Advances in Integrated Exploration for Unconformity Uranium Deposits in Western Canada

R. Matthews[1], R. Koch[2], M. Leppin[3]

1. Camexco Corporation, Saskatoon, Canada
2. Cogema Resourecs Inc., Saskatoon, Canada
3. Uranerz Exploration & Minerals Ltd., Saskatoon, Canada

INTRODUCTION

Unconformity deposits comprise the most significant high grade, low cost uranium resource on a global basis. The general geological setting of this class of deposit is reviewed by Ruzicka (1993) and Gandhi (1995). The Athabasca Basin deposits in Saskatchewan accounted for over 30% of the world production of uranium in 1996. Production came from mines located at Key Lake, Rabbit Lake and Cluff Lake, the first generation of mines in this prolific basin. These mines were generally at shallow depths, less than 200 m. Relatively shallow penetrating geophysical methods, surface geochemical techniques, including radioactive boulder prospecting, in combination with reverse circulation drilling and diamond drilling were used to find these deposits. The future development of a new series of deeper mines in the Athabasca Basin, as well as the potential development of deposits in the Thelon Basin in the Canadian Northwest Territories and the McArthur Basin in Australia, will add to the production importance of unconformity deposits. In particular two new mines in the Athabasca Basin are exceptional in terms of grade and tonnage and depth. The McArthur River deposit, which was recently given federal and provincial government approvals for development, is located at a depth of 550 m, and has reserves and resources estimated at 416 million pounds U_3O_8 with an average grade of 15% U_3O_8. The Cigar Lake deposit, located at a depth of 400 m, has geological reserves estimated at 350 million pounds with a grade of 7.9%. The richest zone contains 226 million pounds at 12.2%. Considering the contained uranium resource the dimensions of these two deposits are significant from an exploration viewpoint. The McArthur River deposit is at its maximum surface projection no more than 30 m wide, but mineralization continues for 1.2 km along strike. The bulk of the Cigar Lake deposit occurs in an equivalent area of one city block. The trend toward deeper exploration, particularly in the Athabasca Basin, is inevitable and is in part the driving force behind this paper. Three case histories for deposits found in the last ten years are described.

General regional geology—Thelon and Athabasca basins

The position of the Thelon and Athabasca Basins in relation to the major geological provinces is discussed by Hoffman (1989). The Athabasca Basin straddles the Rae and Hearne Provinces, whereas the Thelon Basin is located in the Rae Province (Figure 1). The Rae and Hearne form part of the Churchill Structural Province, which is located between the Superior Structural Province to the east and the Slave Structural Province to the northwest. The Rae and Hearne Provinces are separated by a major northeast trending crustal structure, termed the Snowbird Line (Hoffman, 1989). This structural trend passes through the Athabasca Basin and close to the Baker Lake Basin, nearby a line of uranium radiometric anomalies and gravity lows referred to as the Athabasca Axis (Darnley, 1981). Other major Hudsonian shear zones underlie both basins. These shear zones are thought to be a controlling factor during sedimentation. Sub-basins within the Athabasca Basin are bounded by these major faults (Ramaekers, 1981).

The Churchill Structural Province in northern Saskatchewan has been subdivided into several lithostructural crustal units, which are shown in Figure 2 (Lewry and Sibbald, 1979, 1980). The units underlying the Athabasca Basin include the Western Craton and the Cree Lake Zone. The westernmost limit of the Cree Lake Zone corresponds to the boundary of the Hearne Province, while the Western Craton forms part of the Rae Province. These lithostructural crustal units are further divided into domains and the contact between two of these domains, the Wollaston and the Mudjatik Domains, may be important in terms of the position of major uranium deposits. The Virgin River Domain, a northeast trending zone of mylonitic gneisses, forms the boundary between the Hearne-Rae or Cree Lake Zone-Western Craton.

In the western portion of the Athabasca Basin the Western Craton is divided into the Western Granulite, Clearwater and Firebag Domains. The Cluff Lake deposits and the Carswell Structure lie just to the east of the magnetically interpreted northeast trending Clearwater Domain. The Clearwater Domain has been interpreted to be a Hudsonian mobile zone similar to the Wollaston and the Virgin River Domains to the east. The boundary has been defined as a major crustal thermotectonic boundary (Lewry and Sibbald, 1980), which is gradational and marks the transition from mantled gneiss domes to migmatitic gneiss nappe lobes. The crystalline basement of the Mudjatik Domain consists mainly of felsic gneisses of granitic to granodiorite composition with subordinate supracrustal gneisses. Mantled gneiss domes, rocks which have undergone granulite facies metamorphism and have diagnostic arcuate tectonic and magnetic styles, are characteristic of the Mudjatik Domain. In the Wollaston Domain a more linear dome-and-basin pattern is noted, including a higher proportion of supracrustal gneisses of the

In “Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration” *edited by* A.G. Gubins, 1997, p. 993–1024

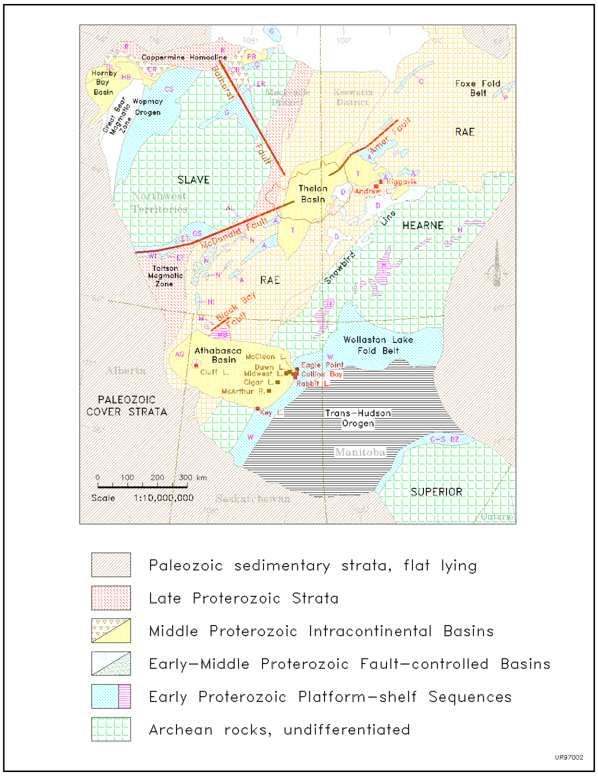

Figure 1: *Location map, Athabasca-Thelon Basins relative to the Hearne-Rae-Slave provinces (modified from Gandhi 1989).*

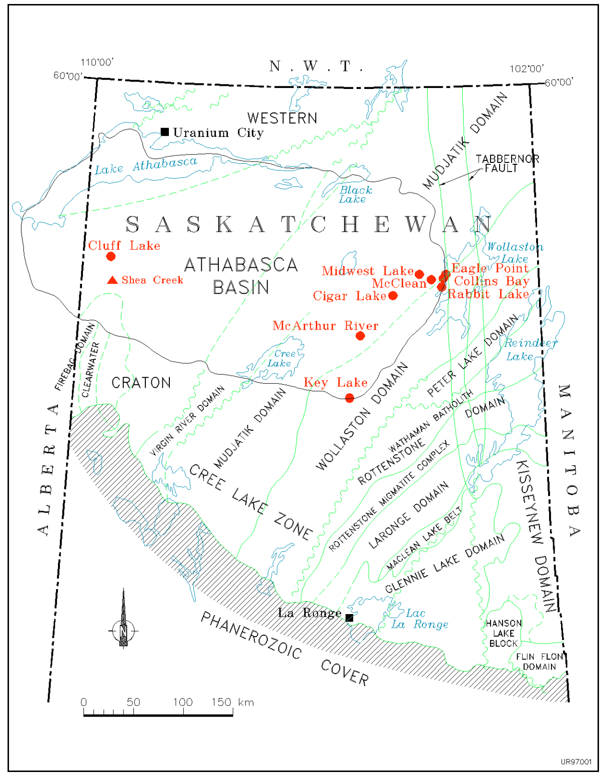

Figure 2: *Lithostructural domain map for northern Saskatchewan, showing the position of the Athabasca Basin and uranium deposits (modified from Sibbald 1983).*

Wollaston Group. The elongate, doubly plunging domes are generally Archean granitic gneisses.

Archean crustal blocks and bordering lithostructural domains, including Hudsonian mobile zones, have different lithological compositions and a different thermotectonic history. The domains can be outlined in the gravity anomaly map for the Athabasca Basin (Figure 3). This map is based on gravity measurements obtained at 13 km intervals (Walcott, 1968). The gravity field was corrected for the reduced attraction caused by the less dense (–0.4g/cm^3) basinal sandstones. Several elongate gravity highs and lows are mapped, trending northeast for hundreds of kilometers. The total gravity relief is approximately 50 mgal. Gravity highs spatially correlate with granulite facies metamorphic rocks and metamorphic terranes, composed of granitic gneisses and supracrustal rocks. These areas likely represent the cores of Archean crustal blocks. The gravity lows are often associated with amphibolite facies terranes, in part retrograde granulites, composed of granitic gneisses and supracrustal rocks, and in part Hudsonian mylonite zones, for example the Virgin River Shear (Wallis, 1970).

A two dimensional, isostatically uncompensated gravity model for the basement underlying the Athabasca sediments is presented in Figure 4. The location of this east-west profile is shown in Figure 3. The model indicates lateral lithological density variations of less than 0.1 g/cm^3 within an upper crust of thickness 25 km. The gravity model and trends of high horizontal gradient were used to map the major crustal blocks shown in Figure 5. The boundary regions are interpreted to represent zones of structural weakness and are sites of repeated tectonic activity, particularly during the Hudsonian orogeny.

The regional aeromagnetic data for the Athabasca Basin is shown in Figure 6. The data is gridded to 813 m and is published by the Geological Survey of Canada. This map may be used to trace keels of metasediments and retrogressed Archean granulites, overlying Archean rocks below hundreds of meters of Athabasca sandstone. Elongated trends of low magnetic intensity often represent these supracrustal rocks, which are likely of Paleoproterozoic age. The interpreted metasedimentary keels and boundaries of crustal blocks are shown in Figure 5. The major supracrustal trends generally follow the postulated crustal structures. Towards the end of the Hudsonian orogeny and after the major fold events, which created the doubly plunging antiforms of the Wollaston Domain, the structural zones were overprinted by major strike-slip movements. At this time there is evidence that graphite was mechanically concentrated along fault planes. The tectonically reworked graphitic strata often form good conductors, which may be geophysically delineated below hundreds of meters of sandstone. Some of the most significant basement conductive zones underlying the eastern Athabasca Basin are shown in Figure 7, together with interpreted major structural zones. The northeast trending, dextral transcurrent fault system was constructed from the conductor maps and magnetic low trends. Many of the uranium deposits appear to be spatially associated with these systems, particularly in areas of duplex structures and associated crustal extension.

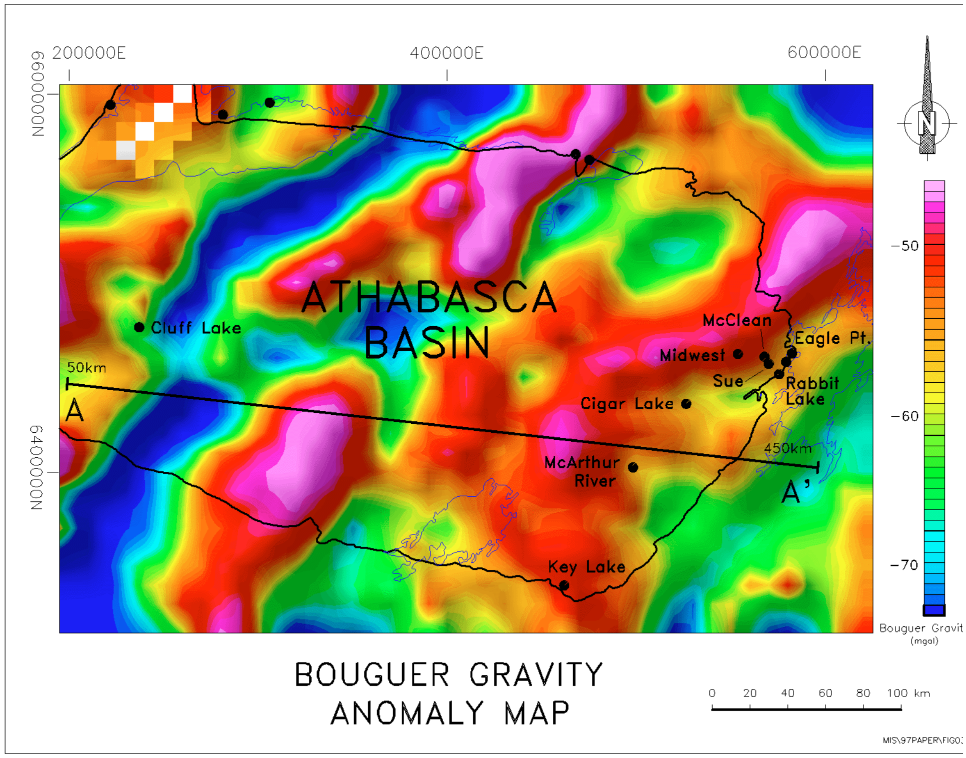

Figure 3: *Bouguer gravity anomaly map. The data was corrected for the reduced attraction caused by basinal sediments of low density. Line AA' indicates the location of the density model in Figure 4. The Athabasca Basin is outlined, and the location of major uranium deposits are shown.*

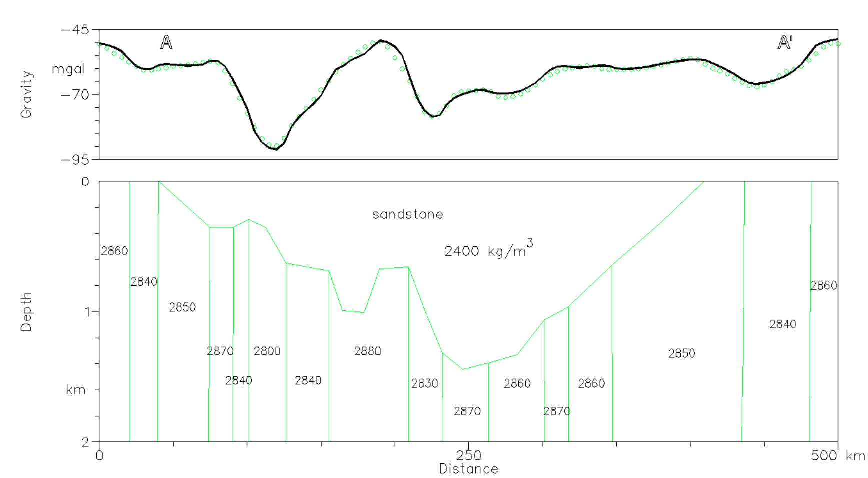

Figure 4: *Line AA' gravity model (location shown in Figure 1). The solid line in the upper panel denotes the calculated gravity anomaly of the density model shown in the lower panel. Circles mark the observed Bouguer gravity anomaly. Density variations occur in the upper 25km of the crust. The thickness of the Athabasca basin sediments is inferred from drillhole and seismic data.*

Figure 5: *Block model of the density structure of the crystalline rocks underlying the Athabasca basin. Dashed lines mark the boundaries of crustal blocks. They are interpreted to represent zones of repeated tectonic activity. Outlined are trends of low magnetic intensity. They often represent supracrustal rocks. The lithostructural domains of the region, and the major uranium deposits are also shown.*

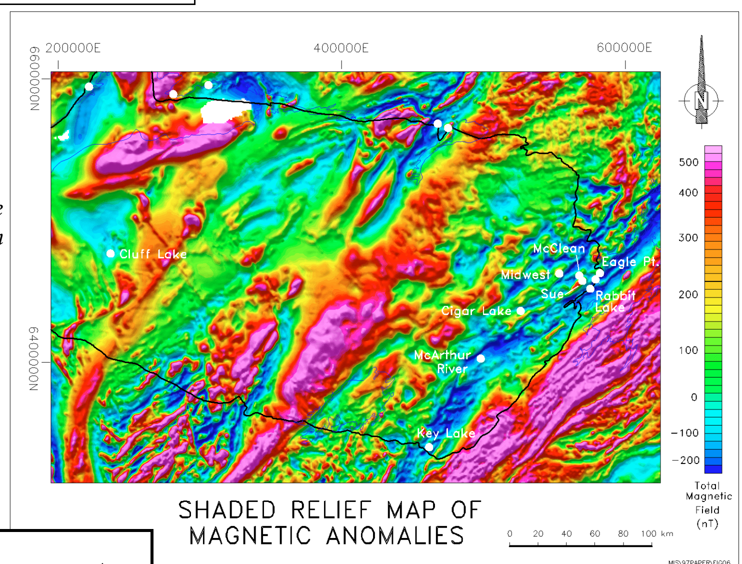

Figure 6: *Shaded relief map of magnetic anomalies. The Athabasca Basin is outlined and the locations of major uranium deposits shown.*

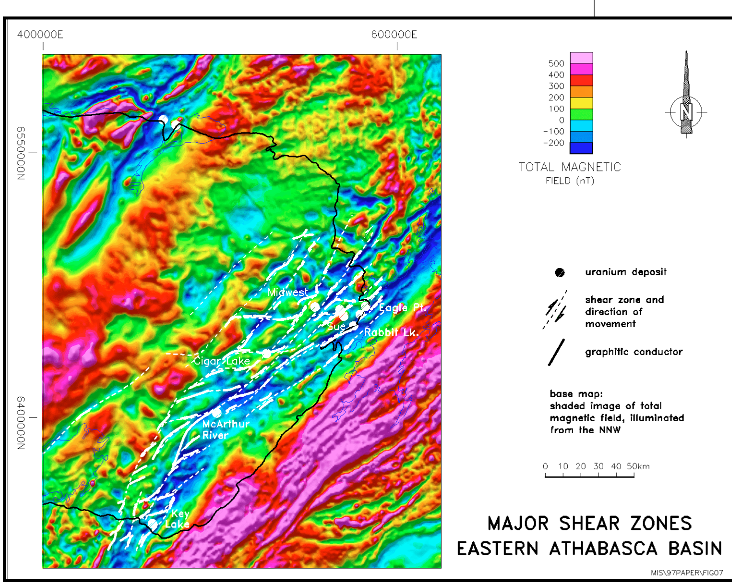

Figure 7: *Major shear zones in the crystalline rocks underlying the eastern Athabasca Basin. These are interpreted using mapped graphitic conductors and linear trends of low magnetic intensity. The base of the map is the shaded magnetic relief shown in Figure 6.*

Empirical parameters of regional exploration and relationship to geophysical and geochemical surveys

Regional exploration methods are tied to the development of the exploration model, particularly its empirical relationships. Properties of the empirical model include the presence of a relatively undeformed Mesoproterozoic sandstone basin, the spatial association of mineralization with a sandstone-basement unconformity and the presence or absence of particular basement rocks—including Paleoproterozoic passive continental margin metasediments with high clarke values of uranium. All deposits are associated with major regional post-sandstone structures, in particular oblique reverse faults, which may have their roots in reactivated basement structures, often along Archean granitoid gneiss-pelitic gneiss contacts. The significance of the overall alignment of deposits in the eastern Athabasca basin with a major Hudsonian crustal boundary, referred to as the Mudjatik-Wollaston boundary, is not fully understood. The boundary is a first order Bouguer gravity contact and corresponds in part with the Collins Bay fault. This fault is a broad structural zone indicated by the High Resolution seismic survey (Hajnal *et al.*, 1997), recently completed over the eastern margin of the basin along the Points North Road (Figure 41). Several uranium deposits are spatially associated with this fault zone, which has both pre-sandstone (Hudsonian) and post-sandstone displacements.

An underlying feature of the empirical model is the association of deposits with many features of apparently Hudsonian origin, including the mylonite zones and associated "transition series" rocks formed during the late-Hudsonian. Transition series rocks are found particularly at Archean granitoid-pelitic gneiss contacts, which often coincidentally are high strain zones. The deposits, however, were formed between 1500 and 1200 Ma, at least 200–300 Ma after the last expressions of metamorphism (~1720 Ma) and basement mylonite zone development. The mylonites themselves have been recrystallized under amphibolite facies metamorphism. These crustal scale faults were intruded by radioelement enriched granites and were the focus of increased heat flow, fluid migration, chemical alteration and anatexis (Wheatley *et al.*, 1995). The last phases of U-enriched granite and pegmatite intrusion occurred in the time interval between 1815 Ma and 1720 Ma (Annesley and Madore, 1996). Despite the age disparity the processes for most unconformity deposits studied to date are intimately linked to reactivated Hudsonian lithostructural elements. Many explorationists would also extend basement controls to immediate source rocks to account for the metal content of the deposits. Others would assign the controls to an indirect source, in which case erosion of basement rocks contributes to metalliferous sandstones, which are subsequently stripped by diagenetic and hydrothermal fluids.

