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SEDIMENTARY-HOSTED MINERAL DEPOSITS: A HIGH-RESOLUTION SEISMIC SURVEY IN THE ATHABASCA BASIN

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ABSTRACT

A 32-km long, high resolution vibroseis reflection profile was acquired across the eastern margin of the Paleoproterozoic intracratonic Athabasca basin. Seismic signals successfully imaged the basin-basement contact at shallow depths (~200 m) and outlined a number of steeply dipping imbricate fault zones. Some of these fracture zones intersect the overlying sandstones and extend several thousand metres into basement. Variations in the levels of weathering and thickness of the basement unconformity appear to be recognizable through spatial changes in the associated reflection waveforms.

INTRODUCTION

The intracratonic Athabasca basin of northern Saskatchewan and Alberta (Figure 1) is the location of a number of uranium deposits (Sibbald, 1986). The known ore zones are situated at the margin of the basin, where the thicknesses of the sedimentary deposits is not more than a couple of hundred metres.

The basin fill comprises the Athabasca Group, a sequence of flat-lying red bed formations (Ramaekers, 1981). The basin is divisible into three fault-controlled subbasins. The metamorphic basement consists of a steeply dipping belt of northeast-trending metapelitic gneisses, granitoid gneisses and migmatitic gneisses of the Trans-Hudson orogen (Sibbald, 1983). The high-grade metamorphism has resulted in remobilisation and ductile interaction of the Archean basement with the Proterozoic supracrustal rocks.

Earlier seismic investigations in the basement were limited to reconnaissance refraction studies (Hobson and MacAuley, 1969; Overton, 1977) and a few isolated reflection experiments (Scott, 1983). The success of these surveys was marginal; therefore no further attempts were made to use these techniques during the following decades. It was recognized, however, that an effective seismic imaging survey program could provide important information for the mining exploration community by outlining the subsurface geology in the deeper part of the basin. In the last 10–15 years, geophysical exploration projects have mainly used EM techniques to outline the ore-related graphitic metapelite zones (Fouques *et al.*, 1986).

In 1994, a consortium of actively exploring mining companies and the Saskatchewan Research Council, in cooperation with the Trans-Hudson Orogen Transect project of LITHOPROBE (Lucas *et al.*, 1993), initiated a high-resolution reflection experiment along the eastern margin of the basin. The aim of the study was to test the use of advanced reflection data acquisition technology in a part of the basin where a number of ore bodies were already recognized and where the regional lithology and structural framework are moderately documented. The instrumentation of the experiment consisted of two large vibroseis energy sources (Hemi-50) and a 480-channel, 24-bit, ARAM24 recording system. The final results of the reflection study are highly encouraging, as the seismic reflections clearly image the basement unconformity and show a number of subparallel faults in the underlying basement.

GEOLOGIC BACKGROUND

The Athabasca basin is located on the eastern margin of the Hearne craton of the Canadian shield, covers approximately 104 000 km^2 of northwestern Saskatchewan and extends nearly 40 km into Alberta (Figure 1). It has an elliptical shape with an average surface relief of less than 30 m (Tremblay, 1982).

The basin is mantled by variable thickness (0~90 m) Quaternary deposits (Schreiner, 1983; Tremblay, 1982). This glacial debris is mainly composed of poorly sorted sand and gravel with abundant boulders. The till-bedrock interface is generally flat and abrupt with local troughs

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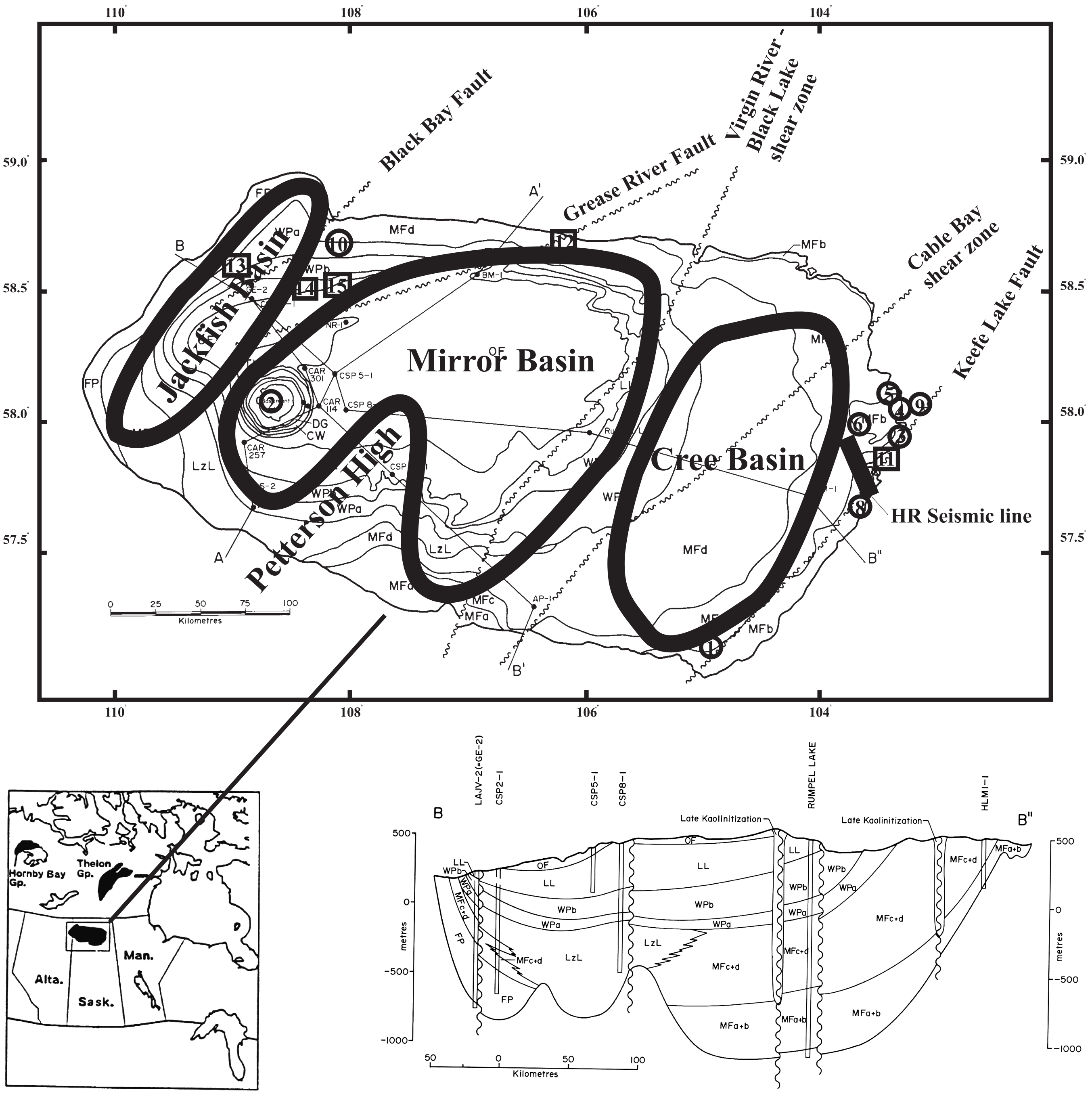

