraulic or gas communication between these coarse bodies if they intersect as suggested by regional airborne EM data. By evaluating the bedrock and Quaternary stratigraphy and mapping the often neglected shallow portion of the subsurface, valuable and potentially life threatening and costly incidents may be avoided.

Conclusions

Surficial sand and gravel deposits are rare in many parts of northeast British Columbia but buried deposits occur in subglacial paleochannels and in large pre-glacial paleo-valleys. Mapping of these buried features has several land use applications including: identification of aggregate resources for road

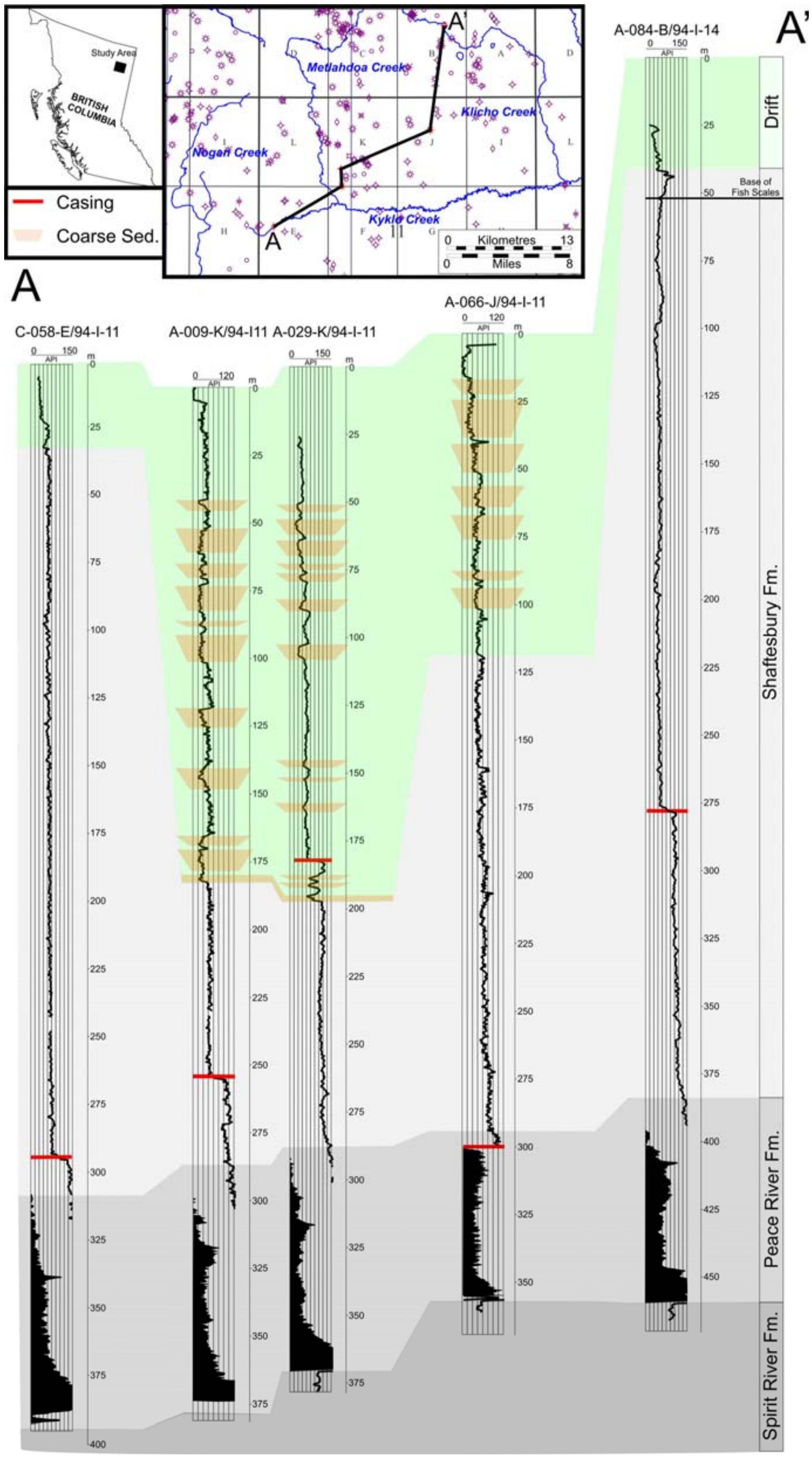

Figure 4: Paleo-valley, identified in downhole geophysical logs, is incised into the Shaftesbury Formation. Clay rich-sediment has a relatively high gamma response, whereas interbeds containing less clay show a lower gamma response.

construction, locating shallow gas exploration targets, engineering and drilling safety applications, groundwater protection, and seismic data interpretation. Traditional mapping techniques such as air photo interpretation are not effective because the paleochannels have little or no surface expression. High resolution airborne EM, however, has been used to delineate shallow paleochannel deposits that are now providing an important aggregate resource and down-hole geophysics provide a useful tool to identify deeply incised paleo-valleys. Building on the success of these methods, large scale investigations of targeted areas are expected in Northeast BC.

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