The biggest single empirical factor driving exploration in the Athabasca Basin is the association with graphitic conductive basement packages. All major deposits in the Athabasca Basin are directly associated with fault structures coincident with graphitic conductors. The Key Lake, Cigar Lake and McArthur River deposits were all essentially found by drilling airborne and ground defined electromagnetic conductors located in magnetic lows. In deeper areas basement supracrustal packages with low magnetic susceptibility, are the first order targets within Hudsonian mobile zones. Deep penetrating ground electromagnetic surveys are applied to locate graphitic units. Graphite can be both metamorphic and tectonic in origin. The presence of tectonically remobilized graphite along the Collins Bay fault, which is oriented at a significant angle to metamorphic foliation, coincides with some of the strongest EM responses.

The presence of graphite, graphite destruction near the unconformity, hydrocarbon buttons and the characteristic smell in the vicinity of deposits has lead to the supposition of graphite destruction and the formation of hydrocarbons such as methane as the main reducing medium (Hoeve and Sibbald, 1978). The question is whether or not graphite is necessary in the formation of unconformity deposits. If graphite simply plays a structural role then the strong possibility exists that just as many deposits fall off conductors. One observation is that there are unconformity deposits with little or no graphite in the immediate vicinity; including Narbalek in Australia, Kiggavik and Andrew Lake in the Thelon Basin and deposits at Cluff Lake (D Zone, Dominique-Peter) in the Athabasca Basin. In the case of the basement-hosted Eagle Point deposit in the Athabasca Basin mineralization is found 50 m from the nearest graphitic conductor, which is associated with the Collins Bay fault. With the exception of the Cluff Lake D Zone the deposits without reported significant graphite are generally basement-hosted, and have relatively low grade and simple mineralogy (i.e., mainly uranium without complex arsenide assemblages). The higher grade and larger deposits at McArthur River, Cigar Lake and Key Lake certainly have a direct association with graphitic conductors.

Recent papers based on stable isotope constraints (Kyser *et al.*, 1989) and geochemical modelling (Kominou and Sverjensky, 1996) have suggested that graphite is not required for the formation of an unconformity deposit. This implies that the role of graphite is restricted to the formation of fault zones, allowing oxidized basinal brine to interact with reduced basement lithologies.

The topography of the unconformity is important in terms of potential control on fluid movements. Gravity surveys have been undertaken in an attempt to define this topography. The recent Lithoprobe seismic transect along the Points North Road (Hajnal *et al.*, 1997) also proved useful in delineating unconformity topography as well as distinct fault related displacements (Figure 38). Many deposits are associated with offsets in the unconformity. Significant differences in unconformity elevations between two drill holes could be the result of faulting or pre-sandstone topography. The eastern portion of the Athabasca Basin is characterized by a change in unconformity elevation of approximately 5–10 m over one kilometer. There are, however, significant disruptions in this gradient resulting from faulting, for example along the Collins Bay fault, where post-sandstone displacements of the unconformity of the order of 100 m over a lateral distance of 400 m are obtained. Differences in unconformity elevation of up to 500 m over a lateral distance of 500 m can occur in the vicinity of basement quartzite ridges. In this case the difference appears related to a combination of faulting together with variations in the original unconformity topography.

The structural control of unconformity deposits is their one unifying characteristic. In the Athabasca Basin major structural corridors control the position of the deposits. The Collins Bay fault (N45°-60°E), the Key Lake fault N60°E, the Cigar Lake fault (east-west) and the P2 fault at McArthur River (N45°E) are continuous linear to arcuate mainly reverse faults, which can be traced for several tens of kilometers. These post-Athabasca faults are rooted in strongly graphitic lithologies and Hudsonian mylonite zones over most of their length. Mineralized areas may be associated with strike-slip duplexes, which were formed during the Hudsonian, but have been reactivated post-sandstone. Mineralization is often located along flexures in these faults or at the intersection with faults with a northwest, northeast or east-west orientation.

One other aspect of geophysical and geochemical exploration involves the detection of the significant alteration zones developed in basement and sandstone around unconformity deposits. The model of basinal, high temperature (200°C) diagenetic-hydrothermal fluids (Hoeve and Sibbald, 1978) interacting with reduced basement rocks has resulted in potential reductant, precipitated mineralization along redox fronts, and has developed significant mineralization-related alteration zones. The alteration zones are characterized by clay mineral transformations, clay enrichment or clay depletion and silicification in sandstone and in basement. These alteration zones can be detected with geophysical and lithogeochemical drill core and boulder surveys.

GEOCHEMICAL EXPLORATION

Introduction

Geochemical exploration for unconformity deposits in the Athabasca Basin initially focused on radioactive boulder trains and associated overburden drilling, till component analysis, organic bog sampling, lake sediment geochemistry, soil surveys and various types of radon surveys. Attention then focused on sandstone-basement alteration patterns above unconformity deposits, regional alteration patterns along major structural zones and more recently to the delineation of these patterns in more subtle "non-radioactive" boulder trains. Models of the sandstone alteration are continually being refined. These models affect boulder prospecting and the interpretation of drill core lithogeochemistry, as well as the significance attached to physical properties and the resulting geophysical modelling.

Geochemical exploration at the present time is focused on the alteration patterns in sandstone and basement associated with unconformity mineralization in drill holes and surface boulder surveys. This section of the paper will focus on developments in these techniques. One other approach used in past exploration programs is the use of shallow drilling surveys to locate alteration chimneys (Clarke, 1987). This method was tested over deep sandstone and extensive basement conductor trends during the eighties. For various reasons the technique has not become a routine exploration tool, although its use is continually being evaluated particularly as exploration moves to deeper areas of the basin.

Alteration chimneys and relationship to fluid events

Previous papers have delineated regional alteration and deposit scale alteration patterns around deposits (Hoeve *et al.*, 1981a; Hoeve and Quirt, 1984; Sopuck *et al.*, 1983; Fouques *et al.*, 1986; Earle and Sopuck, 1989; McGill *et al.*, 1993). This subject is continually evolving as a result of additional orientation studies, and in the last two years the introduction of infrared spectroscopy has added a new dimension to clay mineral identification (Earle *et al.*, 1996).

The other feature of unconformity deposit alteration, which has continually evolved, is paragenetic aspects of the alteration, including associated clay mineralogical studies, stable and radiogenic isotopic studies, fluid inclusion studies and paleomagnetic work on various stages of hematite. The complicated paragenesis often results in poor correlation between the clay mineralogy of a particular paragenetic step and the actual whole rock alteration patterns derived by lithogeochemistry, X-ray diffraction (XRD) and infrared sprectroscopy.

Sampling and analytical techniques

Three different methodologies are used to characterize and quantify clay mineralogical alteration particularly for the sandstone in the Athabasca and Thelon Basins. These involve XRD, normative mineral calculation (Earle and Sopuck, 1989) and more recently infrared spectroscopy, utilizing the PIMA II infrared spectrometer (Earle *et al.*, 1996). Normative mineral calculation is the most used method along with trace element analyses of drill core and boulders. In the Thelon Basin the presence of authigenic feldspar in some samples precludes the use of normative mineral calculations. In this case infrared spectroscopy or XRD methods are used in conjunction with trace element analyses. Trace element analyses are routinely carried out on basement samples. However there is increasing interest in the use of infrared spectroscopy and XRD for discriminating chloritization related to the mineralizing event. The XRD techniques are described in Hoeve *et al.* (1981b). This involves crushing and grinding, followed by extraction of the <2 micron fraction by centrifuging. The clay mineral slurry is transferred to glass slides by the smear-on technique, which gives an orientated specimen suitable for semi-quantitative analysis. The same approach can be carried out for whole rock powders.

The Saskatchewan Research Council (SRC) is at present the main laboratory used by workers in the Athabasca Basin. Recently SRC modified the analytical procedures for the determination of Pb and U contents. A trace element scan using the axial ICP (inductively coupled plasma-source emission spectroscopy) method was used for Pb, and a larger aliquot of the digestion was used in the uranium fluorimetric analysis. These modifications resulted in more precise results particularly at the lower concentrations normally found in sandstone. Detection limits for trace elements are 0.2 ppm for Pb, Ni and Cu, and 0.1 ppm for U. Background partial uranium contents in the Manitou Falls D formation of the Athabasca sandstone is 0.3 ppm U.

The application of near infrared or short-wavelength reflectance spectroscopy to mineral identification is summarized by Hunt (1977) and Clark *et al.* (1990). Reflectance spectra in the 1300–2500 nm spectral range are obtained using an Integrated Spectronics PIMA II spectrometer. Spectral resolution for the unit ranges from 6–10 nm. The sampling interval is 2 nm and therefore 601 channels of data are acquired over the range of the spectrum. Spectra for one drill core or boulder sample (fresh surface) can be obtained in one minute. All samples are heated in a microwave oven to drive off excess water prior to analysis. Mineral proportions are estimated using a procedure described by Earle *et al.* (1996), which utilizes peak positions, heights, ratios and slopes.

Regional sandstone alteration

Regional sandstone alteration patterns in the eastern Athabasca Basin based on data from 6500 drill core samples have been previously discussed by Earle and Sopuck (1989). Large regional alteration patterns have been outlined (Figures 8 and 9), within which are located the major deposits and the majority of the prospects. The large illite anomaly in the southeastern portion of the basin is interpreted to be the result of sandstone-basement interaction along an area of significant post-sandstone faulting, across a broad corridor of 10–20 km. Post-sandstone faults are often localized along reactivated Hudsonian high strain zones, which in turn are focused along Archean granitic gneiss-pelitic gneiss and quartzite-pelitic gneiss contacts. The interaction occurred during the immediate pre-ore silicification and desilicification stages, which resulted in vein-type ore in silicified rocks at the McArthur River deposit, compared to the clay-bound ore at the Cigar Lake deposit.

In the northeastern Athabasca Basin the more isolated illite anomalies are more directly associated with mineralization and are located along major post-sandstone reverse faults. The difference in the nature of the regional illite anomalies and ore deposit alteration appears to be tied in part to different structural-stratigraphic regimes. The deposits in the northeastern Athabasca Basin (Cigar Lake to Eagle Point) are located within a lithostructural block, which exhibits a structural style transitional between the dominant northeast trends of the Wollaston Domain and the circular magnetic patterns of the Mudjatik Domain. The eastern boundary of this transitional block coincides with the position of the Collins Bay fault, which is a major post-sandstone structure. Basement quartzite units (as opposed to basement silicified zones) are not found east of the Collins Bay fault, within the transitional block.

Ore deposit halos

Past work on sandstone ore halos suggests that two end members of sandstone alteration patterns are present; desilification-illitization and silicification-kaolinitization-dravitization (Figure 10). Chlorite (sudoite) can be found in both end members and minor silicification fronts can be found in the desilicification end member. The northern portion of the eastern Athabasca is dominated by the desilicification end member, while the southern area is dominated by the silicification end member. As mentioned previously these differences appear to be tied in part to basement stratigraphy and structural regimes, as well as to the intensity of the various paragenetic stages of alteration, including late meteoric events. The silicification of sandstone is particularly prominent above or in the vicinity of basement quartzite ridges.

The illitic sandstone and basement alteration patterns for the northern deposits—Midwest Lake, Cigar Lake and the Collins Bay B Zone—have been previously documented (Sopuck *et al.*, 1983; Earle and

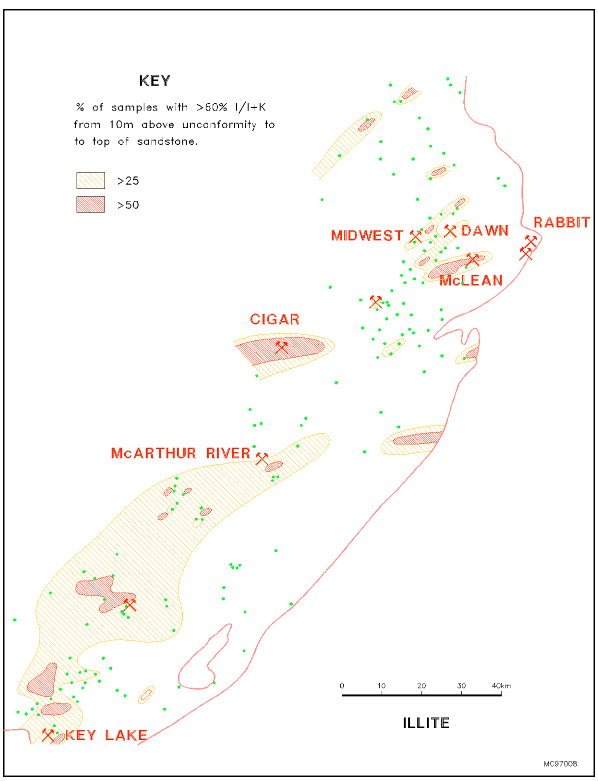

Figure 8: *Regional illite distribution in the eastern Athabasca Basin (from Earle and Sopuck 1989).*

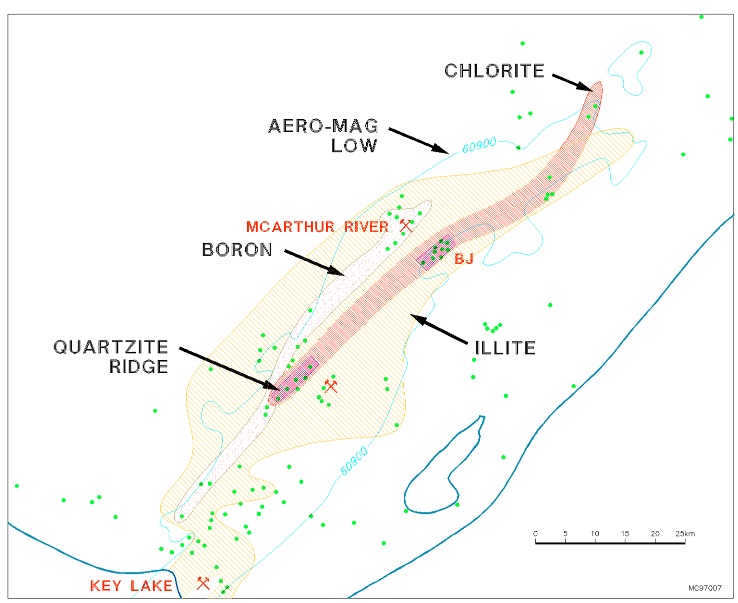

Figure 9: *Lithogeochemical map of the southeastern part of the Athabasca Basin, showing regional illite, chlorite and boron anomalies including the area of low magnetic susceptibility and basement quartzite ridges (from Earle and Sopuck 1989).*

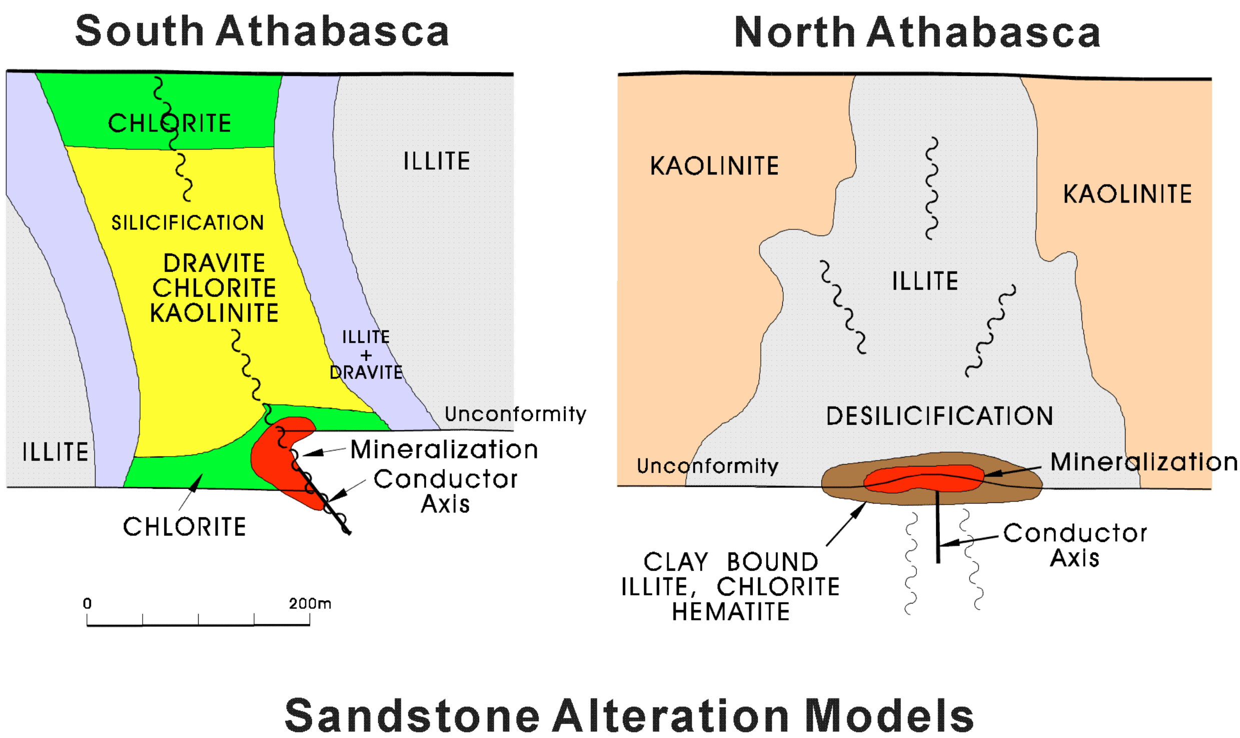

Figure 10: *Two end member sandstone alteration models in the eastern Athabasca Basin.*

Sopuck, 1989). The illite halo at Midwest Lake is of the order of 350 m wide at the base of the sandstone, narrowing to 200 m at the top. This is reflected in the anomalous K_2O/Al_20_3 ratios—a measure of the amount of illite. The illite halo at Cigar Lake is at least 350 m wide with a corresponding uranium halo (>3 ppm). The top of the sandstone uranium anomaly (>1 ppm U partial) is at least 1000 m × 250 m (Clarke, 1987), and is located 400 m above mineralization. In these northern deposits generally smaller halos are developed in Pb, Ni, Co, V, B, Zn, Sr, P_2O_5, and MgO (chlorite and dravite).

The kaolinite halo at Key Lake in the southeastern Athabasca has also been documented by Sopuck *et al.* (1983) and Earle and Sopuck (1989). Recently the halo has been re-examined utilizing infrared spectroscopy (Earle *et al.*, 1996). The paragenesis of the Key Lake kaolinite is a matter of controversy, unlike the paragenesis for illite and certain chlorites, which are usually pre or syn-ore. In the past petrographers have placed the kaolinite as pre-ore (Hubregtse and Sopuck, 1989), syn-ore and post-ore, including a young event at about 300 Ma related to meteoric water incursion. Wilson and Kyser (1987) differentiate three kaolinite types based on stable isotopic and heating experiments, and spatial distribution with respect to the Key Lake deposit. They point to a regional kaolinite, which releases water at higher temperatures than an ore-halo kaolinite (i.e., a more crystalline, regional kaolinite). Based on these results the dominant kaolinite in the sandstone above Key Lake (i.e., the halo kaolinite) may not be related to a meteoric water event as is commonly interpreted, but instead could be closer temporally to the ore event. The above authors also refer to a late fault controlled kaolinite with low δD values. The formation of this kaolinite is associated with a meteoric water event at about 300 Ma, the same time as the major lead loss event advocated by Trocki *et al.* (1984).

McArthur River deposit alteration halo

The geology and lithogeochemistry of the McArthur River deposit has been described by McGill *et al.* (1993) and McGill (1996). The deposit was discovered by Cameco Corporation in 1988 and was delineated by surface drilling through to 1992. Subsequently drilling was carried out underground from the 530 m level along a 300 m portion of the deposit's 1700 m of total strike length. The partners in the joint venture are Uranerz Exploration and Mining and Cogema Resources Inc.

The main structural control for the deposit is a southeast dipping reverse fault (P2 fault) with a vertical displacement of up to 80 m (Figure 11). The hangingwall basement rocks consist mainly of graphitic metapelitic gneisses, including graphite rich fault planes. The footwall basement rocks are predominately made up of arkosic and semipelitic gneisses, together with quartzites. Broad zones of fracturing and brecciation are present in the overlying sandstone. Typically mineralization occurs at depths of 500 m to 570 m and occurs proximal to the fault contact between the sandstone and the overthrust basement rocks. Recently a significant pod of mineralization referred to as the "pelite mineralization" has been found deeper within the fault zone, located within basement metapelitic rocks, which overlie a meta-quartzite unit.

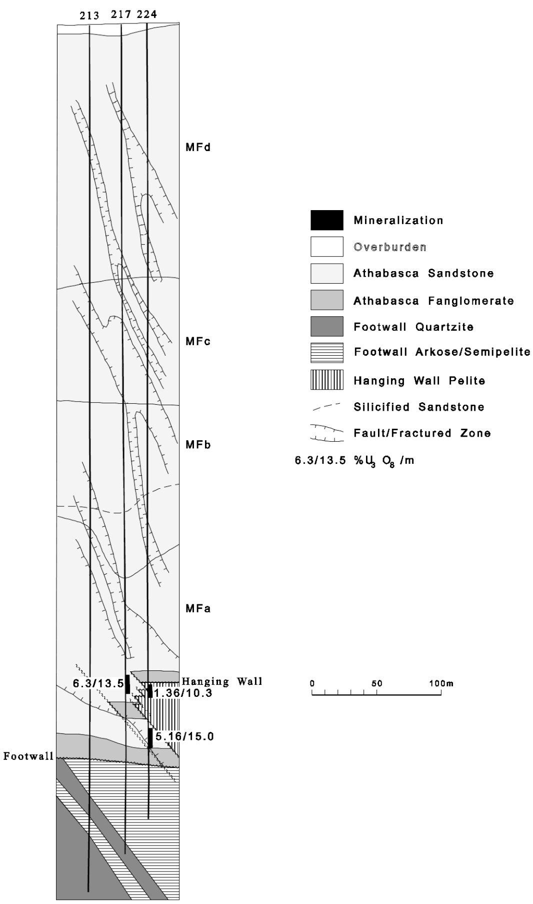

Figure 11: *McArthur River deposit geological cross-section.*

In the vicinity of the deposit, delineated by 2 km of drilling along strike and 90 m across strike, consistent silicification (clay depletion) is noted, as well as uranium enrichment (>1 ppm) extending to the top of the sandstone, significant boron and chlorite (sudoite) enrichments and a distinct clay species distribution. The plan of the drill holes is shown in Figure 12.