Figure 1: *Geology of the Athabasca basin (modified from Hoeve and Quirt, 1984). Stratigraphic symbols after Ramaekers (1979); MF = Manitou Falls Formation; LzL = Lazenby Lake Formation; FP = Fair Point Formation; WP = Wolverine Point Formation; LL = Locker Lake Formation; OF = Otherside Formation; TL = Tuma Lake Formation; DG = Douglas Formation; CW = Carswell Formation. Circle with number inside = unconformity-type deposits ~1350 Ma; square with number inside = Athabasca deposits ~300 Ma. HR = high resolution seismic line; RL = Rumple Lake borehole.*

within the underlying sandstone. Elongations of drumlins and boulder trains indicate a dominant ice-transport direction from the northeast.

The Athabasca Group, a flat-lying quartz-sandstone with minor conglomerate, marine shales and shelf carbonate beds, forms the fill of the basin (Ramaekers, 1981). Presently, the Athabasca sediments are about 2000 m thick at the centre of the basin but originally may have reached thicknesses of 5000–7000 m in the Middle Proterozoic (Pagel *et al.,* 1980). The succession of the Athabasca basin was subdivided by Ramaekers (1981) into two laterally equivalent basal formations, the Manitou Falls in the east and the Fair Point in the west, with nine additional conformably overlying formations (Figure 1). The marine shale (Douglas) and the shelf carbonate (Carswell) formations are restricted in their distribution to the Carswell circular structure. The Carswell window, and its mode of structural emplacement are the subjects of continued debate (Baudemont and Fedorowich, 1996). In the eastern part of the basin, especially in the area of the seismic study, only the Manitou Falls formation comprises the entire Athabasca group. From radiometric studies of diagenetic minerals, the minimum ages derived for these sedimentary rocks were between 1500 and 1720 Ma (Kotzer *et al.*, 1992; Machado, 1990).

The origin of the deposits is uncertain, but indications are that most of the Athabasca Group sediments were transported westerly and northwesterly, probably by streams from an uplifted region in the Wollaston fold belt east and south of the basin, and were deposited on lacustrine or marine shorelines (Ramaekers, 1979) in open water (shelf facies) or nearshore (shore facies). Five marine transgressions were estimated by Ramaekers (1981) interspersed by periods of uplift and marginal deposition. Hoeve and Quirt (1984) interpreted the sequence as mainly fluviatile to nearshore marine with two marine transgressions.

Diabase dykes were emplaced in the Athabasca basin during the period of 1270 to 1000 Ma (Ramaekers and Hartling, 1979; Hoeve and Quirt, 1984) along reactivated Hudsonian fault structures. These intrusions occupied broad north, or northwesterly fracture zones or faults and were most extensive and ascended highest in the Athabasca Group in the centre of the basin. The trend of these intrusive bodies corresponds to tensional directions associated with left-lateral movement along major Hudsonian faults that transect the metamorphosed basement.

The Athabasca deposits uncomfortably overlie an intensely weathered basement surface. This paleoweathered zone, which is well preserved and may reach a thickness of up to 70 m, has the characteristics of the lower levels of a laterite (Hoeve and Sibbald, 1978). Mineralogical zoning is common with kaolinite in the upper, and illite and some chlorite in the lower levels. In the upper level hematite staining is pervasive and prevalent. The kaolinitic and hematitic alteration is superimposed on, and variably affects the lower chloritic zone (Hoeve and Quirt, 1984).

