The dc resistivity method has become a preferred reconnaissance mapping tool for uranium exploration targets in the Athabasca Basin, in northern Saskatchewan, Canada. Regionally, uranium deposits can occur beneath <100 m to >1 km thick sandstone cover rocks, are commonly associated with deeper basement graphitic metasedimentary units and are also often accompanied by clay-alteration zones in the sandstones. As a result, deep-penetrating electromagnetic and electrical geophysical techniques are ideally suited for indirect exploration of these types of deposits. A variety of electrode configurations are being used, however the pole-pole array is currently favoured in the Athabasca Basin due to its high signal levels, its deep penetration and its anomaly resolution. More recently, however, other technologies such as audio-magnetotellurics (AMT/MT) and 24-bit A/D distributed acquisition systems (DAS) have been introduced to extend the depth of exploration below 1 km. In the example presented here, a DAS acquisition system was used to acquire dc resistivity data, using a variety of electrode arrays, to examine the response parameters from the different configurations along a single line located along a known conductive trend at the M-Zone on the Wheeler River property.

Geological setting. The Wheeler River property is situated in the southeastern Athabasca Basin, approximately 35 km northeast of Key Lake, in northern Saskatchewan (Figure 1). The M-zone is a uranium occurrence that lies at the unconformity, under approximately 400 m of Athabasca sandstone, and is associated with a conductive graphitic metasedimentary unit in the basement rocks. Originally discovered in the 1980s, little exploration had been undertaken since then; however, the increasing value of uranium ore has renewed interest in the property. The dc resistivity method is being used because of the subsequent construction of a nearby major three-phase power line (Figure 2) which limits more conventional and less costly ground EM follow-up on the property. dc resistivity is also favored because of its ability to map structurally controlled alteration zones in the sandstones that often accompany unconformity uranium targets.

The Wheeler River property is regionally underlain by 300–400-m thick Athabasca sandstones and conglomerates of upper paleo-Proterozoic age (1540–1740 Ma). Sandstones of the Manitou Falls Formation host most of the uranium deposits in the eastern part of the Athabasca Basin and are composed of orthoquartzite sandstones and conglomerates. Below the unconformity (UC), the crystalline basement comprises the 2.5–2.6 Ga Wollaston Group that is a mixture of graphitic metapelites, metaquartzite and mixed metasedimentary units as well as granitic gneisses.

Unconformity-type uranium mineralization in the Athabasca Basin is structurally controlled by the paleo-Proterozoic unconformity and faults. Oxidizing basin fluids carried uranium from the sandstone while reducing fluids from graphitic faults in the basement carry minerals such as silica from the basement rocks to the unconformity. Uranium is deposited at the top of the fault around the unconformity and alteration occurs above the unconformity due to the fluid flow (Tuncer et al., 2006).

On the Wheeler River property, the M-zone geology is poorly known outside the narrow DDH drilling corridors. The
M-zone, which is situated at the eastern edge of the Wheeler River property, consists of uraniferous intersections along a graphitic pelite conductor, centered around L100S and BL0E, as well as elevation changes in the basement topography, lying at roughly 380–400 m depth. The M-zone conductor has been traced for >1 km strike length; however, very little is known geologically beyond this trend, including the exact geological dip direction for the basement, which is presumed to be steep southeast, conformable to the granite contact. The Archean granitic gneiss unit in the basement is indicated in the southeast half of the grid, based on the magnetic results (Figure 3).

The Wheeler River M-zone mineralized conductor was originally discovered in the mid 1980s using ground transient EM follow-up of airborne survey targets, but has remained unexplored in the years since then. However, the presence of a major powerline on the grid, built during this interim period, to extend power from Key Lake mine to McLean Lake, has complicated additional ground geophysical follow-up. In fact, it is well established that transient EM surveys, locally, are heavily impacted within a several hundred metre vicinity of these powerlines caused by unusually high levels of cultural noise.

Recent drilling at M-zone has detected and confirmed anomalous uraniferous intersections in the sandstone over the M-zone. DAS system dc resistivity surveys were planned in spring 2007 to define the M-zone conductor, detect the granite to the southeast, and detect an alteration chimney associated with the mineralization, in the MT/dc resistivity and IP results.

Distributed acquisition system survey. Although distributed acquisition (DAS) technology is commonplace in the seismic instrumentation industry, it is relatively new to mining exploration electrical geophysics, having only been introduced within the last decade. Titan-24 is an example of a multi-channel, multiparameter DAS system, recording broad band tensor audio magnetotelluric resistivity, dc resistivity and induced polarization (dc/IP) data (Figure 4). DAS systems use a large multichannel, fixed-receiver array, typically 2.4–3 km in length, in combination with a wide variety of possible current injection arrays, accurate 24-bit A/D sampling and digital signal processing to achieve improved depth of penetration, data quality, and detectibility.