Longitudinal sections for uranium, illite-kaolinite and clay depletion are shown in Figure 13. Anomalous uranium greater than 1 ppm (partial) extends to the sandstone-bedrock interface over much of the southern half of the deposit. Silicification (clay depletion) is intense, particularly in the lower part of the sandstone column, 100–150 m above the unconformity. This silicification event is pre-mineralization and in part may have acted as ground preparation for the later brittle structures, which control the McArthur River vein style mineralization. This event, the Q2 drusy quartz event (Kotzer and Kyser, 1995), can be differentiated from an earlier regional sandstone silicification or quartz overgrowth event (Q1), which is one of the earliest recognizable diagenetic events in the basin. The proportions of illite and kaolinite in the sandstone matrix based on geochemistry exhibit a consistent clay layering, which in part coincides with the units of the Manitou Falls formation.

The cross-sections presented in Figures 14 to 16 represent approximately 400 m across the strike of the mineralization. The geotechnical holes to the east (DDH-243 and 257) and the western holes (DDH 251 and 252) have been projected on to the section from distances of 500 m and 50–75 m respectively. Prior to these holes only 90 m of across strike lithogeochemistry was available. Based on the cross-section (Figure 15) uranium contents greater than 1 ppm (partial) extend to the top of the sandstone, but only over a distance of 50–100 m. At a depth of approximately 200 m the greater than 1 ppm uranium halo is at least 450 m wide, a significant anomaly considering the width of the mineralization is only 30 m. A significant anomaly also exists for boron, as reflected in the calculated dravite contents (Figure 16). The dravite anomaly is strongest in the Mfd horizon with the most intense portion located 550 m above the deposit. The most intense dravitization corresponds to values of over 1000 ppm boron.

The PIMA II results (Figure 14) mimic the clay distribution determined by normative geochemistry. The layering of kaolinite to illite to kaolinite is similar to that portrayed in the longitudinal section (Figure 13), however, the PIMA II has identified a more well-ordered kaolinite or "dickite" in the basal sandstone. This also happens to coincide approximately with the intense silicification or Q2 event identified by Kotzer and Kyser (1995), which appears to be pre-ore in age. The question is whether or not this "dickite" is part of the regional "dickite", which is found in background sandstone, located well away from mineralization. The basal sandstone is also located where Kotzer and Kyser (1995) identified a second post-ore generation of kaolinite, referred to as K2.

The kaolinitic and strongly dravitic Mfd horizon (>500 m wide) is similar to the pattern established over the Key Lake mineralization (Earle *et al.*, 1996). Petrographic work, together with the spatial distribution of this kaolinite, suggest it is not late or post-ore, but is pre-ore or syn-ore. The kaolinite paragenesis needs to be resolved, however, the fact remains that a complicated picture of clay mineral species distribution is present.

The presence of the thicker section of illitic sandstone in DDH-257, located 225 m east of the deposit, suggests that sandstones in this area are illitic in character and may be part of the much larger regional illite anomaly present in the southeast Athabasca Basin (Figure 9). The strongly illitic sandstone terminates over the deposit but may pick up again towards the west. Although a complex pattern of clay mineralogy is emerging the fact remains that the pattern is highly anomalous, has significant dimensions and occurs at the top of the sandstone, 550 m above mineralization.

Boulder prospecting

Radioactive boulder trains along with overburden surveys, often involving RCD drilling, played an important role in many of the original discoveries in the Athabasca Basin; Rabbit Lake (Heine, 1986), Key Lake (Dahlkamp and Tan, 1977), mineralized zones in the Carswell Structure (including the D Zone, Tona *et al.*, 1985), Midwest Lake (Scott, 1981), Read Lake (Earle *et al.*, 1990) and BJ Lake (Marlatt *et al.*, 1992). In the last two examples neither electromagnetic ground defined nor drill defined graphitic basement conductors are associated with the mineralization. Of greater significance was the fact that non-radioactive, dravite-bearing boulder trains were related to the mineralization, which is associated with basement quartzite ridges (Marlatt *et al.*, 1992).

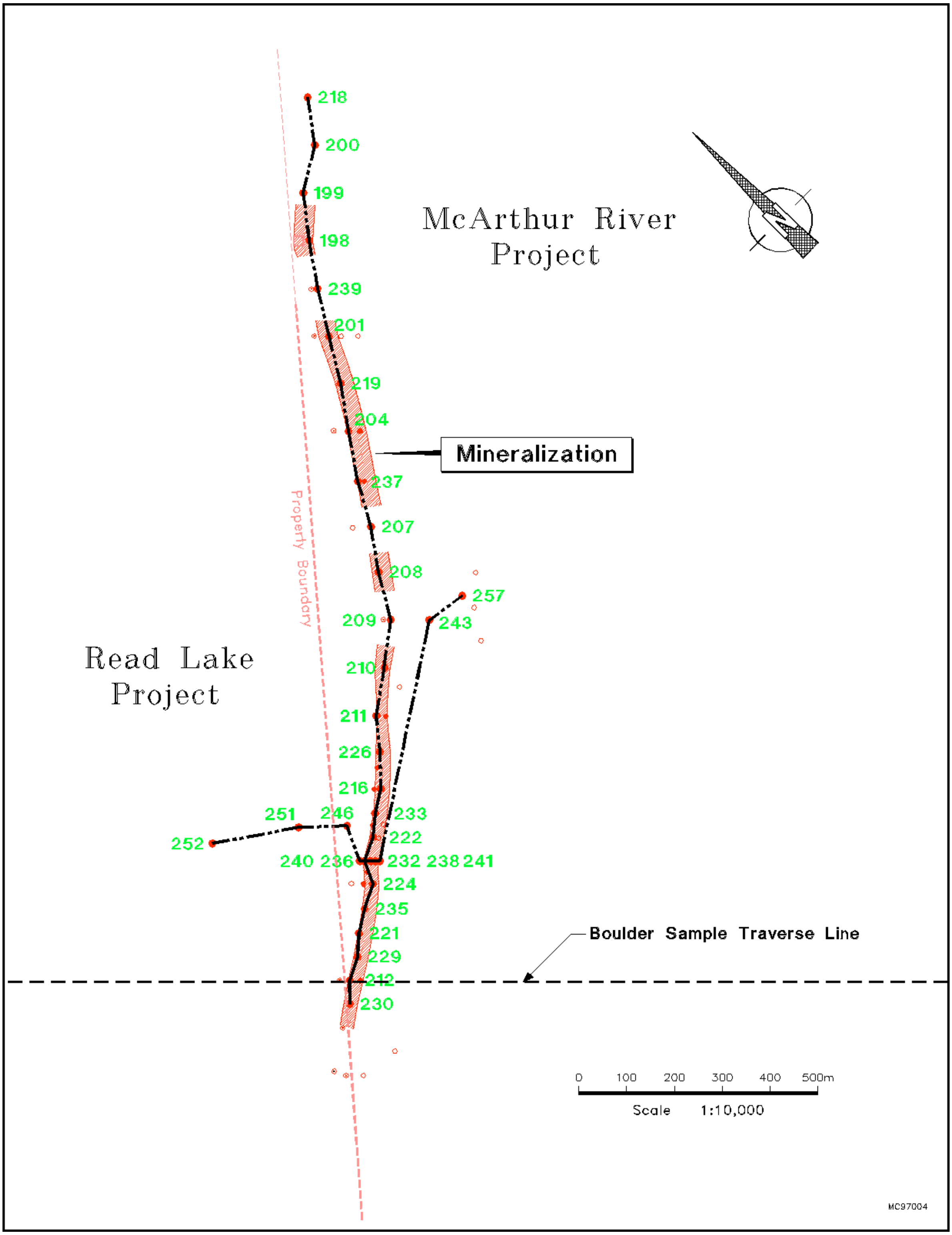

Figure 12: *McArthur River drill hole plan showing position of longitudinal and cross-sections and boulder traverse.*

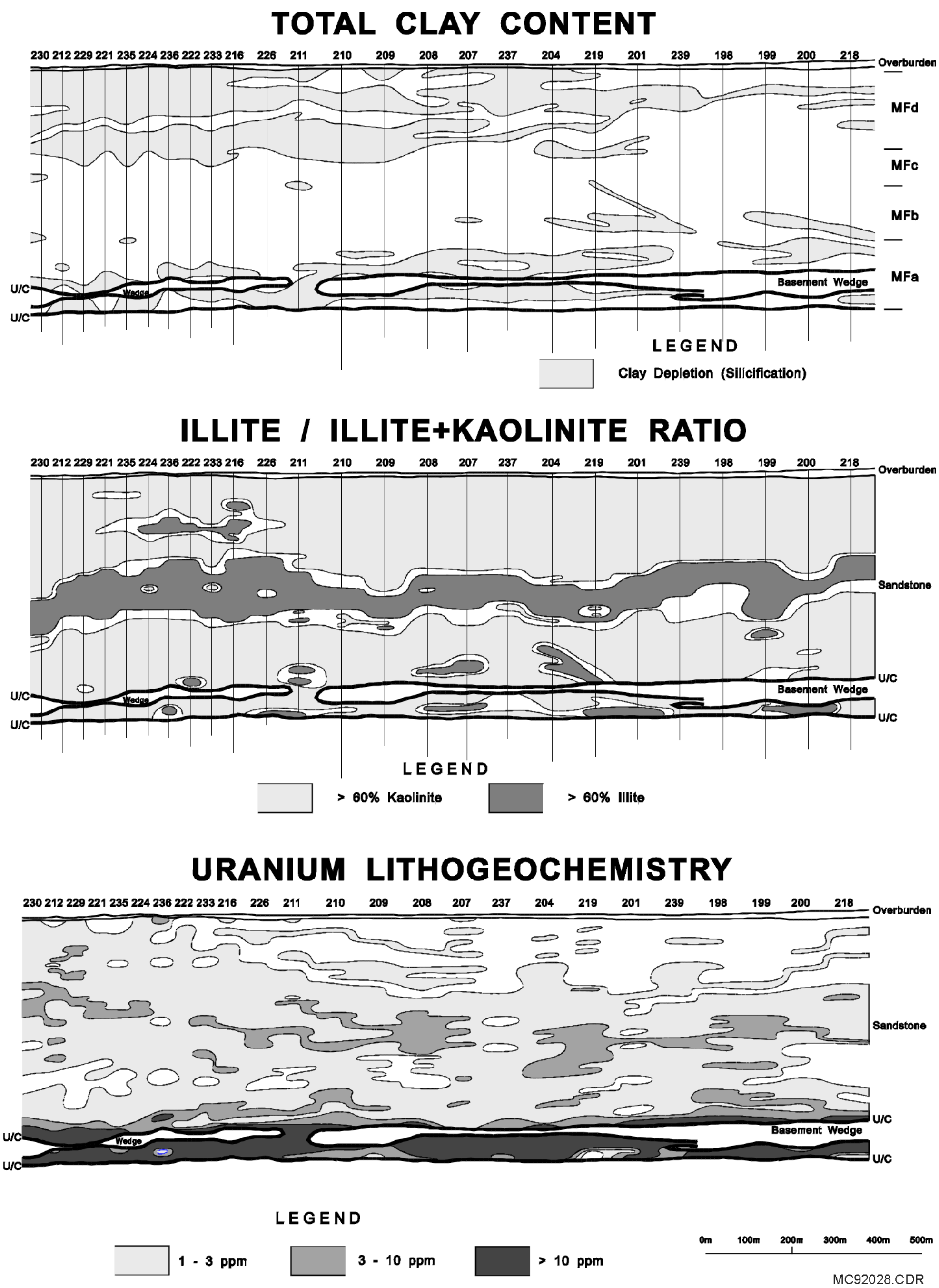

Figure 13: *McArthur River deposit longitudinal section; total clay content, illite/illite+kaolinite ratio, uranium lithgeochemistry.*

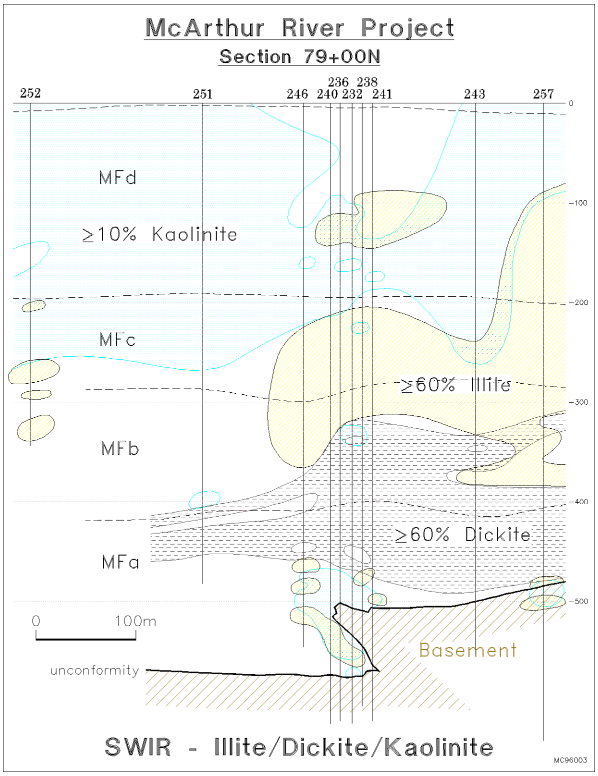

Figure 14: *McArthur River deposit cross-section 79+00N, illite, kaolinite, "dickite" distribution (infrared spectroscopy).*

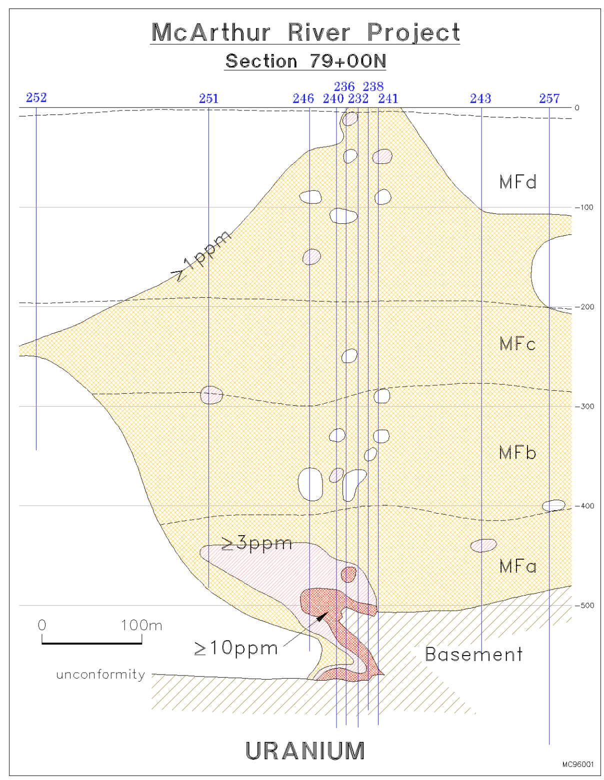

Figure 15: *McArthur River deposit cross-section 79+00N, uranium distribution.*

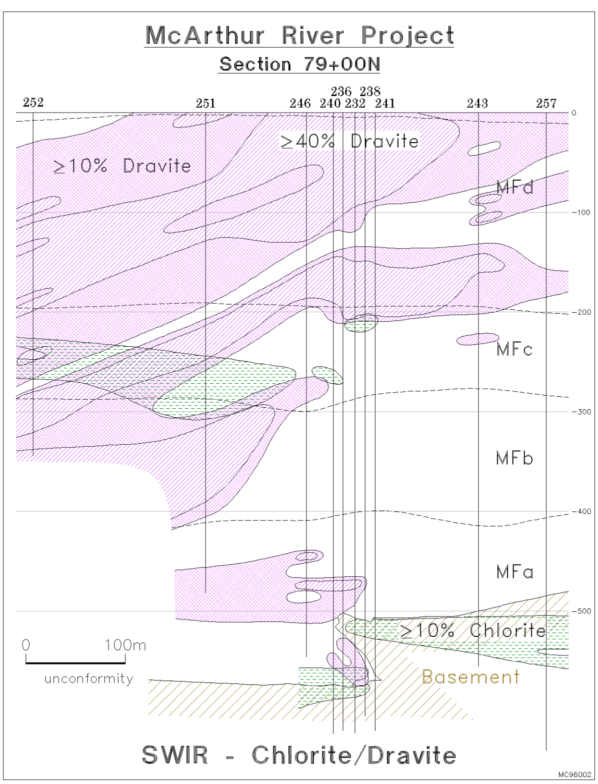

Figure 16: *McArthur River cross-section 79+00N, dravite distribution.*

Despite the success of radioactive boulder trains in locating mineralization it has been apparent since the early eighties that the obvious trains have been discovered. In addition there was the realization that certain deposits did not have an obvious or documented surface radioactive boulder expression; including Dawn Lake, McClean Lake, Cigar Lake and McArthur River. However alteration and elevated uranium contents are found throughout the sandstone column in the vicinity of these deposits. In part the absence of a surface radioactive boulder expression could be related to the lack of understanding of the glacial stratigraphy and/or glacial transport processes for the area as a whole. The most comprehensive overburden stratigraphic information for the eastern Athabasca is found in the Rabbit Lake area. Seven stratigraphic units are described (Geddes, 1982). Two main till units are present; a lower till and an upper till, with the lower till best reflecting bedrock mineralization. Another consideration for the lack of a boulder response could be linked to the sandstone alteration models. Deposits in the McArthur River area are in part associated with competent, often silicified sandstones, while those in the northern portion of the eastern Athabasca Basin are linked to the illitic model, resulting in quartz dissolution and clay enrichment. In the latter case boulders are less competent and may not survive glacial abrasion processes.

After the initial discoveries at Rabbit Lake and Cluff Lake, where overburden drilling surveys were utilized extensively, exploration in the eastern Athabasca Basin focused almost entirely on the drilling of graphitic conductors. Overburden drill surveys were not a significant part of the exploration philosophy and as a result knowledge of the glacial history fell behind. The exception to this trend in exploration was in the Cluff Lake area (Wilson, 1985), where graphite conductors are not obviously associated with mineralization. In this area mobile percussion rigs were used extensively to link radioactive boulder occurrences to the trace element contents of the fine fraction in basal till. In this case the -80 mesh or 180 micron fraction was analysed for 13 elements. Uranium anomalies of 6–12 ppm were considered significant.

Meanwhile in the eastern Athabasca Basin exploration companies focused on more subtle boulder trains, such as the dravite train at BJ Lake (Marlatt *et al.*, 1992). The fine fraction of the Midwest boulder train was examined (Simpson and Sopuck, 1983) utilizing portable percussion equipment. Till train dimensions were significantly enhanced utilizing uranium analyses of the -250 mesh fraction, although uranium values were low, in the range 1 to 38 ppm U. However overburden sampling in the eastern Athabasca was generally ignored until the development of a boulder lithogeochemical technique (Earle *et al.*, 1990). This technique was devised to prioritize areas for drilling along conductors, in particular to pick up the subtle clay mineralogical and geochemical patterns associated with alteration chimneys. The analytical techniques employed were similar to those used on sandstone drill core to delineate alteration chimneys. Although the technique to date has not been instrumental in locating significant mineralization, since most orientation studies have been after the fact, the technique has become a useful exploration method and may become more valuable as exploration moves towards deeper areas and examines areas off conductor trends. Approximately 20,000 boulder samples have been collected to date in the eastern Athabasca Basin.