The basement beneath the Athabasca basin is composed of severely deformed medium to highly metamorphosed Archean and Paleoproterozoic sedimentary, volcanic and plutonic rocks which trend in a north-northeast direction (Lewry and Collerson, 1990). The Virgin River-Black Lake shear zone (Snowbird line, Lewry and Collerson, 1990) divides the basement rocks into the Rae and Hearne cratons (Figure 1). The Hearne Province is further subdivided into the Mudjatik and Wollaston domains which comprise parts of the Cree Lake Mobile belt (Lewry and Collerson, 1990). The Cree Lake zone underwent complex multiphase deformation and medium- to high-grade thermal reworking during the Paleoproterozoic. The Mudjatik domain consists mainly of felsic gneisses of granitic to grandioritic-tonalitic-trondhjemitic composition, in part charnockitic, with subordinate supracrustal gneisses and late intrusive rocks. The felsic gneisses are interpreted, for the most part, to be remobilized plutonic rocks of Archean age (Lewry and Sibbald, 1980). The supracrustal rocks are arranged in thin discontinuous zones with arcuate and even closed outcrop patterns (Sibbald, 1983).

The Wollaston Domain comprises a Paleoproterozoic supracrustal succession of continental margin metasediments (Wollaston Group). These metasedimentary rocks are complexly deformed, polymetamorphosed (Madore and Annesley, 1993), and unconformably (and tectonically) overlie a strongly remobilized Archean basement complex. Two main pulses of Kenoran magmatism took place at 2735–2700 Ma and 2630–2590 Ma (Annesley *et al.,* 1996). Field relationships and U-Pb geochronology provide evidence of strong reworking, interfolding, and tectonic interleaving of the Archean orthogneisses with the Wollaston Group metasediments at 1810-1775 Ma. U-Pb monazite ages of 1816–1812 Ma give the timing of peak high-T, low-P metamorphic conditions in the seismic survey area. Calc-alkaline plutonism, synchronous with peak-temperature metamorphism, occurred at 1820–1810 Ma. The boundary zone between the Wollaston and Mudjatik domains (Figure 1) is enigmatic, and possibly significant in that many of the unconformity-type uranium deposits occur along or adjacent to it. Lewry and Sibbald (1980) suggested that the junction between the Wollaston and the Mudjatic domains is lithologically and thermotectonically gradational, while Annesley and Madore (1989) proposed that the boundary might be a major tectonic discontinuity.

The Athabasca basin is the youngest of a series of intracratonic basins that formed following the Hudsonian orogeny (Ramaekers, 1981). The basin was formed at approximately 1700–1750 Ma (Fahring and Loveridge, 1981) as a series northeast-southwest oriented sub-basins controlled by major Hudsonian-age faults (Figure 1). The close association with major faults and the structural complexity all suggested to Ramaekers (1981) that the basin originated as a set of pull-apart basins in connection with a wrench fault system as in modern extensional tectonic environments (Crowell, 1974; Steel, 1976). The more or less contemporaneous adjacent sub-basins have similarities and differences in their sedimentary fill, reflecting some dissimilarities in source areas and tectonic history. Some red bed sequences start with siltstone and arkoses rather than conglomerates.

Hoeve and Quirt (1984) postulate that several stages of contrasting structural characteristics observed in the sedimentary fill broadly correspond to evolutionary stages recognized in other intracratonic basins. Radiometric evidence indicates that basin formation was preceded by episodic uplift. An early tensional tectonic regime initiated the basin formation and was followed by a non-tectonic phase during which subsidence continued. A new, episodic period of tectonic reactivation (1350–1050 Ma) is associated with the intrusion of diabase dykes and two stages of mineralization. During the next tectonically quiescent period (1050–350 Ma) subsidence reached its maximum depth (~5000–7000 m) before the initiation of slow epirogenic uplift around 800 Ma. The last stage of the mineralization was associated with a final tectonic uplift period of 300–250 Ma.

The ores in the Athabasca basin are recognized as characteristic unconformity-type uranium deposits and are well documented in the literature (Sibbald, 1986; Hoeve and Quirt, 1984). The mineralization is in close proximity to the sub-Athabasca unconformity and the paleoweathered zone (Figure 2). The ore is structurally controlled by steeply dipping faults which usually offset the unconformity by up to 50 m. These fractures follow the traces of conductive graphitic pelitic gneisses in the basin floor. The mineralization that straddles or flanks the traces of the graphitic gneisses tends to form long linear deposits in clusters of several pods. These deposits may be up to 2000 m long, 100–200 m wide and a few tens of metres thick. The ore pockets consist of a high-grade uranium reach ore (pitchblende, Ni-Co arsenides, base-metal sulphides, U/Ni zonation), at or just below the unconformity, and have an associated lower grade envelope extending a few hundred metres into the sandstone which is highly altered, or downward into the basement. Immediately surrounding the high-grade core is a shell of secondary hematite.

EXPECTED SEISMIC SIGNATURES— SEISMIC EXPLORATION HISTORY

Acoustic properties of the Athabasca basin rocks are not well known. Investigations of this nature are limited to a study of samples from three boreholes of the Midwest Lake deposits (Hajnal *et al.*, 1983; King *et al.*, 1988) and analysis of a sonic log from the Rumple Lake test hole (Figures 1 and 3). The surface glacial tills have P-wave velocities of 1000–1500 m/s, while the Manitou Falls formation at Midwest Lake ranges between 4500 to 4750 m/s with densities ranging from 2434 to 2508 kg/m^3. The porosity of the sandstone can vary between 5 to 10% while the clay content can reach 31 to 40%, reducing the P-wave velocity to 3900 m/s. The seismic log of the Rumple Lake hole indicates an average P-wave velocity (Figure 3) for the Athabasca Group of around of 4400 m/s with local fluctuations of several hundred metres per second.

The altered rocks in the regolith zone of the basin floor can have reduced P-wave velocities between 3900–4200 m/s due to increase in porosity and clay resulting from destruction of feldspars and mafic constituents in the crystalline basement. The unaltered basement granites and gneisses have P-wave velocities of 5800 to 6100 m/s.