The DAS surveys at Wheeler River were preceded by a 2D synthetic modeling study to test for the optimal array parameters and to compare the responses from the various arrays, including pole-pole (plpl), pole-dipole (pldp), and dipole-dipole (dpdp). The DAS survey included a single test line of joint dc resistivity and IP acquisition directly over the M-zone, using multiple array configurations, in combination with a tensor MT audio-magnetotelluric survey line. The survey was then completed over an additional 12 adjacent survey lines using pole-dipole dc resistivity and induced polarization.

Two-dimensional synthetic modeling and inversions. In an effort to optimize the dc resistivity survey results at Wheeler River, the surveys were preceded by a 2D synthetic modeling study that tested the array parameters, such as dipole size (a-spacing) for the DAS array (24 continuous dipoles) configuration as well as comparing the responses from the various electrode arrays, including pole-pole, pole-dipole, and dipole-dipole. Of these array types, pole-pole is currently favored in the Athabasca Basin because of its high signal levels, its deep penetration and its anomaly resolution, having proven effective to >600 m. However, for shallower UC depths, it was felt that either dipole-dipole or pole-pole methods might provide higher resolution than pole-pole, as suggested in other dc array depth-penetration studies. Although the normal Titan-24 DAS acquisition mode utilizes the pole-dipole array, the final choice of array configuration for the Wheeler River
survey was to be based on the results of the synthetic modeling and the eventual field testing.

A series of 2D synthetic models were created that simulate the expected dc resistivity results over a typical 300 m deep, Athabasca graphitic target, using a 50 m, 100 m, and 150 m dipole DAS dc pole-dipole array that might typically be used, in the pole-pole, pole-dipole and dipole-dipole configurations. The geologic model and physical properties were drawn from the geophysical model shown in Figure 5. It includes a thick (300 m) resistive sandstone caprock (3 kΩ-m), less resistive half-space basement (1 kΩ-m), and a thin (100 m) graphitic (5 Ω-m) conductor (Figure 6).

The procedure for the synthetic modeling study was as follows: A common geologic model was used to calculate the 2D forward responses for the dc resistivity, utilizing the UBC Dcipf2d code of Oldenburg and Li (1994), using a simulated DAS array geometry in a variety of configurations. These synthetic forward responses were then input into 2D inversions, with parameters identical to those typically used for dc surveys. The final 2D inversion results were then directly compared to the original geologic model for assessment.

The 2D forward dc resistivity results over a 300 m deep tabular conductor (Figure 6) were calculated for a standard pole-dipole DAS array, with current injections between the receiver dipoles and also extending beyond each end (n=0.5–33.5) and whose fixed 24-channel receiver set-up combines both pdp-right and pdp-left voltage measurements at each injection point. The synthetic 2D results demonstrate the progressive changes in the expected measured dc response when using dipole sizes varying incrementally from 50 m, 100 m, and 150 m. Similar comparisons were obtained for dpdp and plpl arrays. The results qualitatively indicate that the 50 m dipole data provides insufficient penetration in the 300–400 m UC depth range, particularly for the dpdp array, and that the 100 m dipole might provide better anomaly resolution,

Figure 6. Two-dimensional synthetic forward dc resistivity models, calculated for (a) 50 m, (b) 100 m, and (c) 150 m dipole DAS dc pole-dipole array, from 100-m width graphitic conductor model, buried below 300 m sandstone.

Figure 7. Two-dimensional synthetic inversions, calculated from (a) dipole-dipole, (b) pole-dipole, and (c) pole-pole array 2D forward-dc model results, for 300 m deep UC target, using typical DAS dc resistivity survey configuration with 100 m dipoles. Notice similarity in responses at UC, but also relative differences in depth penetration versus lateral resolution and anomaly width, particularly between dpdp and plpl.

Figure 8. M-zone two dimensional dc resistivity inversions from L100S DAS survey data, using (a) dipole-dipole, (b) pole-dipole, and (c) pole-pole array measurements. Notice relative differences in vertical depth penetration versus shallow-deep resolution, including the apparent west dip of the basement graphite and the inferred clay-alteration zone lying above 400 m UC depth in sandstone directly over the M-zone conductor.
over the 150 m spacing, in spite of its improved penetration, particularly for pole-pole array. These predictions were subsequently tested in the following 2D inversion stage.

Figure 7 presents the 2D synthetic dc resistivity inversion results using the 100-m spaced dipole-dipole, pole-dipole and pole-pole forward model data, over a 300 m deep tabular conductor, obtained previously. They were calculated using the Res2dinv code of Loke and Barker (1996a). As expected, the dipole-dipole results appear to provide the best resolution at the UC depth but perhaps lack sufficient penetration needed to adequately resolve the basement geology. As was also predicted, in addition to showing remarkably similar resolution at the UC, the pole-pole results provide the greatest depth of investigation, although its wide anomaly pattern might lessen its deep geologic mapping resolution capability. Overall, however, of the arrays tested, the 100 m pole-dipole results appear to feature the best combination of depth penetration and shallow-to-deep anomaly resolution for the UC target in the 300–400 m target range, albeit closely followed by pole-pole. Similar results from the 50 m and 150 m dipole inversion studies also support these conclusions. As a proof of concept, all three arrays would nevertheless be tested in the field, using the 100 m dipole spacing.