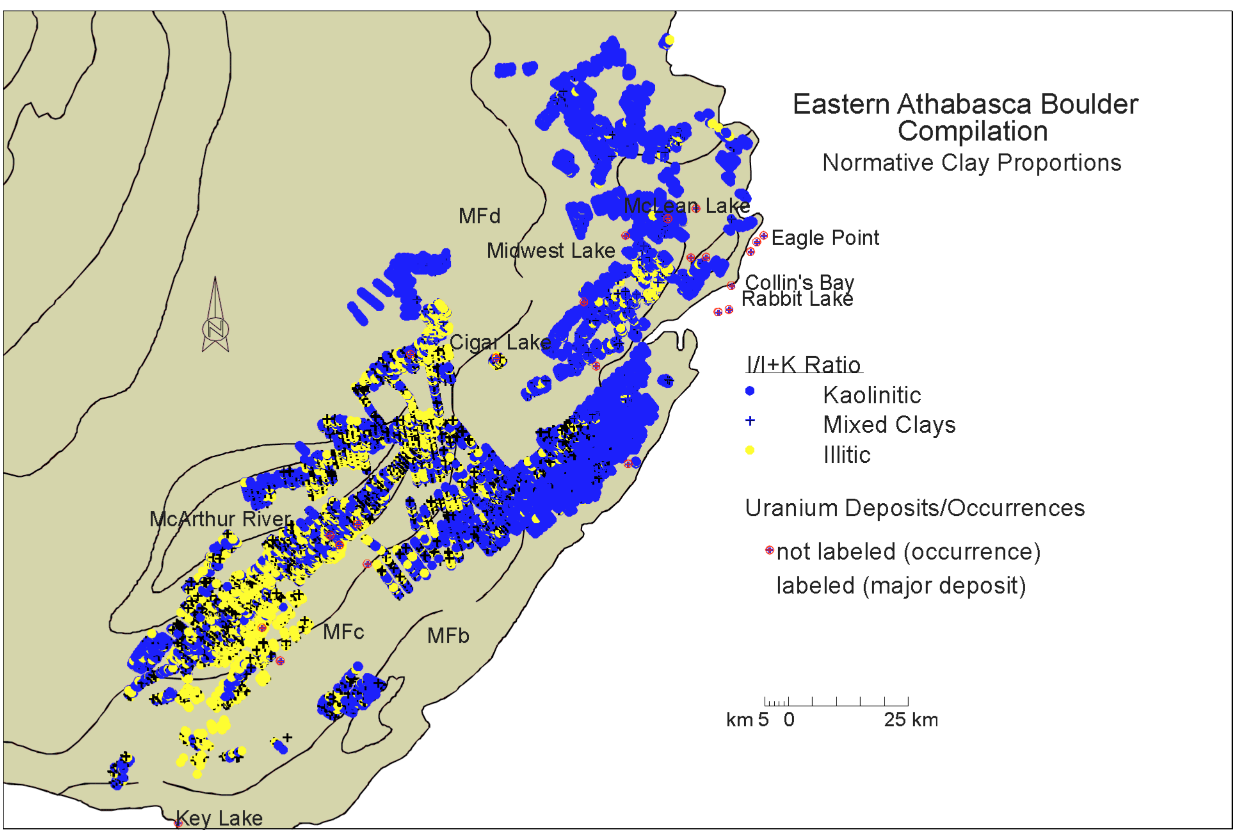

Figure 17: *Regional boulder compilation, eastern Athabasca Basin.*

Sampling and analytical procedures for boulder lithogeochemistry

Sampling and analytical procedures have been described by Earle *et al.* (1990). Composite sandstone samples consisting of approximately ten boulders at each site are collected, within a 10 m radius of the sample station. Reconnaissance samples are generally collected at 100 m intervals along lines perpendicular to ice direction, spaced generally 500–1500 m apart. More detailed surveys or follow-up surveys involve 50 m sample spacing along lines spaced 300–500 m apart.

Analytical procedures are the same as those used for sandstone samples, described under the drill core sandstone sampling procedure. The total uranium content utilizing a three acid dissolution and subsequent fluorometry technique was standard procedure in the first few years. Unfortunately the total dissolution was not the best choice, particularly for deeper sandstone areas. The uranium introduced by contributions from detrital heavy minerals interfered with the interpretation of subtle anomalies in deeper areas. The detection limits of the partial dissolution methods now employed are 0.1 ppm U and 0.2 ppm Pb. The threshold for anomalous samples over deeper sandstone areas (underlain by Manitou Falls D horizons) is approximately 0.5 ppm U.

Regional trends

A compilation of the clay proportions in approximately 20,000 boulders in the eastern Athabasca region is shown in Figure 17. A regional illite anomaly is outlined in the southern part of the eastern Athabasca Basin, which encompasses the significant mineralized zones. In this area mineralization is associated with kandites (kaolinite and/or "dickite") within the illitized sandstones, which also exhibit varying degrees of silicification and dravitization. The illite/kandite distributions in the boulders mimic the distribution depicted by the drill hole compilation (Figure 8).

Deposit area McArthur River

Boulder results for a portion of the McArthur River project are shown in Figure 18. Approximately 400 boulder samples are included. The McArthur River deposit is associated with the contact between illitic and kaolinitic boulders, based on the normative geochemical clay calculation procedure. This contact corresponds to the P2 fault, the main controlling structure for the McArthur River deposit. The sand-

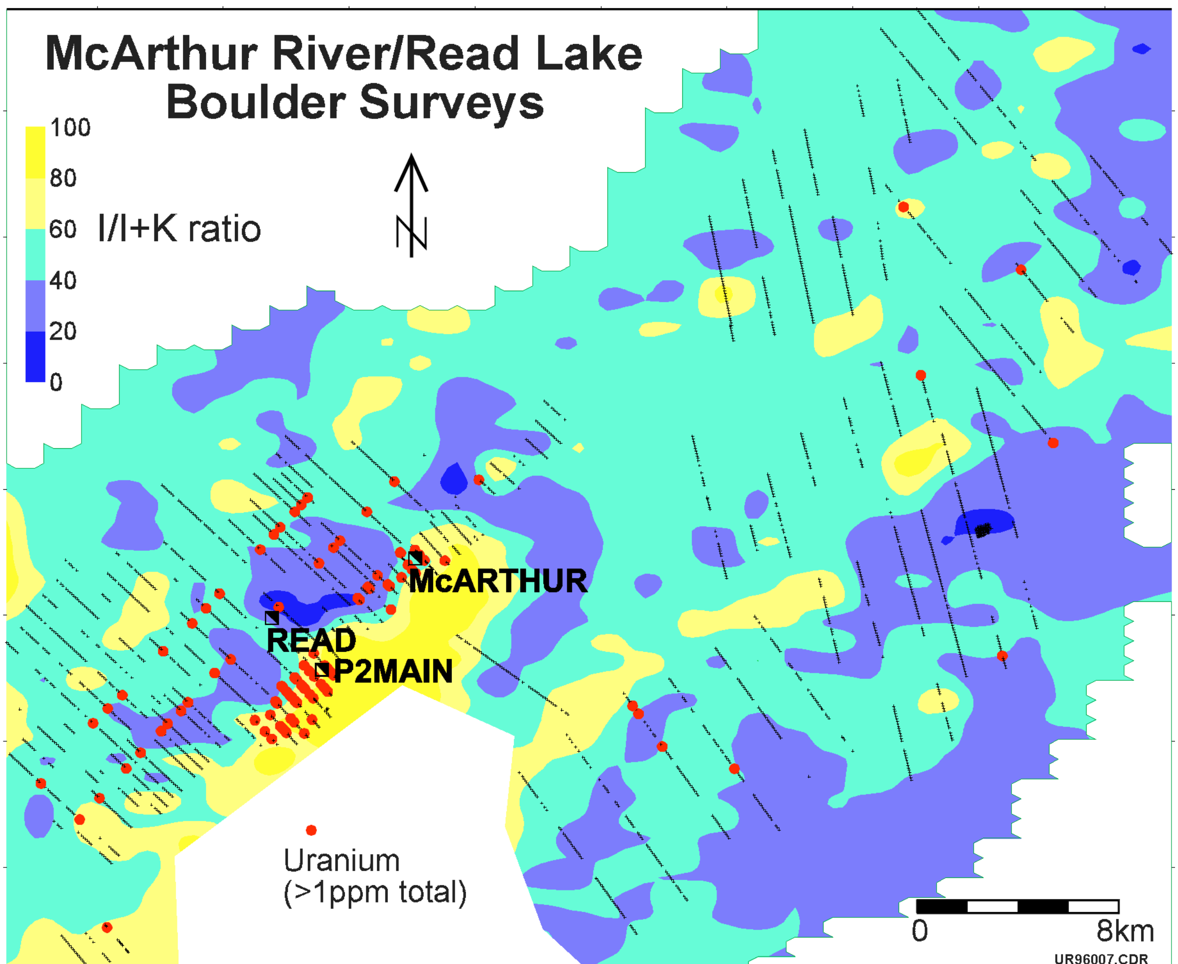

Figure 18: *Portion of McArthur River project boulder compilation, illite/illite+kaolinite (normative geochemistry) with uranium boulders >1 ppm U (position of McArthur River deposit shown).*

stone alteration chimney, characterized previously by geochemistry and infrared spectroscopy, predicts that the dominant kandite species over the deposit should be kaolinite and not "dickite", the regional kandite species. The results from a line of boulders collected over the illite-kaolinite contact are shown in Figure 19. Infrared spectroscopy clearly indicates the kaolinitic verses dickitic nature of the contact area, which is coincident with the main ore controlling structure, the P2 fault. Kaolinite, anomalous dravite and anomalous chlorite in boulders define the alteration chimney over an across-strike (glacial and P2 fault) distance of 400 m. The contribution of infrared spectroscopy is that it has allowed the discrimination of kandite species, which appears to be important in defining mineralization related structures. Boulders above the alteration chimney also have anomalous uranium contents (0.8–1.5 ppm U) over a restricted area.

GEOPHYSICAL EXPLORATION

Since the discovery of the Cigar Lake deposits by Cogema Canada Ltée in 1981 geophysical exploration in the Athabasca Basin has tended to focus on the delineation of discrete basement graphitic conductors and associated structures, primarily by electromagnetic techniques (McMullan *et al.*, 1987). Horizontal Loop Electromagnetic (HLEM) surveys continue to be widely used along the shallow (<150 m) margins of the Athabasca group sandstones to map conductive structures, alteration features, as well as graphitic conductors. Time Domain Electromagnetic (TDEM) Fixed Loop surveys have been used in both mapping and reconnaissance modes in the deeper parts of the basin, though interpretations are often ambiguous due to secondary conductive features, which are commonly encountered in areas favourable to uranium mineralization. These features include contact responses, fault offsets of the sandstone-basement unconformity, conductive structure/alteration, conductive blocks of graphitic metasediments and conductivity associated with the sandstone-basement unconformity, such as regolith and basinal brines. Use of Moving Loop TDEM surveys has grown in the last ten years as an alternative approach for improved discrimination of conductive features. TDEM in-loop and off-loop sounding surveys have been applied successfully on occasion to identify conductive alteration features in both the sandstone and basement. Sounding inversions have also been employed to a more limited extent to identify unconformity offsets, though success largely depends on a good conductivity contrast between the sandstone and basement.

Although airborne electromagnetic and magnetic methods continue to be used as a first pass tool in exploration for uranium deposits, apart from a number of isolated cases relatively few airborne magnetic, EM or radiometric surveys have been carried out over the last ten years. Basic coverage was completed in the early eighties and since then exploration along the margins of the Athabasca Basin has matured and focus has shifted to deeper portions of the basin. Airborne databases are occasionally reprocessed with digital filters with the objective of extracting

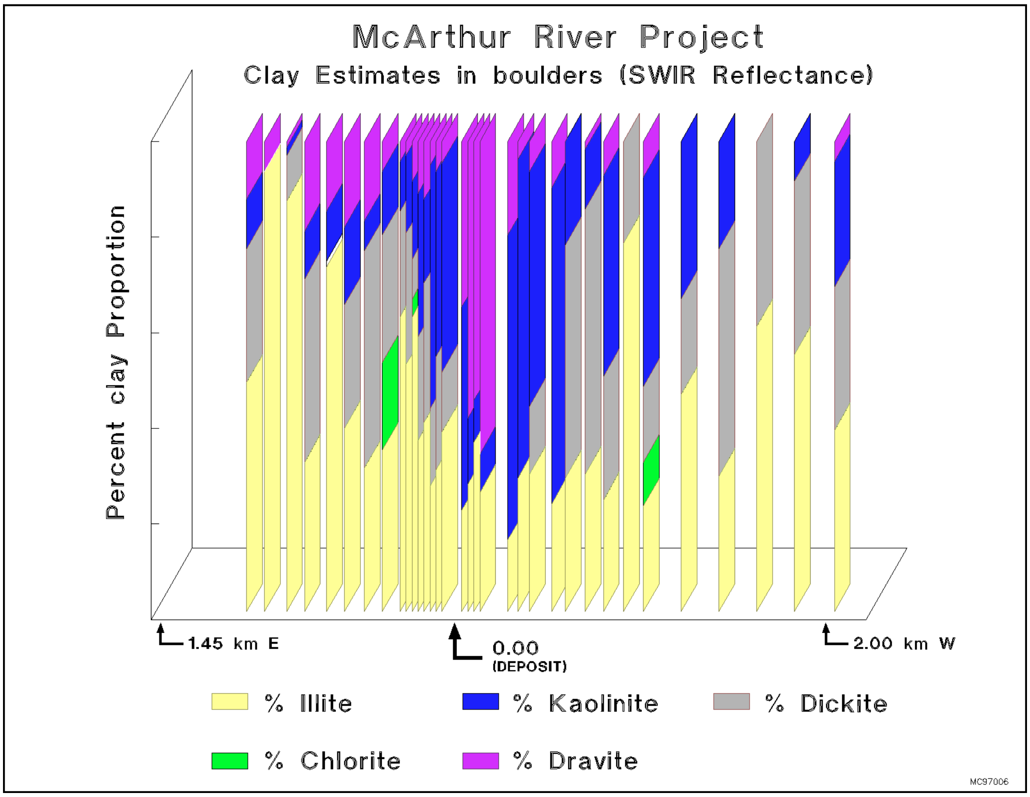

Figure 19: *Detailed boulder traverse across McArthur River deposit—clay determinations and proportions by infrared spectroscopy. The position of the traverse is shown in Figure 12.*

additional information not obtained from the original interpretations, such as definition of conductive basement units, alteration haloes, and improved conductor discrimination. However there will likely be a significant resurgence of flying in the Athabasca Basin within the next decade, since the depth of penetration of airborne EM systems has been significantly improved. Historical airborne magnetic data, together with ground follow up surveys, are continually being reworked to derive additional lithostructural information, including the identification of fault systems and alteration features, such as sandstone hematization and destruction of magnetic minerals in the basement.

Gravity surveys have generally focused on the specific task of identifying structure/alteration features known to be associated with existing unconformity uranium deposits. Notable amongst these are faults, which are usually associated with Athabasca uranium deposits, and which often give rise to vertical offsets of the sandstone-basement unconformity, typically of the order of 30 to 80 m. Anomalies of the order of .5 to 1 mgal are common and successful detection of a fault depends on the size of the offset, the density contrast between the sandstone and basement and the level of noise in the data. Quartzite ridges and paleotopographic high/low combinations in general are also known to be associated with some uranium occurrences and often produce significant gravimetric anomalies, in the range of .5 to 2 mgal. Alteration features are often seen as high/low gravity combinations associated with silicification/desilicification of the overlying sandstone in the vicinity of favourable structures.

Resistivity mapping techniques were commonly used in the late seventies and early eighties in the Athabasca Basin and are still occasionally employed for specific problems to map alteration features and basement lithologies, usually in areas where mineralization or other favourable features have already been identified. It remains an important exploration tool in the Thelon Basin where graphitic host lithologies are not as common. Helicopter EM surveys have been used with success as a resistivity mapping tool over the Sue deposits as well as in the Northwest Territories (Hasegawa *et al.*, 1990). Gradient and dipole-dipole resistivity/IP surveys have enjoyed a small resurgence in recent years in areas where the Athabasca sandstone is relatively thin (<300 m) as a means of mapping the more subtle alteration features in the general vicinity of the known deposits. Electric field EM techniques, such as VLF-Resistivity, and Controlled Source Audio-MagnetoTellurics (CSAMT) have seen limited application, primarily to map basement lithologies and conductive/resistive alteration zones within the Athabasca group.

The application of Borehole EM surveys has fallen off due to the relatively high costs involved, the delays associated with bringing in crews and equipment at irregular intervals and the difficulty associated with keeping drill holes open. The importance of intersecting the targeted basement graphitic conductors has diminished as exploration has refocused attention on the geochemistry, alteration and structures associated with basement graphitic zones.

Geophysical case histories are presented in the following sections for the Andrew Lake, McArthur River and Sue deposits. These case histories clearly illustrate the variety of methods used over the last ten years to locate and define these important discoveries. Large loop EM results are also presented for the Shea Creek project area, located in the western part of the Athabasca Basin. The results illustrate the success of large loop EM methods in defining graphitic conductors at very large depths.

ANDREW LAKE DEPOSIT

Geophysical signature

The Andrew Lake deposit is located on the Sissons project, which is situated in the Rae province at the southwest termination of the Woodburn Group along the east margin of the Thelon Basin (Figure 1) in the District of Keewatin, Northwest Territories. The project is curently operated by Cogema Resources Inc. in joint venture with PNC Exploration (Canada) Co. Ltd. and Daewoo Corporation. The Andrew Lake deposit is estimated to contain a geological resource of 45 million pounds U_3O_8 at an average grade of 0.55% U_3O_8. Uranium mineralization in the area was first encountered in 1974 when radioactive frost boils were discovered at Lone Gull (Kiggavik) during systematic geophysical coverage of the area with airborne radiometric surveys. In 1987–1988, Urangesellschaft Canada Ltd. discovered uranium mineralization at Andrew Lake and on the End grid by drilling geophysical targets (Hasegawa *et al.*, 1990). The fourth hole of the program intersected 1.0% U_3O_8 over 40 m. Structurally controlled uranium mineralization at the Andrew Lake deposit is hosted mainly in deformed metagreywackes of the Woodburn Group (Figure 20). The mineralization is to a lesser extent hosted in all of the rock types in contact with mineralized metagreywacke, including iron formation, syenite and lamprophyre dykes, Lone Gull granite, paragneiss and granite gneiss.

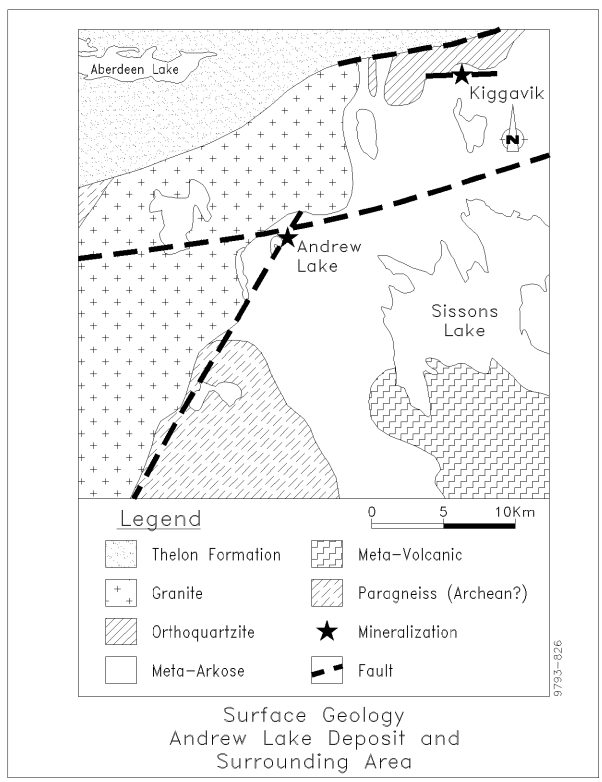

Figure 20: *Surface geology of the Andrew Lake deposit and surrounding area.*

In the Sissons area airborne and ground geophysical surveys, consisting of Helicopter EM and magnetics, resistivity, VLF-Resistivity and gravity surveys, were completed over many of the grids on the project. The use of gravity and resistivity data to assess drill targets was of primary importance. Airborne surveys were flown with a Dighem IV (Fraser, 1979) towed bird, symmetric dipole system, operated at a nominal survey altitude of 30 m. The electromagnetic system utilizes a multi-coil coaxial/coplanar configuration to energize conductors with different geometries. The gradient array technique was employed to carry out ground apparent resistivity surveys in the Andrew Lake area of the Sissons project. The current dipole length was 1600 m while the potential dipole separation was 25 m.

Airborne total field magnetics for the area surrounding the Andrew Lake deposit is shown in Figure 21 and an apparent resistivity map calculated from the HEM data for the deposit area is presented in Figure 22. The apparent resistivity was generated from the in-phase and quadrature EM components for all three coplanar frequencies, using a pseudo-layer half-space model (Fraser, 1978). The pseudo-layer half-space model effectively represents a two layer case, where the resistivity of the upper layer is considered to be infinite and the resistivity of the second (lower) layer is that of the conductive half-space. An apparent resistivity map for the 56,000 Hz coplanar data has been produced for a portion of the project area (Figure 22). Colour contour plots of the residual Bouguer gravity and the gradient array resistivity data over the Andrew Lake deposit are shown in Figures 23 and 24 respectively.

The Andrew Lake deposit is associated with magnetic and apparent resistivity lows. In the case of the Dighem resistivity data the lowest values (<2200 ohm-m) are located to the west of the deposit in a background of greater than 7000 ohm-m. The deposit is situated asymmetrically with respect to the magnetic data. Its long axis is approximately sub-parallel to the north-south trend of the overall magnetic low. The airborne magnetic and apparent resistivity signatures have been interpreted to represent alteration effects from structures associated with the deposit.