A comparison of these elastic-wave velocities suggests that zones of increased porosity or clay content and the associated variations in density, within the red beds, can have reflection coefficients between 0.05 to 0.1, sufficiently high to be mappable by modern seismic reflection techniques. The impedance contrasts at the regolith zone (Figure 3) can also be favourable for seismic imaging if the alteration produces distinct zones with characteristic acoustic properties. If the weathering is gradational, the acoustic impedance changes may be insufficient for detection. Rapid, seismically detectable physical property changes can also be

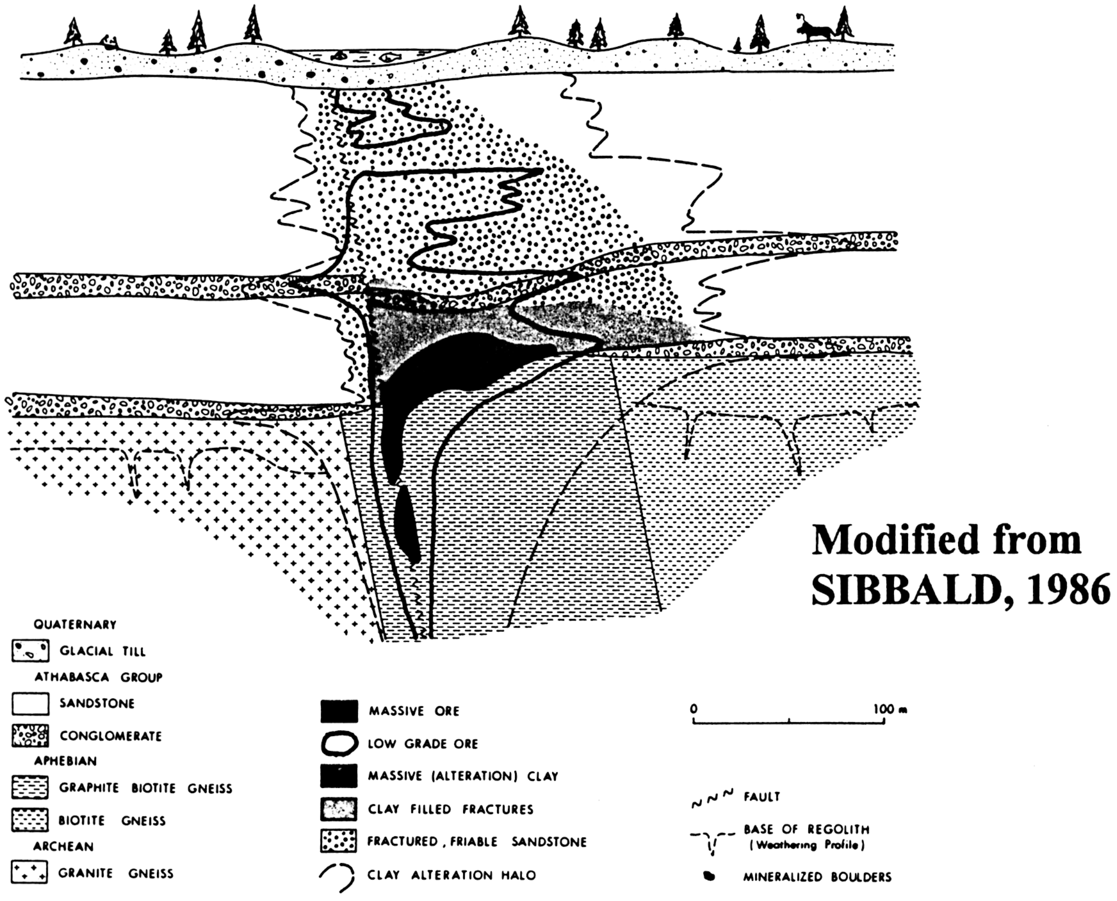

Figure 2: *Schematic cross-section of an unconformity-type uranium deposit. Massive ore and massive (alteration) clay are marked with the same shade as their locations coincide.*

expected in the clay-halo zones just above the ore, or in the highly altered fault zones which cut basement.

Seismic methods have not been extensively tested in the Athabasca basin, although the reconnaissance refraction surveys by Hobson and MacAuley (1969) and Overton (1977) were very successful in outlining the sandstone-basement contacts throughout the entire basin. Subsequent attempts to use this technique are not documented in the literature. Several rudimentary reflection experiments (Fouques *et al.,* 1986; Scott, 1983; Hajnal and Reilkoff, 1980) met with only marginal success. All of these experiments detected weak reflections contaminated by complex coherent noise patterns. Contrary to these observations, a simple one-dimensional synthetic seismogram computed from the properties of the Rumple Lake sonic log (Figure 3a) reveals a number of potentially recognizable reflections within the Athabasca Group sandstones. The combined paleoregolith and basement contact zone also appears to be the source of intricate but large amplitude reflections. The introduction of near-surface generated multiple arrivals (Figure 3b) suggests that these coherent noise events can have highly detrimental