A test survey line was acquired directly over the center of the M-zone, on the Wheeler River property. Along line 100S, the M-zone uranium mineralization occurs at 0+00E at the unconformity, directly over a graphitic metapelitic conductor that lies in the basement beneath approximately 380–400 m of Athabasca sandstone. The DAS array was 3 km in length and consisted of 30 continuous, 100-m spaced receiver electrodes centered over the deposit. For the dc resistivity and IP surveys, the survey procedure consisted of current injections at 100 m intervals at the midpoints of the receiver dipoles and then extending 450 m beyond each end of the receiver array. The dc/IP survey data were initially acquired in the pole-dipole array mode, and the system was then reconfigured to

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**Figure 9.** M-zone two-dimensional dc resistivity inversion results, collated from 13 survey lines and shown as depth slice plans, from 100 to 1000 m. Notice (a) fault-like near-surface lineament at 100 m that coincides with powerline (PL), (b) followed by relative homogeneity at 250 m, (c) at 380 m the development of weakly conductive, alteration-like signature that coincides with M-zone, and (d-f) from 500–1000 m the progressive strengthening as well as SE–NW migration of a linear resistivity low in the basement that is consistent with M-zone graphitic conductor with a potentially northwest dip.
sequentially acquire pole-pole and dipole-dipole data at identical sites on the same survey line. Tensor audio magnetotelluric data were also obtained in the 0.1.–10 k Hz frequency bandwidth for direct comparison.

**Two-dimensional DCIP inversion.** Two dimensional inversions of (a) dipole-dipole, (b) pole-dipole, and (c) pole-pole array dc resistivity data acquired over M-zone line 100S (Figure 8) are remarkably similar to those predicted in the synthetic inversions (Figure 7). This includes the relative differences in vertical depth penetration, with dipole-dipole having the least penetration (<600 m), followed by pole-dipole (>1 km) and, as expected, pole-pole has the greatest (>1.5 km). Other contributing factors, not shown, were the relative noise levels in the raw data, which were greatest for the dpdp and the least for pldp, closely followed by plpl, which further diminished the dc/IP penetration and arise from inherent primary voltage signal and telluric noise levels in each of the arrays.

One last but significant result for exploration is the relative lack of discernable powerline effect in the dc resistivity data and inversions, except as a narrow lineament in the shallowest depth levels (Figure 9a), relative to what might have been expected from transient EM. However, in spite of a similar result for the tensor MT (Figure 10e), the powerline no doubt contributed to a below average IP data quality that weakens the apparent IP effect over the M-zone for the northernmost lines at Wheeler River (Figure 10b-d).

**Multiparameter two- and three-dimensional inversion.** Figure 10 compares the 2D dc, IP, and MT inversions obtained over M-zone with three-dimensional inversion results that combined pldp data obtained from thirteen consecutive 100–200 m spaced lines adjacent to M-zone. The 3D dc/IP inversions were performed using the Res3dim code of Loke and Barker (1996b) and the 2D MT inversion was based on the Pw2di code of de Lugao and Wannamaker (1996). These highlight the remarkable similarities between the various technologies and model types, in relation to the geologic interpretation overlay, such as the apparent west dip of the M-zone conductor, albeit steeper in the 3D dc/IP results, the possible SE dipping granite-metasediment contact, best defined in the MT, the unexplained layer-like polarizeable unit in the overlying Athabasca sandstones above the UC, and the coincident IP high/dc low feature, highlighted in the 3D results, that is consistent with the graphitic target host rock.

The Wheeler River three-dimensional dc/IP inversion results are also shown as 3D volumes of the chargeability and resistivity, from surface to >1 km depth (Figure 11). These images highlight the well-correlated behavior of the dc resis-
tivity and chargeability features, notably near-surface dc low/IP low features caused by lake-bottom sediments, layer-like IP high/dc low at base of sandstone near unconformity, as yet unexplained, and deep dc low lineament and coincident IP high that correspond to M-zone graphitic conductor, and potential alteration zone lying in sandstones above it.

Conclusions. Two-dimensional synthetic modeling and inversion studies have provided useful information on some basic questions regarding dc survey design and implementation in the Wheeler River-Moore Lake geologic environment and other areas of the Athabasca Basin area that are being explored. DAS systems have permitted the successful testing of a wide variety of electrode array configuration for targets at great depth. Multiparameter and multidimensional inversion results offer complementary and sometimes contrasting images in complex 3D geology.