The gradient array resistivity results from two 500 m × 800 m rectangles (Figure 23) provide a good comparison with Figure 22. The Andrew Lake deposit falls within a narrow, near north-south trending zone of low values of apparent resistivity (<1000 ohm-m) in a background of higher resistivity (>3000 ohm-m). The resistivity data has outlined north-south and north-northeast/south-southwest structures, which have been interpreted as important in controlling the uranium mineralization of the deposit. The gradient array technique has outlined alteration and/or structural features associated with the Andrew Lake deposit.

A colour contour plot of the residual Bouguer gravity reduced with a slab density of 2.7 g/cm^3, together with the outline of the deposit, is shown in Figure 24. The Andrew Lake deposit is characterized by a northeast-southwest trending, oval-shaped residual gravity low of 0.5 mgal. The gravity low has a wider footprint than the outline of the deposit and is interpreted to represent widespread, near-surface alteration effects. Although the gravity data is diagnostic it does not contain

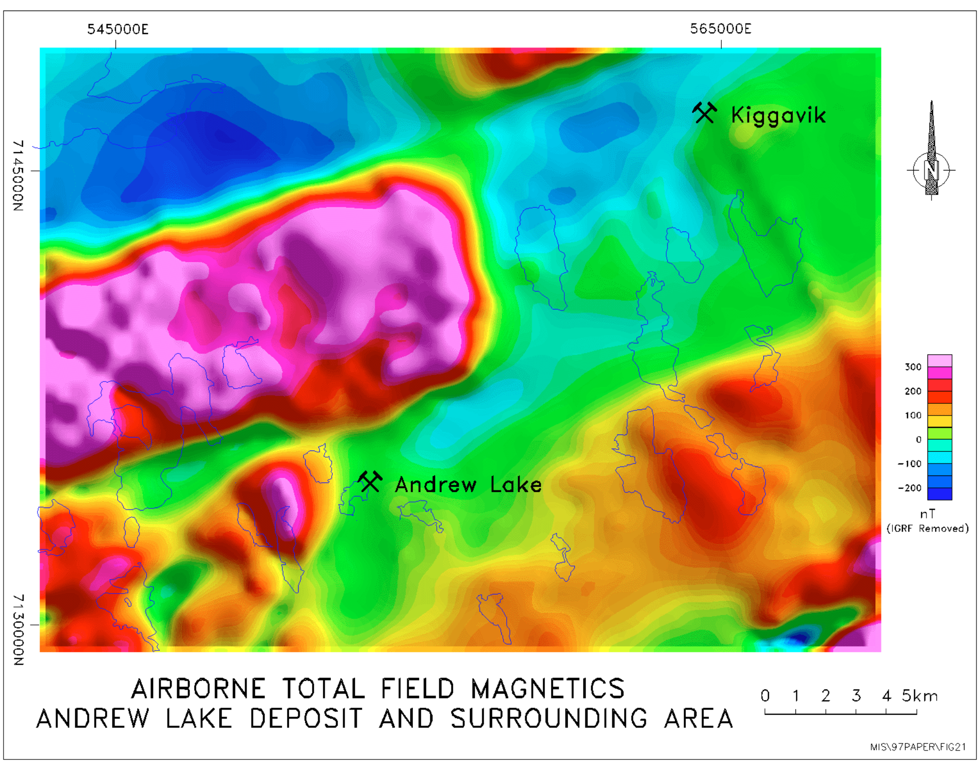

Figure 21: *Airborne total field magnetics, Andrew Lake deposit and surrounding area.*

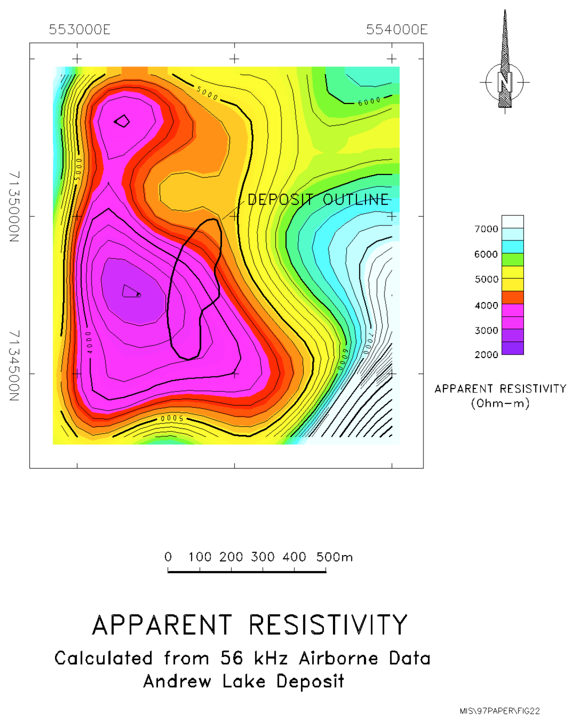

Figure 22: *Apparent resistivity calculated from 56 kHz airborne data, Andrew Lake deposit.*

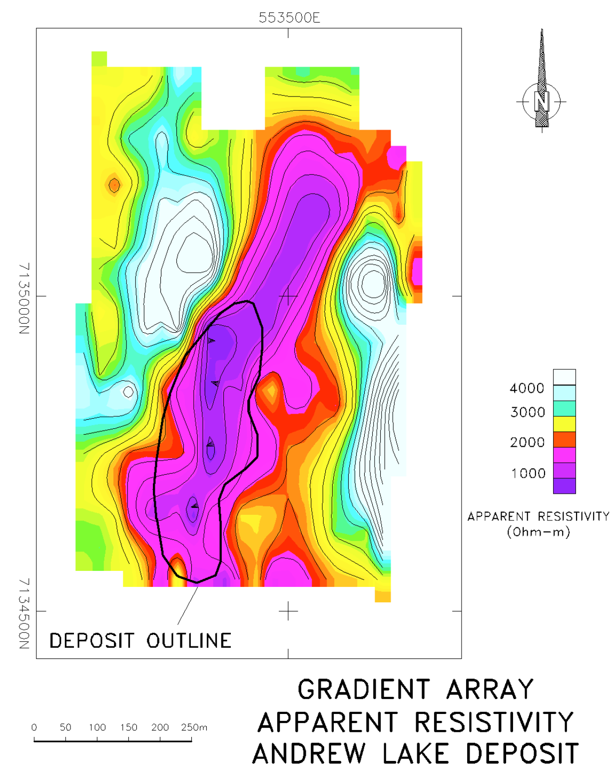

Figure 23: *Gradient array apparent resistivity, Andrew Lake deposit.*

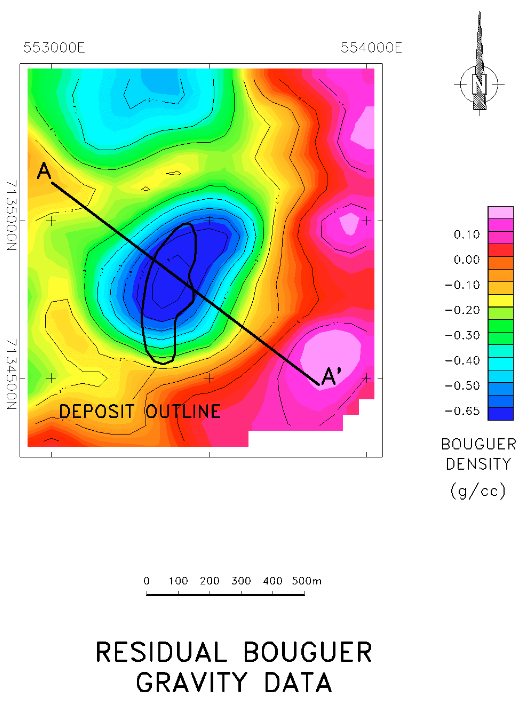

Figure 24: *Residual Bouguer gravity data reduced with a slab density of 2.7 g/cm³, Andrew Lake deposit.*

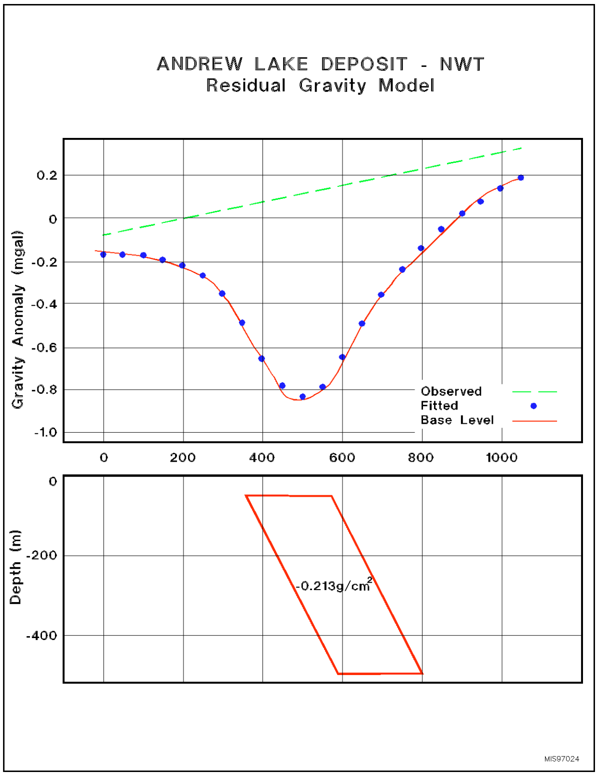

Figure 25: *Andrew Lake deposit, residual gravity model.*

as much near-surface detail about the structure or alteration associated with the deposit when compared to the gradient resistivity data. The gradient array resistivity data is more detailed in character and correlates better with the deposit outline. Line A - A' in Figure 24 has been extracted from the data set for modelling using GRAMOD, an interactive gravity anomaly inversion program marketed by Geosoft. The Andrew Lake deposit was modelled assuming a tabular model. The model results (Figure 25) indicate a depth to the top of the structure of approximately 50 m, a dip of 63° to the east and a depth extent of greater than 300 m.

THE SUE DEPOSITS

Geophysical signature

The Sue deposits, which were discovered in 1988 to 1989 (Ey *et al.*, 1992; Baudemont *et al.*, 1993), are part of the McClean project, which is located in northern Saskatchewan near the eastern edge of the Athabasca Basin (Wallis *et al.*, 1983). The McClean project (Figures 1 and 2) is presently operated by Cogema Resources Inc. The participants in the project are Cogema Resources Inc., Denison Mines Limited and OURD (Canada) Co. Limited. The known mineable reserves at McClean Lake are 50 million pounds U_3O_8 at an average grade of 3.3% U_3O_8. The Sue A and B deposits were discovered by Minatco Ltd. in 1988. The Sue A discovery hole graded 0.8% U_3O_8 over 12.5 m. The larger Sue C deposit was subsequently discovered off the main EM trend. Uranium mineralization grading 21% over 18 m was intersected. Within the project area the basement geology is characterized by a dome and basin structure in which large Archean granitoid domes alternate with Aphebian metasedimentary basins (Figure 26). Uranium mineralization in the McClean project area occurs in two distinct settings; within the Hudsonian basement (Sue C, CQ), and within the Athabasca sandstone and along the sandstone-basement unconformity (Sue A, B, McClean, Jeb). In each case the mineralization is structurally controlled and localized along regional structural features and is spatially related to the Aphebian graphitic gneiss (Figure 27). The faults control the extent of the mineralization and generally represent reactivated Hudsonian structures, which have in places resulted in significant displacement of the unconformity surface. The reactivation of late Hudsonian faults commonly occur along the margins of the granitic domes. The ore zones are invariably associated with alteration haloes that are characterized by strong clay alteration, silicification and a generally higher background in uranium and indicator elements.

Airborne and ground geophysical surveys, consisting of airborne EM and magnetics, Horizontal Loop Electromagnetics (HLEM), resistivity, VLF-Resistivity and gravity surveys, were completed over portions of the Sue Area. The use of electromagnetic and resistivity data to assess drill targets was an essential component of the exploration program. Airborne surveys were flown with a Dighem V towed bird, symmetric dipole configuration, operated at a nominal survey altitude of 30 m. Gradient array surveys in the Sue area utilized a current dipole length of 1200 m, together with a potential dipole separation of 12.5 m.

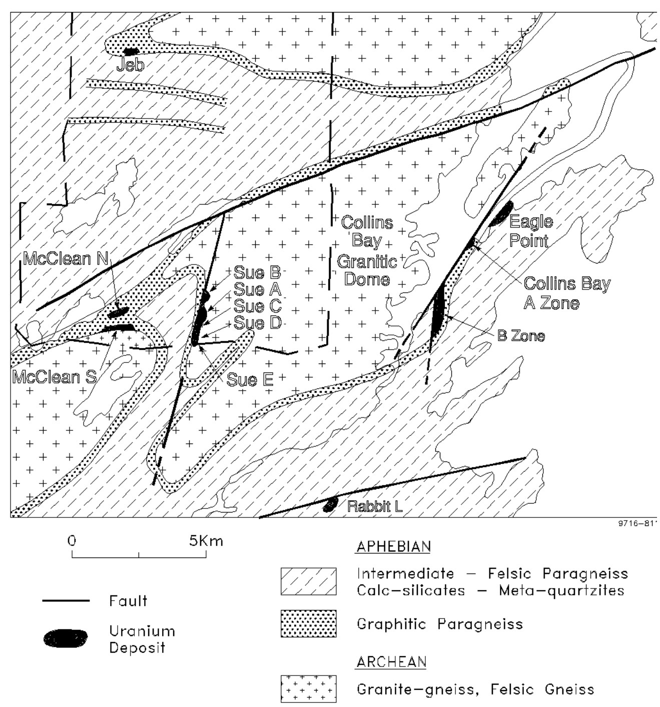

Figure 26: *Interpreted geology of the McClean Lake area.*

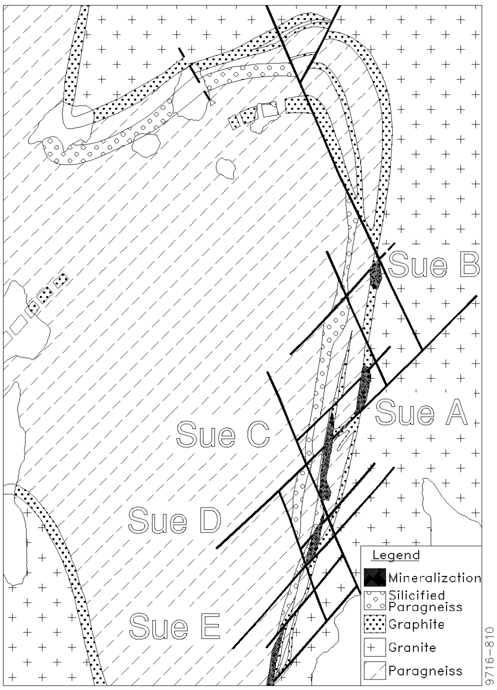

Figure 27: *Detailed geology of the Sue deposits area.*

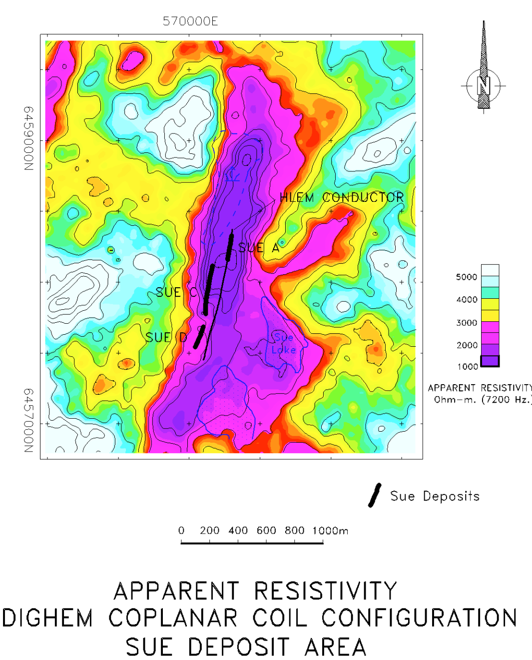

Figure 28: *Apparent resistivity - 7200 Hz Dighem coplanar coil configuration, Sue deposit area.*

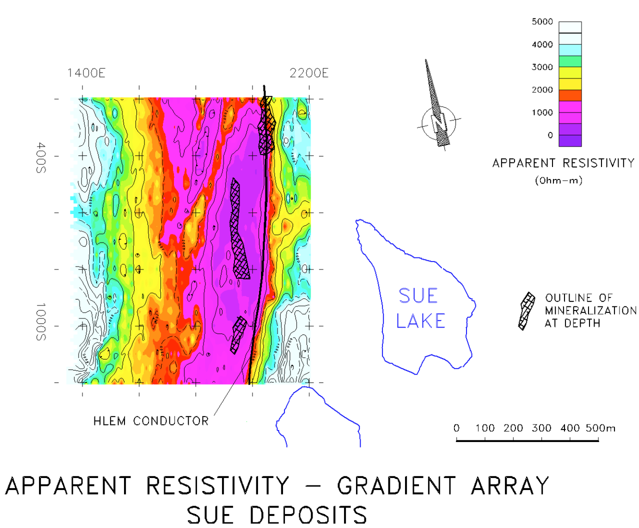

Figure 29: *Apparent resistivity - gradient array, Sue deposits.*

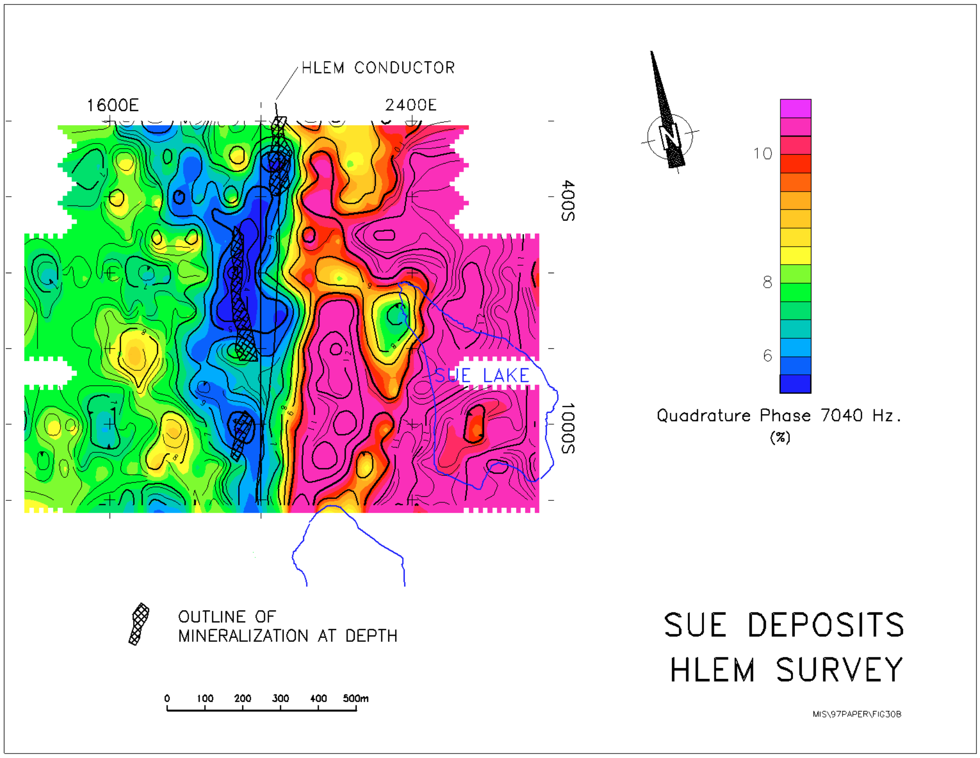

Figure 30a: *MaxMin 1-10 HLEM survey, in-phase 7040 Hz, Sue deposits.*

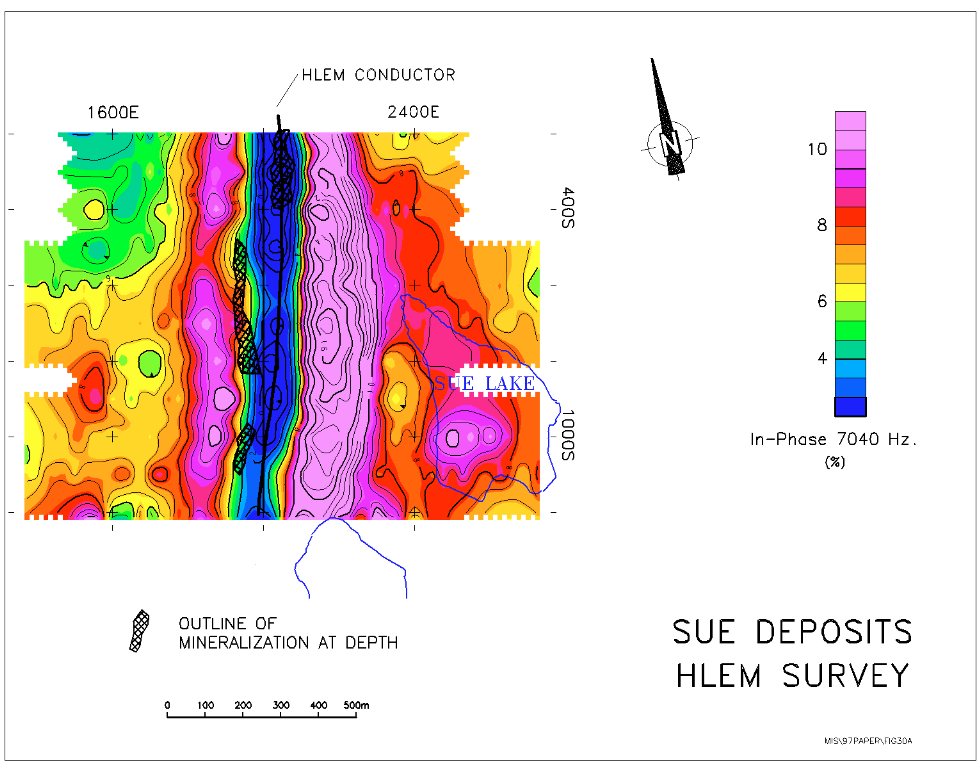

Figure 30b: *MaxMin 1-10 HLEM survey, quadrature phase 7040 Hz, Sue deposits.*

HLEM surveys were carried out using an Apex MaxMin I-10 system. Readings of the in-phase and quadrature components of the secondary field were obtained at 25 m station intervals. As a result of test work it was determined that a 150 m cable provided the optimum response for the depths encountered in this area, together with frequencies of 440 Hz to 28160 Hz.