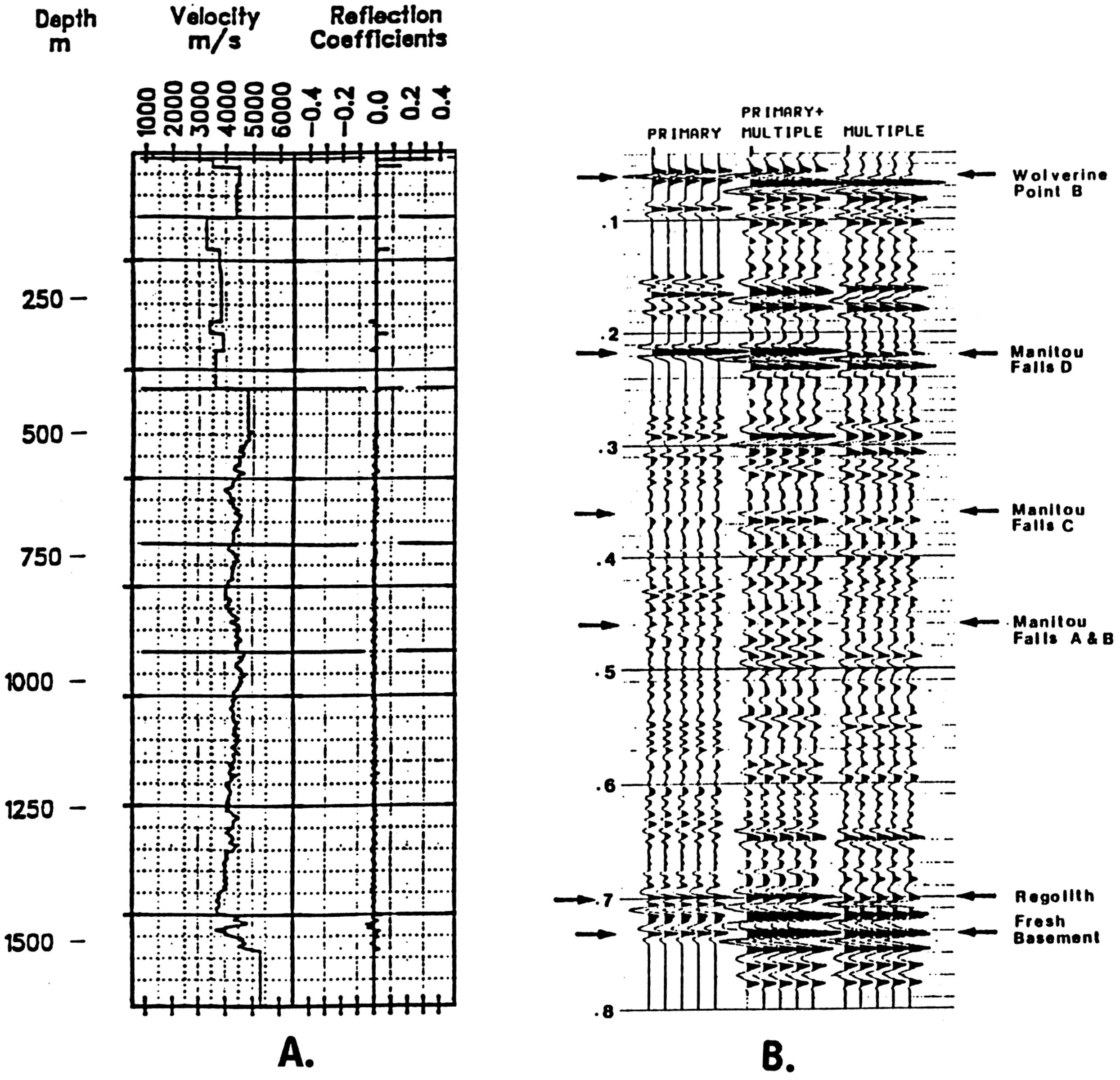

Figure 3: *Velocity depth function for Rumple Lake borehole (0-300 m velocities were derived from sample measurements, 300-1600 m velocities are from sonic log survey). Also shown are one-dimensional synthetic seismograms computed assuming vertical incident seismic waves and 90 Hz centre frequency Ricker wavelet.*

influences on the primary signals, and under certain conditions may lead to field observations in which the desired events will be difficult to recognize.

1994 HIGH-RESOLUTION REFLECTION EXPERIMENT

In 1994 a consortium of mining companies, in cooperation with LITHOPROBE and the Wollaston EAGLE project, initiated a 32-km high-resolution seismic reflection experiment along the Points North road at the eastern margin of the basin (Figure 1). The survey was conducted in an area of active exploration and in the proximity of several known ore deposits. The objectives of the program were to test the applicability of the most advanced seismic reflection data acquisition technology in the basin, to map the basement contact in an area where it was shallow (~200 m) and to image the underlying basement lithostratigraphy and structure to a depth of about 9000 m (3.0 s two-way travel time, TWT).

The deployment of two Hemi-50 (2 × 20,000-kg) vibroseis units as surface energy sources was the first fundamental departure from the techniques of the earlier experiments. This seismic energy configuration eliminated one of the major problems faced by all of the earlier explosive source-dependent experiments. Drilling shotholes in the marginally consolidated and boulder infested glacial till is technically a very demanding operation. This difficulty forced most of the previous programs to place the explosives either on the surface or in very shallow holes, leading to the generation of mostly coherent noise and very marginal signal levels. The objective of mapping the very shallow basement unconformity while attempting to detect signals from considerable basement depths necessitated some compromises in the deployment of the observational detector spread. The 5-m station and 10-m source spacing of a 480-channel symmetric split spread array configuration provided only 1200 m maximum offset. This distance was more than that required to image the bottom of the sandstone but appeared to be insufficient for the deeper targets. The field recording of these deeper arrivals, however, was secured through the regular LITHOPROBE data acquisition program.