The airborne apparent resistivity data was generated from the in-phase and quadrature EM components for all three coplanar frequencies, using a pseudo-layer half-space model (Fraser, 1978). A resistivity map for the 7200 Hz coplanar data for the project area is shown in Figure 28. Results of the gradient array apparent resistivity surveys are shown in Figure 29. Figure 30a is a contour map of the 7040 Hz HLEM in-phase response obtained over the Sue deposits, while Figure 30b shows the 7040 Hz quadrature response.

A strong, well-defined near north-south trending apparent resistivity low is evident in Figure 28, with values less than 1500 ohm-m in the vicinity of the Sue deposits. This resistivity low hosts a moderately conductive, narrow bedrock conductor at a depth of approximately 80 m, with a probable dip towards the east. The conductor has a north-south strike length of more than 2.6 km, although the strongest portion of the apparent resistivity low is only about 1 km in length. The absence of strong resistivity lows at the north and south ends of this zone is due to the apparent depth of the conductor and the resulting low amplitude EM responses. At the north end of the Sue area the apparent resistivity data is indicative of the change in strike to near east-west of the geological units that host the conductive trends. Many of the resistivity patterns in the area appear to be closely related to lakes or swampy ground, which exhibit resistivity values in the 800–2000 ohm-m range, and are obviously influenced by the weakly conductive overburden. Exceptions were evident in the Sue area, where bedrock conductors are indicated.

The gradient array resistivity data delineates a prominent, near north-south trending 500 m wide zone of lower apparent resistivity (Figure 29). Areas underlain by strong resistivity lows, with values of apparent resistivity less than 1000 ohm-m, are interpreted to represent areas of argillic alteration. The Sue A, C and D deposits are associated with an oval-shaped zone of low apparent resistivity. The interpreted HLEM conductor is situated along the eastern margin of this low (Figure 29). Several narrow, linear zones of higher apparent resistivity within the overall zone of low resistivity (Figure 27) may be related to narrow units of silicified paragneiss or silica flooding along structural conduits.

The 7040 Hz in-phase HLEM component data has defined the position of the graphitic conductor associated with the Sue deposits. The position of the conductor axis is clearly defined by a linear, near north-south trending trough (Figure 30a). The positive shoulders of the anomaly have a pronounced asymmetry to the east between lines 4+00S and 12+00S, indicating that the conductor has a moderate easterly dip. The mineralization of the Sue A deposit is directly associated with the Sue conductor.

The 7040 Hz quadrature component response (Figure 30b) has a quite different appearance compared to the in-phase data. The quadrature data are characterized by two contrasting background areas, that are sharply divided along the general trend of the Sue conductor axis. North-northwest and north-northeast lows are located west of this sharp contact. The outlined quadrature trends have a strong structural component. Figure 30b is in effect a pseudo-resistivity map. The Sue C and D deposits lie within the quadrature lows. A strong north-northeast bias is apparent in the data; for example the orientation of the Sue A and Sue C deposits. The coincidence of the strike and shape of these lows with resistivity features provides good evidence that HLEM surveying could be used as a reconnaissance tool when searching for alteration in an environment similar to that associated with the Sue deposits. Many of the structural features have also been previously mapped from drilling and VLF surveying and have been described by Baudemont *et al.* (1993).

MCARTHUR RIVER DEPOSIT

Geophysical signature

Geophysical surveys carried out over the McArthur River deposit have been discussed in papers by McGill *et al.* (1993) and Marlatt *et al.* (1992). Airborne electromagnetic surveys were flown over the McArthur River project area in 1977 and 1978 using a Mark VI INPUT system. These surveys delineated conductive trends some five kilometers to the east of the McArthur River deposit, but no discernible conductors were detected along the western half of the project area, which includes the deposit. Due to the high background noise levels, the deeper western portion was reflown in 1981. In the vicinity of the deposit, where depths to basement exceed 500 m, a few scattered 1 and 2 channel responses were obtained. These have been attributed to locally more conductive sandstone. No graphitic conductors were identified in the basement on the west side of the property, due to the great depths involved.

Useful results were obtained from a high resolution total field and gradiometer aeromagnetic survey, which was flown in 1982 by Questor Surveys over the eastern Athabasca Basin. Figure 31 shows the total magnetic field in the vicinity of the McArthur River deposit area. It lies within a broad magnetic low of 200 to 250 nT, which ranges in width from 5 km southwest of the deposit to perhaps 15 km to the northeast. This was interpreted to represent a significant Aphebian metasedimentary sequence, which was therefore potentially favourable for basement hosted graphitic conductors, similar to those encountered at the nearby Cigar Lake deposit. Consequently the western portion of the property was considered favourable despite the absence of suitable INPUT responses.

Airborne radiometric and VLF surveys conducted in the seventies identified several interesting areas but did not identify any anomalies in the vicinity of the deposit. Initial ground follow up of the airborne EM anomalies on the east side of the McArthur River project area, included Fixed Loop TDEM surveys, together with ground radiometric prospecting, magnetic and VLF coverage. Gravity profiles and a variety of resistivity mapping methods were utilized on a more limited basis.

Three large loop survey configurations, illustrated in Figure 32, have been used for mapping the conductors in the deeper portions of the Athabasca Basin (Powell, 1990). These are: 1) Fixed Loop; 2) Moving Loop; and 3) Stepwise Moving Loop. The first configuration employs a stationary transmitter loop, which excites a target conductor, usually located off to one side for optimal coupling. One or more roving receivers map the conductor along several lines extending away from the loop. This is the simplest and most commonly used of the large loop methods. The second configuration involves a generally smaller transmitter loop which moves in tandem with one or two receivers located at fixed separations from the loop. This configuration has generally been used where the Fixed Loop approach has proven to be troublesome, usually when the situation is more complicated than a simple conductor in a resistive host. The cost per reading is significantly higher than Fixed Loop, however, because of the time and labour required to move a large loop, one

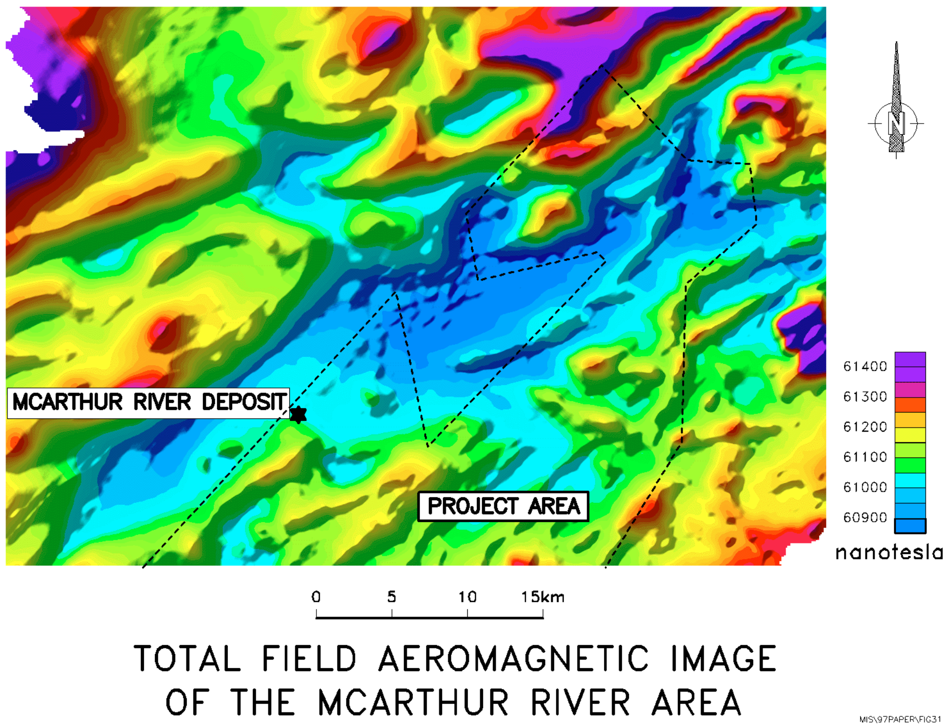

Figure 31: *Airborne magnetic survey, total field intensity, McArthur River project area.*

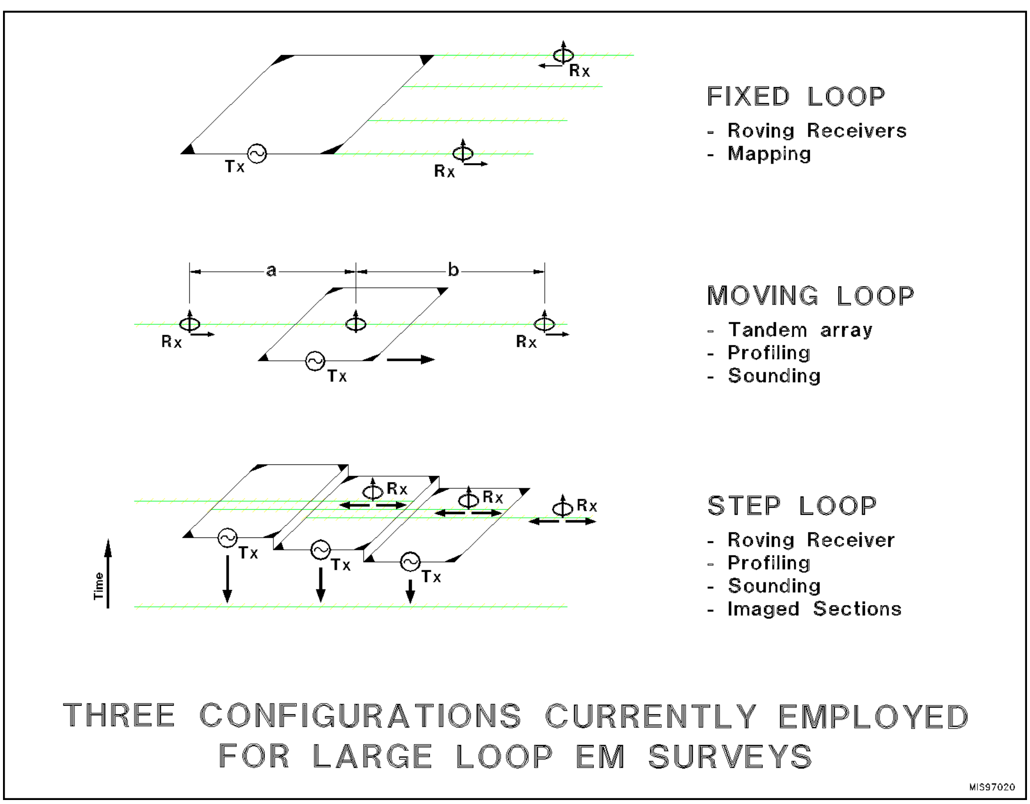

Figure 32: *Configurations employed for large loop EM surveys.*

station at a time, down a survey line. The third configuration, adapted from the common receiver array (Macnae and Lamontagne, 1987), is a hybrid of the first two methods. It involves a series of back-to-back loops with receiver readings taken over some distance through each loop, along a common cut line. Intermediate loops may be added to improve resolution in anomalous areas. This method has many of the advantages of both the Fixed and Moving Loop approaches with a cost per reading comparable to Fixed Loop, and a cost per kilometer of line surveyed comparable to Moving Loop.

On the McArthur River property, as exploration progressed to basement depths in excess of 300 m, large Fixed Loop TDEM surveys were carried out in a reconnaissance mode to locate basement conductors (McMullan *et al.*, 1987). This work included coverage over portions of the western half of the property. In 1984 a reconnaissance DEEPEM survey located the P2 conductor, and after the discovery of the P2 Main mineralization in 1985 additional DEEPEM coverage extended the P2 conductor over a 13 km strike length. Following the initial 1988 discovery of the McArthur River (P2 North) mineralization additional conductor definition in the vicinity of the deposit was carried out with the Geonics EM37 system. Between 1980 and 1992 approximately 1500 km of Fixed Loop TDEM coverage was completed on the McArthur River project. Fixed Loop EM37 stacked profiles for the channel 15 horizontal component are plotted in Figure 33, together with the interpreted conductor axes and an outline of the mineralized zone. The results indicate the strong central P2 conductor at a depth of about 500 m with weaker flanking conductors to the south. The mineralized zone occurs immediately west of the P2 conductor.

The results obtained over line 90+00N near the northern end of the deposit from Fixed Loop EM37 coverage are compared in Figure 34 with a correlation processed common receiver array Moving Loop UTEM profile (Polzer *et al.*, 1989). The P2 conductor is clearly indicated at 27+50W as a strong response, which decays slowly and persists to late time. The late time decay for a semi-infinite thin sheet results in a conductance estimate of about 30 siemens. The late time channels of the vertical component of the UTEM data are plotted as a Stepwise Moving Loop profile (Powell, 1990) in Figure 35. Stackplots of the data for each loop are presented in the upper plot (Figure 35a). Responses from loops 4 and 7 indicate that the P2 conductor is a strong conductor centered at 27+50W at a depth in excess of 400 m. Weak surficial conductors at 25+50W and 30+00W appear to locally distort the response of the P2 conductor.

The center plot (Figure 35b) is a pseudosection presentation of the vertical component channel 6 UTEM data. This plot is produced in a fashion analogous to dipole-dipole IP data, with each reading plotted at the mid-point between receiver and transmitter at an apparent depth equal to half the receiver-transmitter spread. The data, which includes all loops and all spreads, are then gridded and contoured. This presentation indicates a strong, deep, single conductor response at 27+50W. The approximate top position of the conductor can be roughly picked from the inflection at the top-centre point of the anomaly. This occurs at an apparent depth of about 475 m. The extent of Aphebian metasediments can be identified as an area of higher mid-to-late time amplitude (>2%) on the section.

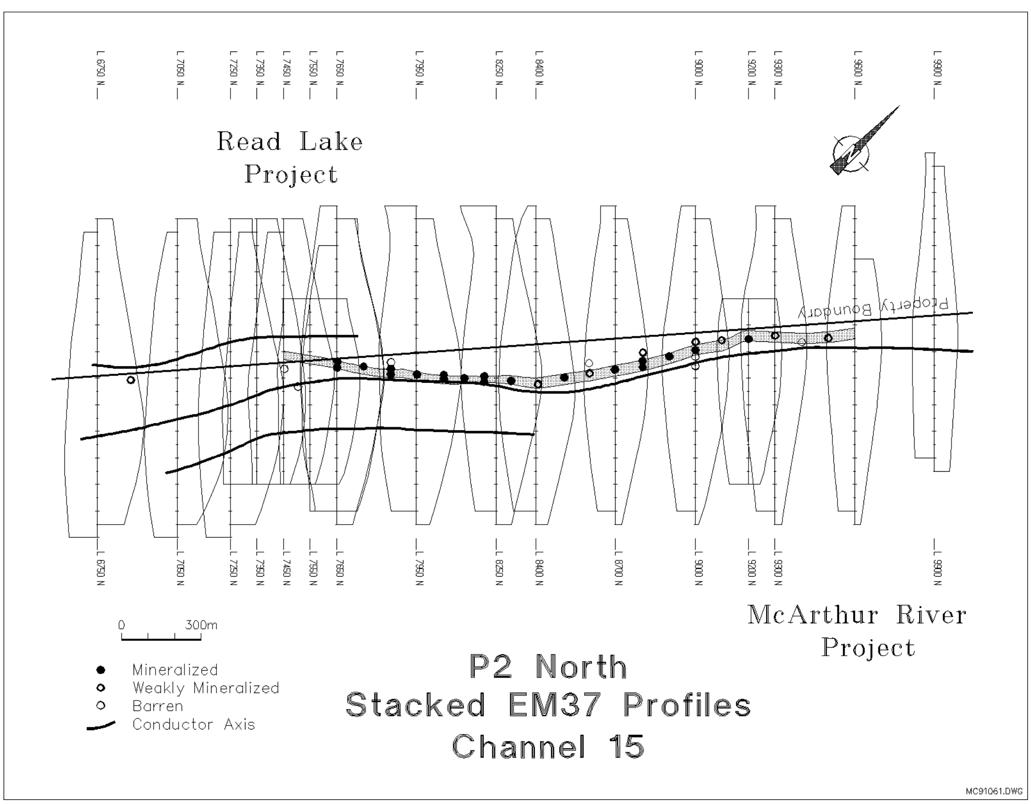

Figure 33: *Stacked EM37 profiles, Channel 15, P2 North area, McArthur River deposit.*

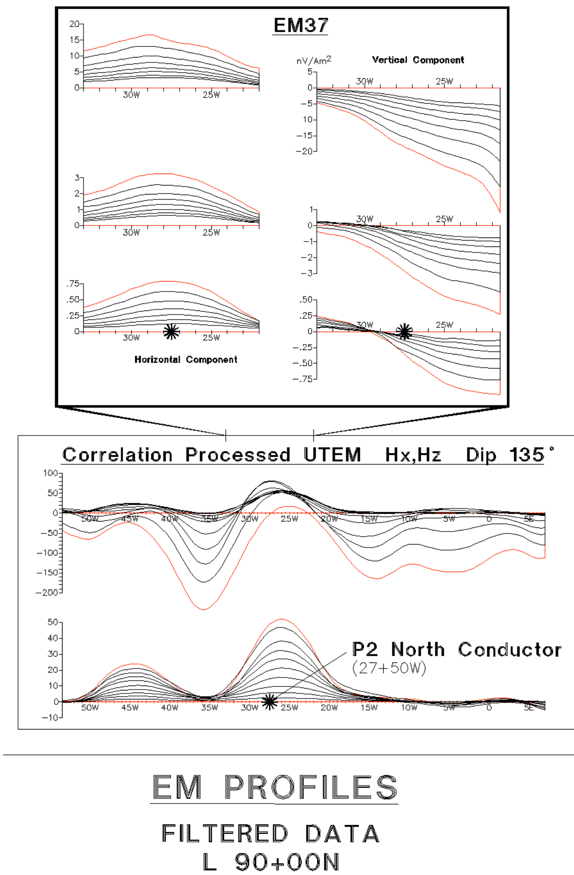

Figure 34: *Comparative EM profiles, Line 90+00N, McArthur River deposit.*

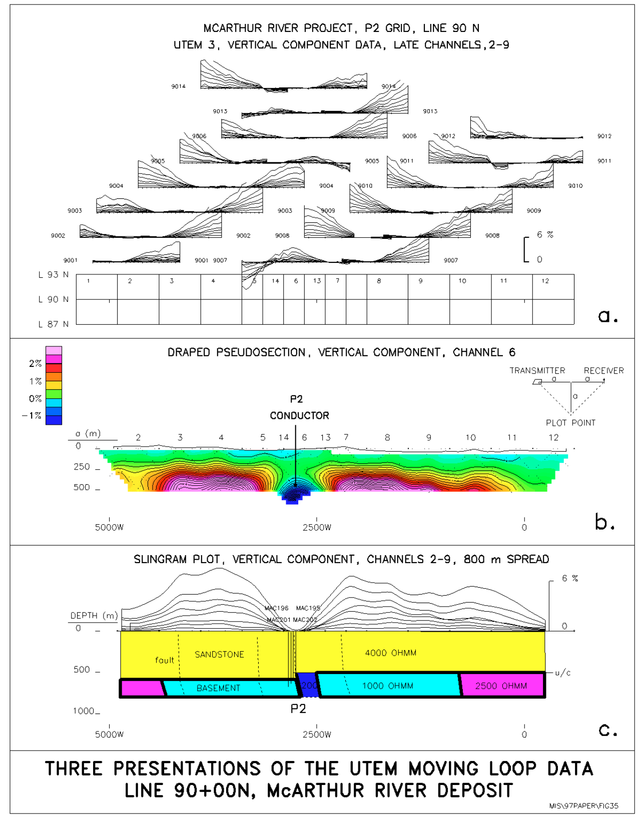

Figure 35: *Three presentations of the UTEM Moving Loop data, Line 90+00N, McArthur River deposit.*

The lower plot (Figure 35c) displays the late channels (2 to 9) of the UTEM data in Slingram (HLEM) fashion for a constant transmitter-receiver spread of 800 m. These plots are equivalent to the standard Moving Loop approach. The channel 6 plot corresponds to a horizontal slice through the pseudosection (Figure 35b) at an apparent depth of 400 m. An unmistakable late-time response from a single discrete conductor is apparent. Modelling of the Slingram data with MultiLoop (Lamontagne Geophysics Ltd., Kingston, Ontario) indicates a conductor of approximately 30 to 40 siemens at a depth of 500 m, dipping approximately 75° to the east.