The individual field records (Figure 4) clearly show that visible signals were generated at the top of the basement. The abrupt changes in

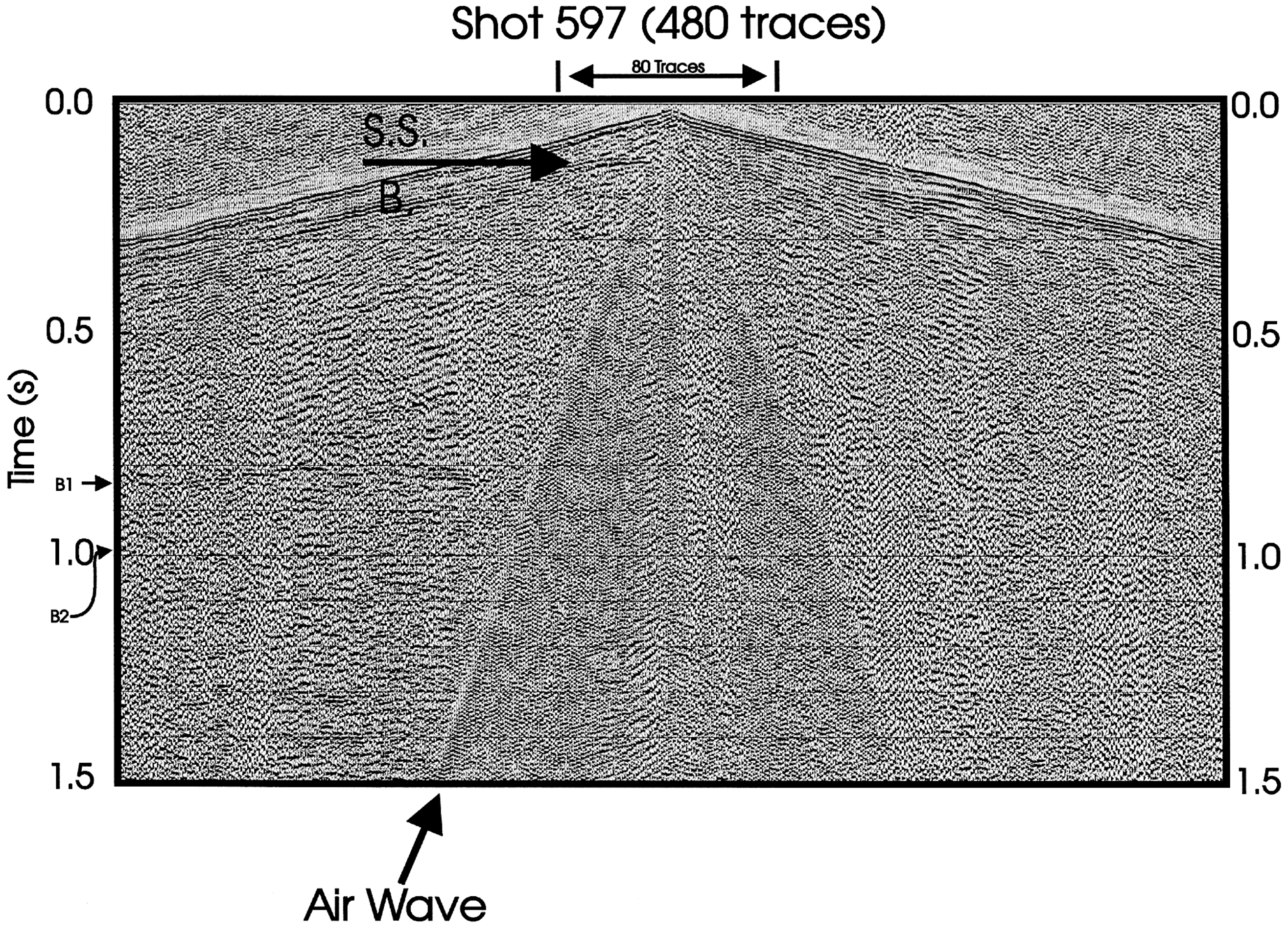

Figure 4: *A 480-channel field record (shot 597). S.S. = sandstone; B. = Basement.*