An interpreted section accompanies the Slingram plot in Figure 35c. This section incorporates the existing drilling information, an imaged resistivity section produced by Lamontagne Geophysics Ltd. and modelling of the UTEM vertical component data using EMIGMA (Petros Eikon Inc., Georgetown, Ontario; Parker *et al.*, 1996). In addition to the strong P2 conductor in the basement, a few very weak conductors are noted on the section within the sandstone. These are believed to be related to significant fault structures. They are seen as relatively large responses in very early time only (channels 17–20) and have amplitudes consistent with near-surface conductors. Modelling of individual loops indicates a basement resistivity of about 1000 ohm-m in the general area of the P2 conductor. This is thought to be related to Aphebian metasediments, which are known to host the deposit. A smaller block of more conductive basement hosts the P2 conductor itself. Further to the east basement resistivities are significantly higher (2500 ohm-m) reflecting a probable granitoid unit at the east end of the profile. However more conductive basement is identifiable at depths of 1000 m and greater, indicating that the granitoid/metasediment contact probably dips at a shallow angle to the east.

Various other geophysical methods have proven useful in assisting with the definition of the basement geology, the interpretation of structural trends, and the mapping of alteration patterns. Ground magnetic coverage indicates that the P2 conductor follows a poorly defined, northeast-southwest trending magnetic corridor, interrupted by several east-west trending breaks, which coincide with the interpreted strike of transcurrent faults. The McArthur River deposit falls within a similarly trending gravity/magnetic low, which is believed to represent the combined effect of the large unconformity offset and the metasedimentary package, which hosts the deposit. A prominent 1 to 1.5 mgal gravity high located east of the deposit is thought to be related to a paleotopographic, basement quartzite ridge.

Resistivity methods have proven useful in defining basement geology as well as sandstone alteration. Three resistivity techniques have been employed in the vicinity of the deposit: Controlled Source Audio-MagnetoTellurics (CSAMT) to examine deeper features, and VLF-Resistivity and UTEM Inductive Source Resistivity (ISR) surveys (Mac-

Nae and Irvine, 1988) have been used to map shallow resistivity features. All of these surveys indicate a very resistive sandstone package, approximately 400 m thick, located directly above and to the west of the P2 conductor. The CSAMT survey indicates a package of conductive basement similar to that shown in Figure 35c.

SHEA CREEK CASE HISTORY

The Shea Creek Project is wholly owned and operated by Cogema Resources Inc. and is situated in northwestern Saskatchewan approximately 20 km due south of Cluff Lake (Figure 2). The project is located in the western Canadian shield within the south-western Rae Province, west of the Virgin River shear zone. The area of interest lies near the boundary between Archean crust of the Slave-Thelon (ex Firebag) Domain and the western edge of the Athabasca Lozenge (ex Western Granulite/Clearwater granulite facies). A weakly mineralized zone was discovered in 1992 in the third hole on the project, while drilling the Saskatoon Lake conductor (Koch and Dalidowicz, 1996).

UTEM III standard Moving Loop and Fixed Loop UTEM arrays (Powell, 1990; Figure 32) were used to locate a deep graphite conductor, at a depth of the order of 800 m. For the Moving Loop array a trailing receiver was positioned 1800 m to the west of the transmitting loop (Figure 36a). The size of the loop and the positioning of receivers is dependent upon the search depth. A general rule of thumb is that the loop size should approximate the search depth, while the distance from the centre of the loop to the receiver should be approximately twice the estimated depth to the conductor.

During field operations the transmitting loop moves in step with the receiver along the cut lines. On Line SH-6 the reading interval was 200 m. The plotting position is the mid-point between the centre of the transmitting loop and the receiver. The anomalous response in the Hz profile data is comparable to a conventional Slingram type response having a trough and corresponding positive shoulders. At least two basement conductors are present on the line (Figure 36a). The conductor located by the black filled arrow has been interpreted as a good quality basement conductor. This conductor has a very strong late time channel 1 response and has a calculated conductance of greater than 100 siemens. Curve matching of the late time channel Hz component profiles with Moving Loop model data was carried out. A best fit gave an approximate depth to the conductor top of 800 m. Positive Hz component late time asymmetry of the anomaly shoulders also suggests an easterly dip. Drilling on this conductor intersected a horizontal radioactive shear zone at a depth of 705 m. The mineralized interval returned a 0.1% U grade cut-off over 0.7 m.

A second conductor located to the east has been interpreted to be a moderate, discrete basement conductor. Its position is interpreted to mark a boundary between relatively resistive stratigraphy to the west and more conductive units lying to the east. The location of this conductor also coincides with the axis of an airborne Geotem conductor, one of the reasons for conducting ground follow up programs in the area. Large Fixed Loop array surveys, employing 1600 m × 1000 m transmitter loops, were used to map the strike extent of the strong basement conductor. An example of the Fixed Loop data is shown in Figure 36b. Due to the large depths to the unconformity the observed anomalous responses are very broad. Stacking of the Hx anomaly peak occurs only in the last two to three time channels. Decay curve analysis of the Fixed Loop data indicates a long time constant.

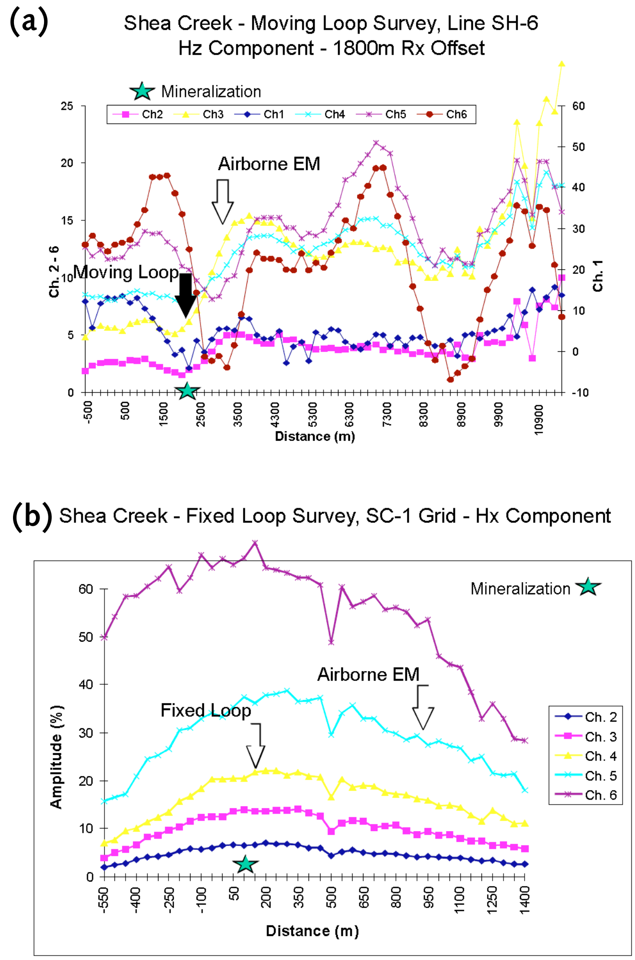

Figure 36: *(a) Hz component, Moving Loop array, Shea Creek project. (b) Hx component, Fixed Loop array, Shea Creek project.*

CONCLUSIONS AND FUTURE TRENDS

The discussion and review of geophysical and geochemical techniques presented in this paper illustrate the approaches successfully employed over the last decade to locate unconformity-type uranium mineralisation in the Athabasca and Thelon Basins. Over a wide range of depths EM and magnetic methods, together with resistivity mapping, including the use of ground and Helicopter EM systems, and to a lesser degree gravity techniques have played a roll in mapping basement geology, structure and sandstone alteration.

As indicated in the Exploration 1987 paper by McMullan *et al.* as exploration moves to sub-Athabasca depths greater than 500 m modifications to EM techniques have been made. Large loop, moving source Time Domain EM arrays, both in standard Moving Loop and Stepwise Moving Loop configurations (Powell, 1989), have played an important role (Figure 32). Other methods, which are likely to see increased application as we move deeper into the basin include seismic reflection and

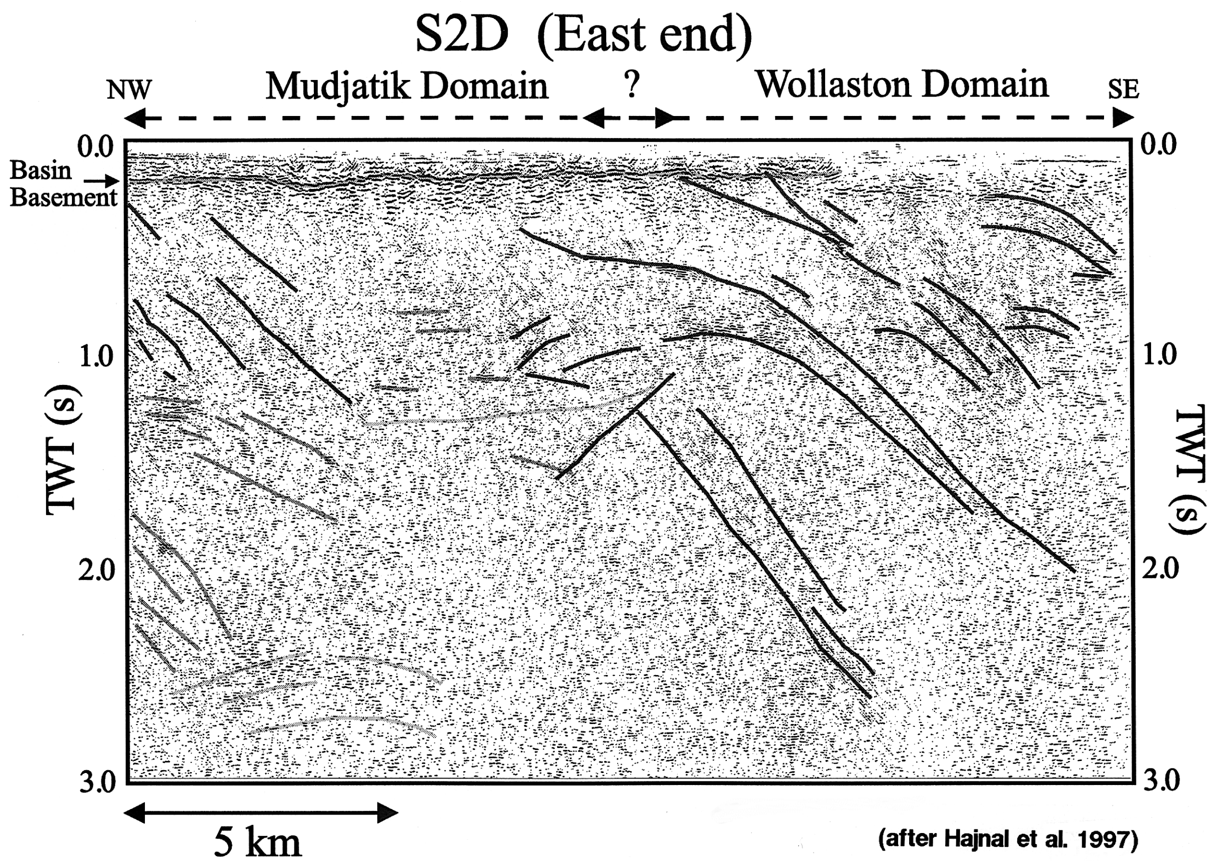

Figure 37: *Eastern 18 km segment of the High Resolution seismic survey (from Hajnal et al., 1997).*

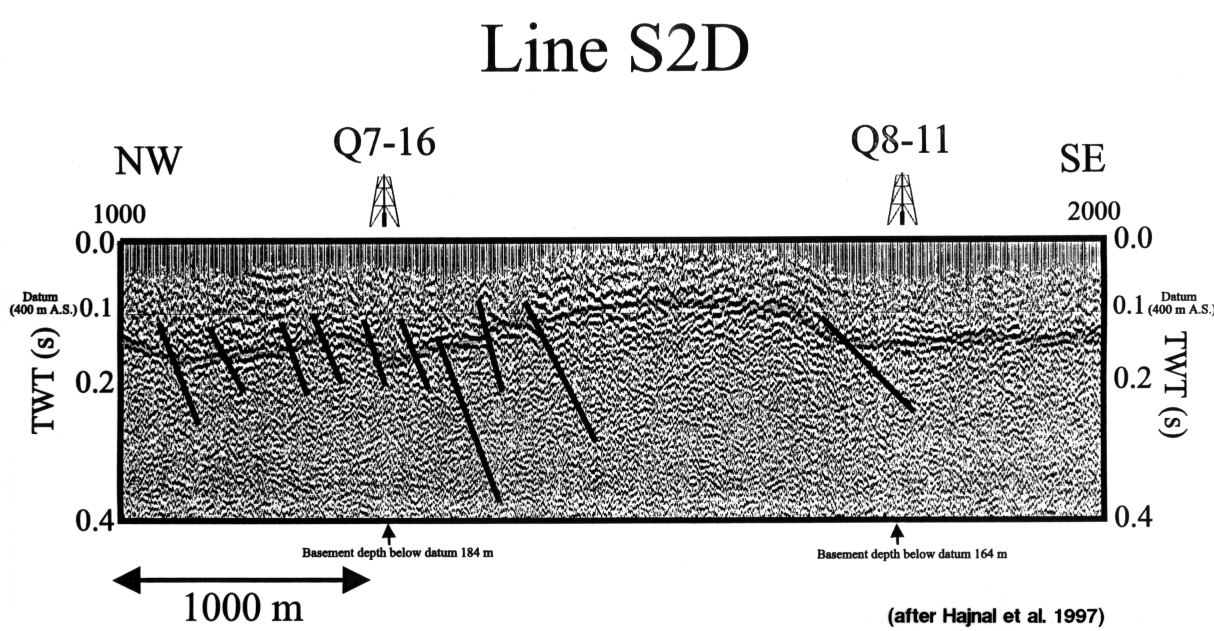

Figure 38: *Detail 5 km section of the High Resolution seismic survey showing the sandstone-basement contact (from Hajnal et al., 1997).*

refraction surveys, as well as EM sounding surveys and the regional application of the MagnetoTelluric method. Recently a High Resolution reflection seismic experiment (Hajnal *et al.*, 1997) was carried out across the eastern margin of the basin (Figure 41) as an extension to the Trans-Hudson Orogen Transect Lithoprobe survey along the Wollaston Lake road. This survey successfully imaged the unconformity at relatively shallow depths (~200 m) and resolved a number of steeply dipping faults, which appear to have a deep crustal expression. In many cases these fracture zones also intersect the overlying sandstone. Examples of the derived, interpreted sections are shown in Figures 37 and 38. This survey is the first time that an appropriately designed seismic survey has successfully overcome difficult near surface conditions and provided a clear image of the unconformity and associated structure. It is envisaged that the seismic method will see increased use in the future, particularly in deeper portions of the basin, despite the high cost and significant logistical problems.

Apart from a number of isolated cases no significant amount of Fixed Wing airborne EM flying has been carried out over the last ten years. In recent years, however, advances have been made in Fixed Wing EM systems in both hardware design and post-processing of the data, resulting in improved depth of penetration. For example the latest Geotem-DEEP system (Smith, 1997) represents a significant improvement over the INPUT Mark VI system, which is credited for the bulk of the flying carried out in the late seventies and early eighties. The Geotem system uses lower operating frequencies, has a larger dipole moment (Figure 39) and routinely collects three component data. The increase in system signal-to-noise ratio of more than a factor of ten over the earlier systems contributes to the system's greater depth of exploration (Figures 40a and 40b). A conductor can only be detected with confidence if at least three channels are anomalous and above the noise level. As the noise levels are reduced deeper conductors can be detected. It is likely that basement depths in the 300 to 600 m range can now be explored using the latest systems, and reflying of portions of the Athabasca basin will certainly be a major consideration over the next few years. Airborne EM, as well as ground follow up EM and resistivity techniques together with geochemical methods, have also been used with some success in outlining sandstone alteration. This application will certainly continue in an attempt to define indications of deep unconformity mineralisation.

The importance of magnetic remanence in defining the fluid history of the Athabasca Basin has been recognised (Kotzer and Kyser, 1990), though it has yet to see significant application to geophysical exploration. Small amplitude (<100 nT), short wavelength anomalies are occasionally noted in surveys and are believed to be related to secondary hematite associated with fluid movement along fractures in the sandstone. Attempts to use magnetic surveys to map iron depletion associated with bleached zones within the basement have also enjoyed some success. This application is one of a number of more innovative methods that could see wider application in shallower areas. In deeper parts of the basin it is likely to be less successful, since alteration has a minimal near surface impact on sandstone susceptibilities, which are already quite low.

Remote sensing data is also starting to play a more significant role. With the launch in 1995 of Canada's RADARSAT satellite surface variations can now readily be mapped even in highly vegetated regions, and the surface expression of sandstone structures, previously only poorly resolved, can now be identified with more confidence (Figure 41).

Mineralogical and trace element halos have significant dimensions and can extend to the top of the sandstone in the Athabasca Basin, above deposits located greater than 500 m in depth. These halos can be detected in near miss situations during drill programs and on the surface by shallow drilling or boulder prospecting techniques. The use of lithogeochemistry, XRD and more recently infrared spectroscopy contribute different aspects to the detection of these halos. The interpretation is tied to the complex paragenetic schemes developed for unconformity deposits, and in particular the intensity of individual

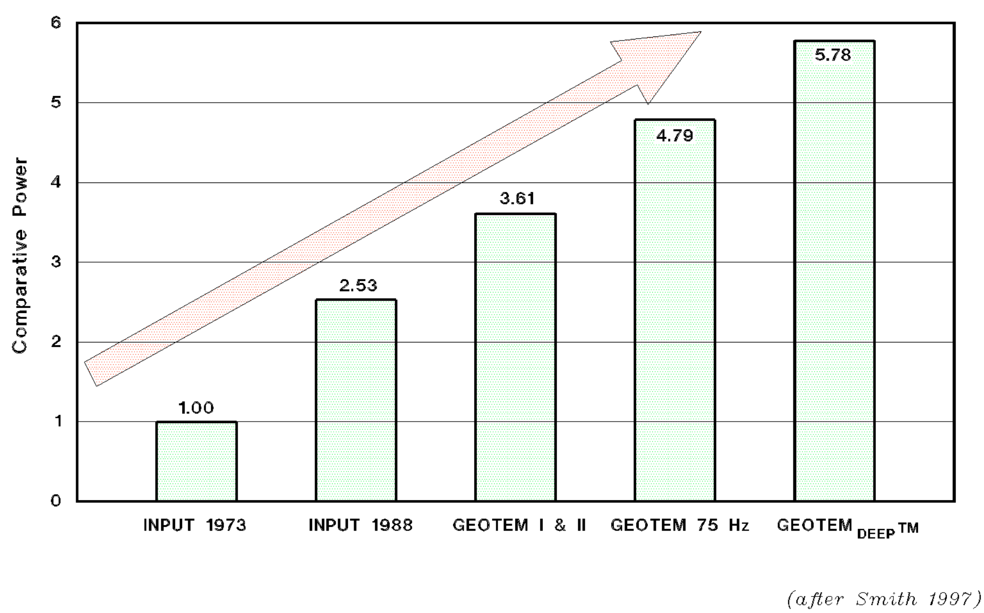

Figure 39: *Comparative power of airborne Time Domain systems (modified from Smith 1997).*

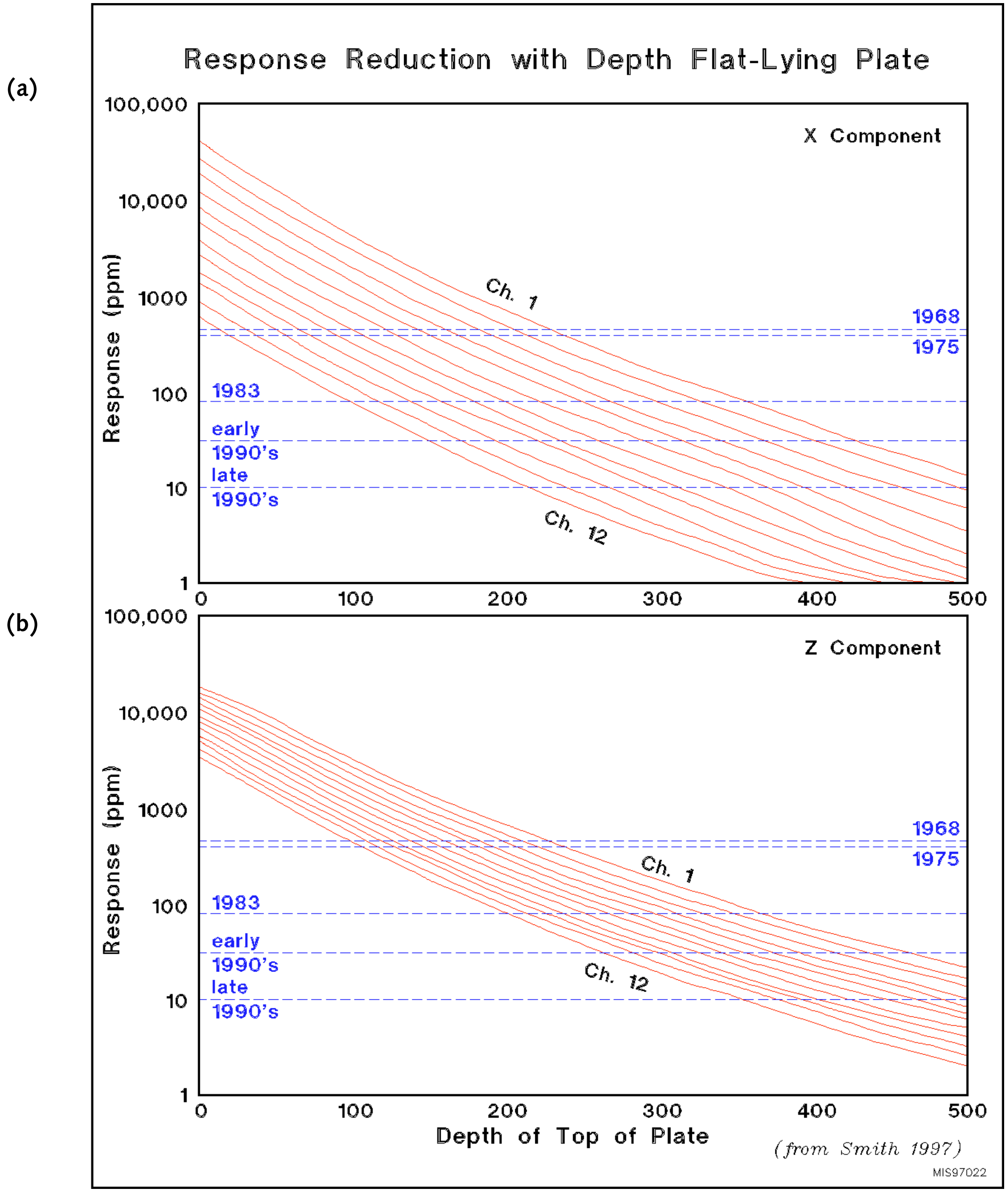

Figure 40: *Response reduction with depth of airborne Time Domain systems, (**a**) z component, flat-lying plate, (**b**) x component (modified from Smith 1997).*

paragenetic steps. As an example the significant silicification event in sandstone at McArthur River (Q2 event) is a fundamental aspect of ground preparation for the ensuing mineralization and also for the development of the silicification end member of the alteration models. The silicification appears tied to the presence of remobilized silica from basement quartzite ridges. Increased knowledge of the paragenesis, and in particular integration of the paragenetic steps with exploration data, is a difficult but important step in advancing exploration methodology. This will become more important in terms of a possible shift away from the standard approach of exploring for EM conductors.

Infrared spectroscopy has proved to be a useful exploration tool in terms of routine semi-quantitative clay mineralogical analyses and also in discriminating clay mineral crystallinities. The kaolinite-"dickite" relationship at Key Lake and McArthur River was not known from past work and may be important in identifying mineralized structures. To date kaolinite is associated with mineralization at several southeastern Athabasca deposits and prospects, whereas well-ordered kaolinite or "dickite" is present in the regional sandstone.

Each sandstone basin may require different geochemical techniques or combinations of techniques depending on its fluid history. Sandstone units in the Thelon Basin, for example, have authigenic feldspar development, which negates the use of normative clay mineralogy by geochemistry. The developments in portable infrared spectroscopy will likely be matched by developments in the routine use of hyperspectral airborne and possibly satellite data in areas with less vegetation.

ACKNOWLEDGEMENTS

The authors wish to thank the management of Cameco Corporation, Cogema Resources Inc. and Uranerz Exploration and Mining for their permission to publish this paper. The authors also would like to acknowledge the support and contribution of the other joint venture partners: including PNC Exploration (Canada) Co. Ltd., Daewoo Corporation, Denison Mines Ltd., Urangesellschaft Canada Ltd. and OURD (Canada) Co. Ltd. Thanks also go out to Wally Harildstad for his drafting skills and Tammy Rybchinski for her word processing.

REFERENCES

Annesley, I.R., and Madore, C., 1996, U-Pb zircon, monazite, and titanite geochronology in the Wollaston Lake area, Saskatchewan; Timing of deformation, metamorphism and magmatism; Minexpo'96 Symposium, Advances in Saskatchewan Geology and Mineral Exploration; Program and Abstracts, Saskatchewan Geological Society.

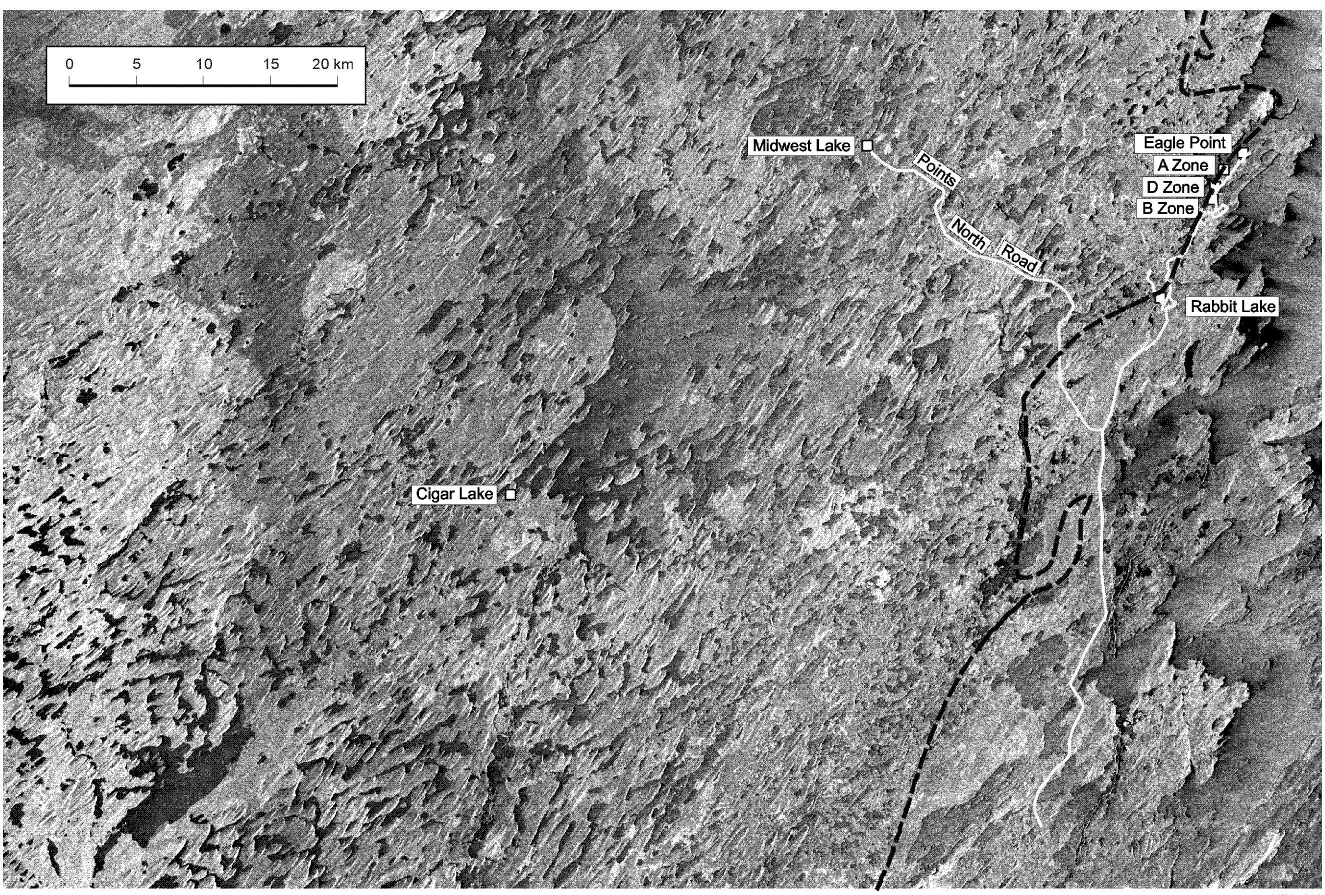

Figure 41: *Radarsat Standard Beam Mode scene for the eastern Athabasca area.*

Baudemont, D., Piquard, J.P., EY, F., and Zimmerman, J., 1993, The Sue uranium deposits, Saskatchewan, Canada; Exploration Mining Geology, Vol. 2, No. 4, p.321-331.

Clarke, L.A., 1987: Near-surface lithogeochemistry halo as an aid to discovery of deeply buried unconformity-type uranium deposits, Athabasca Basin, Canada; Journal of Geochemical Exploration, 28, p.71-84.

Clark, R., King, T., and Swayze, G., 1990, High spectral resolution reflectance spectroscopy of minerals; Jour. Geophysical Res., Vol. 95, p. 12653-12680.

Darnley, A., 1981, The relationship between uranium distribution and some major crustal features in Canada; Mineralogical Magazine, Vol. 44, p.425-436.

Dahlkamp, F.J., and Tan, B., 1977, Geology and mineralogy of the Key Lake U-Ni deposits, northern Saskatchewan; *in* Geology Mining and Extractive Processing of Uranium; Inst. Mining Met., London, p.145-147.

Earle, S., and Sopuck, V.J., 1989, Regional lithogeochemistry of the eastern part of the Athabasca Basin uranium province, Saskatchewan, Canada; *in* Uranium Resources and Geology of North America; IAEA-TECDOC-500, p.264-296.

Earle S., McGill, B., and Murphy, J., 1990, Glacial boulder lithogeochemistry: an effective new exploration technique in the Athabasca Basin, Saskatchewan; *in* Modern Exploration Techniques, L.S. Beck and C.T. Harper, eds.; Sask. Geol. Soc., Special Publ. No. 10.

Earle, S., Wheatley, K., and Wasyliuk, K., 1996, Application of reflectance spectroscopy to assessment of alteration mineralogy in the Key Lake area; Minexpo'96 Symposium, Advances in Saskatchewan Geology and Mineral Exploration; Program and Abstracts, Saskatchewan Geological Society.

Ey, F., Piquard, J.P., and Zimmerman, J., 1992, The Sue uranium deposits, Saskatchewan, Canada; *in* New Developments in Uranium Exploration, Resources, Production and Demand; IAEA-TECDOC-650, p.214-223.

Fouques, J.P., Fowler, M., Knipping, H.D., and Schimann, K., 1986, The Cigar Lake uranium deposit: discovery and general characteristics; *in* Uranium Deposits of Canada, E.L. Evans, ed., CIM Spec. Vol. 33. p.218-229.

Fraser, D.C., 1978, Resistivity mapping with an airborne multicoil Electromagnetic system; Geophysics, V. 43, p.144-172.

Fraser, D.C., 1979, The Multicoil II airborne electromagnetic system; Geophysics, V. 44, p.1367-1394.

Gandhi, S.S., 1995, An overview of the exploration history and genesis of Proterozoic uranium deposits in the Canadian Shield; Exploration and Research for Atomic Minerals, Vol. 8, p.1-47.

Gandhi, S.S., 1989, Geology and uranium potential of the Thelon Basin and adjacent basement in comparison with the Athabasca basin region; *in* Uranium Resources and Geology of North America; Proceedings of a Technical Committee Meeting, Saskatoon, September 1-3, 1987; International Atomic Energy Agency, Vienna, IAEA-TECDOC-500, p.411-428.

Geddes, R.S., 1982, The Vixen Lake indicator mineral train, northern Saskatchewan; *in* Prospecting in Areas of Glaciated Terrain-1982, p.264-281.

Hajnal, Z., Annesley, I.R., White, D., Matthews, R. B., Sopuck., V., Koch, R., Leppin, M., and Ahuja, S., 1997, Sedimentary-hosted mineral deposits: a high-resolution seismic survey in the Athabasca Basin; *in* Proceedings of Exploration '97.

Hasegawa, K., Davidson, G.I., Wollenburg, P., and Yoshimasa, I., 1990, Geophysical exploration for unconformity deposits in the northeastern part of the Thelon Basin, Northwest Territories, Canada; Mining Geology, 40 (2), p.83-95.

Heine, T.H., 1986, The geology of the Rabbit Lake uranium deposit, Saskatchewan; *in* Uranium Deposits of Canada; E.L. Evans, ed.; CIM Special Vol. 33, p.134-143.

Hoeve, J., and Sibbald, T.I.I., 1978, On the origin of the Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada; Econ. Geol., 73, p.1450-1473.

Hoeve, J., and Quirt, D., 1984, Mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the middle-Proterozoic, Athabasca Basin, northern Saskatchewan, Canada; Saskatchewan Research Council, Tech. Rept. No. 187.

Hoeve, J., Rawsthorn, K., and Quirt, D., 1981a, Uranium metallogenic studies: Collins Bay B Zone, II. Clay Mineralogy; *in* Summary of Investigations 1981, Saskatchewan Geological Survey, Misc. Report 81-4, p.73-75.

Hoeve, J., Rawsthorn, K., and Quirt, D., 1981b, Uranium metallogenic studies: clay mineral statigraphy and diagenesis in the Athabasca group; *in* Summary of Investigations 1981, Saskatchewan Geological Survey, Misc. Report 81-4, p.76-89.

Hoffman, P., 1989, Precambrian geology and tectonic history of North America; *in* The Geology of North America—An Overview; A.W. Bally and A.R. Palmer, eds., Geological Society of America, Vol. A, p.497-512.

Hubregtse, J.J., and Sopuck, V.J., 1989, Alteration parageneses of the Helikian sandstone and the Aphebian basement of the Key Lake mine and other uranium deposits in the eastern Athabasca Basin (Saskatchewan, Canada); *in* Uranium Res. and Geology of North America, IAEA-TECDOC-500, p.379.

Hunt, G., 1977, Spectral signatures of particulate minerals in the visible and near infrared; Geophysics, Vol. 42, p.501-513.

Koch, R., and Dalidowicz, F., 1996, Shea Creek—A deep geophysical exploration discovery, Saskatchewan Geol. Society; MinExpo '96 Symposium, in press.

Lewry, J.F.. and Sibbald, T.I.I., 1979, A review of the pre-Athabasca basement geology in northern Saskatchewan; *in* Proceedings of Symposium on Uranium Exploration Techniques; G.R. Parslow, ed., Saskatchewan Geological Survey, Special Publication No. 4, p.19-58.

Lewry, J.F.. and Sibbald, T.I.I., 1980, Thermotectonic evolution of the Churchill Province in Northern Saskatchewan; Tectonophysics, Vol. 67, p.45-82.

Kominou, A.. and Sverjensky, D.A., 1996, Geochemical modelling of the formation of an unconformity-type uranium deposit; Econ. Geol., 91, p.590-606.

Kotzer, T.G.. and Kyser, T.K., 1990, Fluid history of the Athabasca Basin and its relation to uranium deposits; *in* Summary of Investigations 1990, Saskatchewan Geological Survey, Misc. Report 90-4.

Kotzer, T.G., and Kyser, T.K., 1995, Petrogenesis of the Proterozoic Athabasca Basin, northern Saskatchewan, Canada, and its relation to diagenesis, hydrothermal uranium mineralization and paleohydrology; Chem. Geol., 120, p.45-89.

Kyser, T.K., Wilson, M.R., and Ruhrmann, G., 1989, Stable isotope constraints on the role of graphite in the genesis of unconformity-type uranium deposits; Canadian Journal of Earth Sciences, Vol. 26, p.490-498.

Macnae, J., and Irvine, R.J., 1988, Inductive source resistivity: a tool for outlining silicification in gold exploration; Exploration Geophysics, 19, p.471-480.

Macnae, J., and Lamontagne (1987, Imaging quasi-layered conductive structures by simple processing of Transient Electromagnetic data; Geophysics, Vol. 52, p.545-556.

McGill, B.D., 1996, The McArthur River deposit—a geological update; Minexpo'96 Symposium; Advances in Saskatchewan Geology and Mineral Exploration, Program and Abstracts, Saskatchewan Geological Society, p.26.

McGill, B.D., Marlatt, J.L., Matthews, R.B., Sopuck, V.J., Homeniuk, L.A., and Hubregtse, J.J., 1993, The P2 North uranium deposit, Saskatchewan, Canada; Explor. Mining Geol., Vol. 2, No. 4, p.321-331.

Marlatt, J., McGill, B., Matthews, R., Sopuck, V., and Pollock, G., 1992, The discovery of the McArthur River uranium deposit, Saskatchewan, Canada; *in* New Developments in Uranium Exploration, Resources, Production and Demand; IAEA-TECDOC-650, p.118-127.

McMullan, S.R., Mattthews, R.B., and Robertshaw, P., 1987, Exploration geophysics for Athabasca uranium deposits; *in* Proceedings of Exploration '87, Ontario Geological Survey 3, p.547-566.

Parker, D.H., Boivin, M., Murray, I.M., and Groom, R.W., 1996, Case study of the application of EMIGMA to the Lac Volent data; *in* Proc. of the Sixty Sixth Annual Meeting of the Society of Expl. Geophysicists, Denver, Colorado.

Polzer, B., Macnae, J., Lamontagne, Y., and Koch, R., 1989, Lateral resolution and enhancement of TEM data by correlation processing; *in* Proc. of the Fifty-Ninth Annual Meeting of the Society of Expl. Geophysics; Dallas, Texas.

Powell, B.W., 1990, Large loop EM surveys in the Athabasca Basin; *in* Modern Exploration Techniques; L.S. Beck and C.T. Harper, eds., Saskatchewan Geological Society Special Publication 10, p.74-93.

Ramaekers, P., 1981, Hudsonian and Helikian basins of the Athabasca region, northern Saskatchewan; *in* Proterozoic Basins of Canada, F.H.A. Campbell, ed., Geological Survey of Canada, Paper 81-10, p.219-233.

Ruzicka, V., 1993, Unconformity-type uranium deposits: *in* Mineral Deposit Modelling; R.V. Kirkham, W.D. Sinclair, R.I. Thorpe, and J.M. Duke, eds., Geological Survey of Canada, Special Paper 40, p.125-149.

Scott, F., 1983, Midwest Lake uranium discovery; *in* Uranium Exploration in the Athabasca Basin, Saskatchewan, Canada; E.M. Cameron, ed., Geological Survey of Canada, Paper 82-11, p.41-50.

Sibbald, T.I.I., 1983, Geology of the crystalline basement, NEA/IAEA Athabasca test area; *in* Uranium Exploration in the Athabasca Basin, Saskatchewan, Canada; E.M. Cameron, ed., Geological Survey of Canada, Paper 82-11, p.1-17.

Simpson, M.A. and Sopuck, V.J., 1983, Till geochemistry near the Midwest Lake uranium deposit; *in* Uranium Exploration in Athabasca Basin, Saskatchewan, Canada; E.M. Cameron, ed., Geological Survey of Canada, Paper 82-11, p.207-214.

Smith, R., 1997, Advances in airborne time domain EM technology; *in* Proceedings of Exploration '97.

Sopuck, V.J., Carle de, A., Wray, E.M., and Cooper, B., 1983, The application of lithogeochemistry in the search for unconformity-type uranium deposits, northern Saskatchewan, Canada; Journal of Geochemical Exploration, Vol. 19, p.77-99.

Tona F., Alonso, D. and Svab, M., 1985, Geology and mineralization in the Carswell Structure—a general approach; *in* The Carswell Structure Uranium Deposits, Saskatchewan; R. Laine, D. Alonso and M. Svab, eds., Geological Association of Canada, Special Paper 29.

Trocki, L.K., Curtis, D.B., Gancarz, A.J., and Banar, J.C., 1984, Ages of uranium mineralization and lead loss in the Key Lake uranium deposit, northern Saskatchewan, Canada; Econ. Geol., Vol. 79, p.1378-1386.

Walcott, R.I., 1968, The gravity field of northern Saskatchewan and northeastern Alberta; gravity map series of the Dominion Observatory, Department of Energy, Mines and Resources, Ottawa, Canada.

Wallis, R.H., 1970, A geological interpretation of gravity and magnetic data, Northwest Saskatchewan; Canadian Jour. of Earth Sciences, Vol. 7, p.858-868.

Wallis, R.H., Saracoglu, N., Brummer, J.J., and Golightly, J.P., 1983, Geology of the McClean uranium deposits; *in* Uranium Exploration in Athabasca Basin, Saskatchewan, Canada; E.M. Cameron, ed., Geological Survey of Canada, Paper 82-11, p.71-110.

Wheatley, K., Murphy, J., Leppin, M., Cutts, C., and Climie, J.A., 1995, Advances in the exploration model for Athabasca unconformity uranium deposits; paper presented at the 1995 IAEA meeting in Kiev.

Wilson, J.S., 1985, Exploration in the Carswell Structure; *in* The Carswell Structure uranium deposits, Saskatchewan, R. Laine, D. Alonso, and M. Svab, eds., Geol. Assoc. of Canada Special paper 29, p.176-188.

Wilson, M.R., and Kyzer, T.K., 1987, Stable isotope geochemistry of alteration associated with the Key Lake uranium deposit, Canada; Econ. Geol., Vol. 82, p.1540-1557.