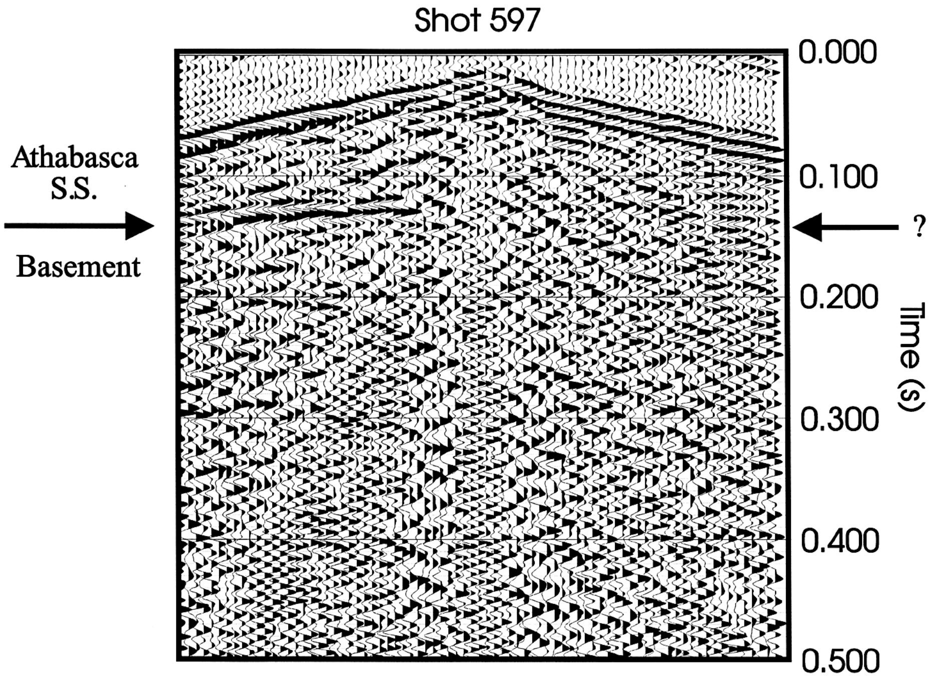

Figure 5: *The inner 80 traces of field record 597.*

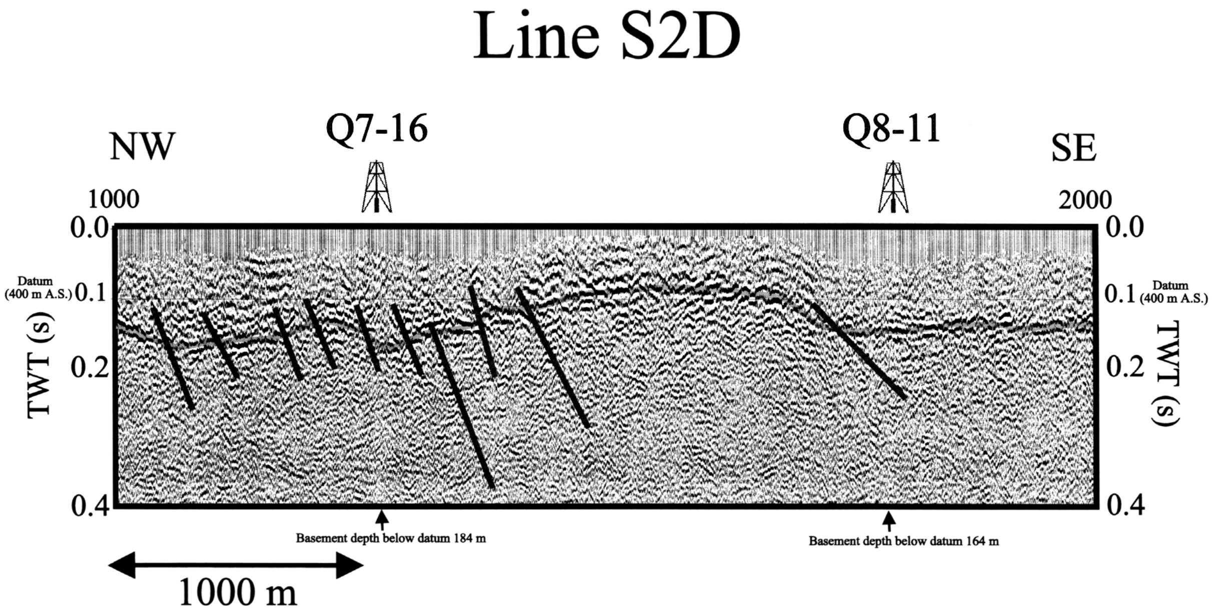

Figure 6: *A 5-km long seismic section of the sandstone-basement contact. Q7-16 and Q8-11 are test hole locations. Signal enhancements processing steps include: refraction statics and mute; band-pass filtering; spectral balance; deconvolution, KL filtering and stack.*

these basement reflection signatures, even within one record, suggest a reflective zone with considerable structural complexity. Additional reflectivity (B_1, B_2) is also evident from the deeper part of the basement. The first arrival energy is strong and the change in its move-out velocity indicates that direct mapping of the thickness of the Quaternary deposits can be attempted using these events. The data also indicate that beyond a 200-m offset (40 + 40 traces) the first arrival energy and the shallow reflections interfere with each other. An unwanted but unavoidable part of the source-generated events is the V-shaped coherent noise pattern within the central part of the record.

To avoid complications with muting and interference of events, the inner 80 traces (Figure 5) of each field record were selected for processing and construction of the final shallow seismic sections. This decimation of the field records reduced the data redundancy to 50-fold. The data were subjected to a number of standard signal enhancing operations (Figures 6 and 8). The final basement seismic images are strong and distinct, without any direct negative effects of the reduction in data fold. Figure 6 outlines a 5-km length of the basement subsurface between stations 1000 and 2000, approximately the same distance east of the western end of the profile. The seismic images depict a central basement high flanked by two local subbasins. A number of subparallel faults which offset the basement floor by variable amounts are mapped by the reflections. The resolution of these displacements is controlled by the frequency content of the seismic signal. Combined spectral analysis of a number of basement arrivals (Figure 7) show that the full input frequency spectrum (30–130 Hz) was transmitted to this depth level. Considering the input signal characteristics the minimum fault displacement

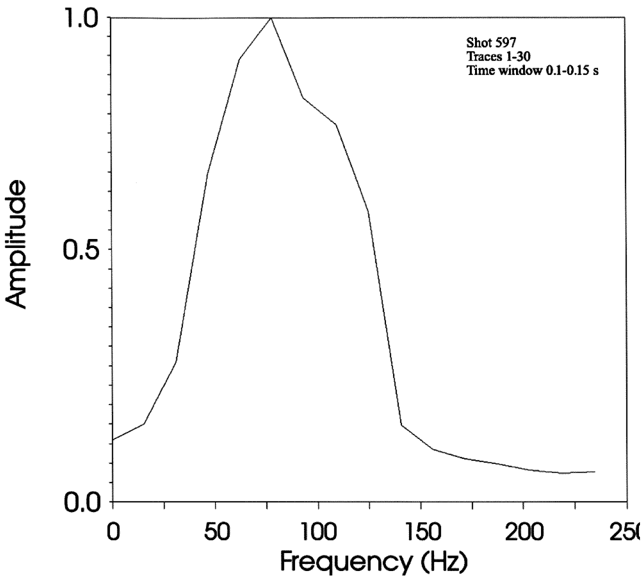

Figure 7: *Amplitude spectra of basement unconformity reflection arrivals.*

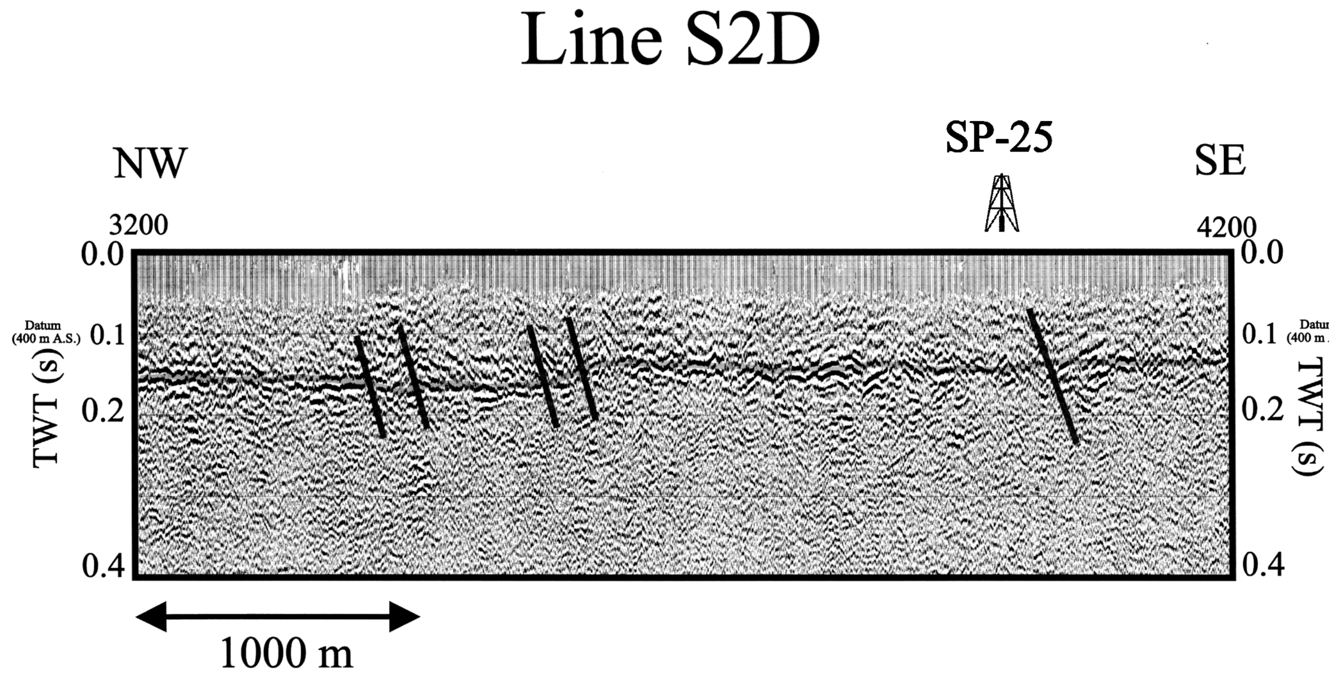

Figure 8: *Shallow seismic section of the basement unconformity in the central part of the survey line. Signal processing of this part of the data set is equivalent with the procedures indicated under Figure 6.*

that can be resolved by the survey is around 8 m. The depth extensions of these faults are not well defined on the sections. However, reprocessing of the full data set further enhanced the signal levels, allowing visual recognition of most of these fault contacts to significant depths.

Some of the basement offsets can be rather abrupt and as much as 20–25 m (Figure 8), demonstrating that the structural setting associated with an unconformity-type ore deposit can often be recognized from seismic reflection images. The spatially variable characteristics of the seismic waveforms from the basement interface (Figures 6 and 8), indicate a laterally changing geologic environment. The complexity of the reflectivity is thought to be the consequence of the numerous basement-cutting imbricate faults, the variable level of alteration within the paleo-regolith, and changes in the thickness of the weathered layer. The intricate nature of the basin floor is well known and documented (Wallis *et al.,* 1983) in the vicinity of the ore deposits. Direct correlation of changes in waveform to specific alteration types, however, is difficult because the acoustic properties of the different weathered zones have not been effectively investigated. Attempts are nevertheless made to resolve this problem.

The eastern 18-km segment of the high resolution seismic investigation crossed the eastern margin of the basin and the inferred contact zone of the Mudjatik and Wollaston lithotectonic domains (Figures 1 and 9). The seismic signals image the known thinning of the sandstone to the southeast and the reflection events terminate in the area of the projected basin edge. Below the sandstone cover, in the upper 9000 m of the section (3.0 s TWT), a number of distinct reflectivity patterns are evident. These several-kilometre-long subparallel reflection zones outline a complex imbricate listric fault system mainly within the Wollaston fold belt with an average dip of 40°–45° which are interpreted as detachment zones between slivers of preserved Proterozoic metasediments. The distinct intervals of subparallel reflectivity appear to be limited only to the eastern half of the section, thus only to the Wollaston domain. Based on this inference, we conclude that contact between the two lithotectonic zones actually lies a few kilometres further west of the position presently marked by surface geologic projections (Sibbald, 1983). Since the survey line within the Wollaston belt portion of the study turns south and strikes at 45° to the regional structural trend, the seismic section reveals only apparent dips.

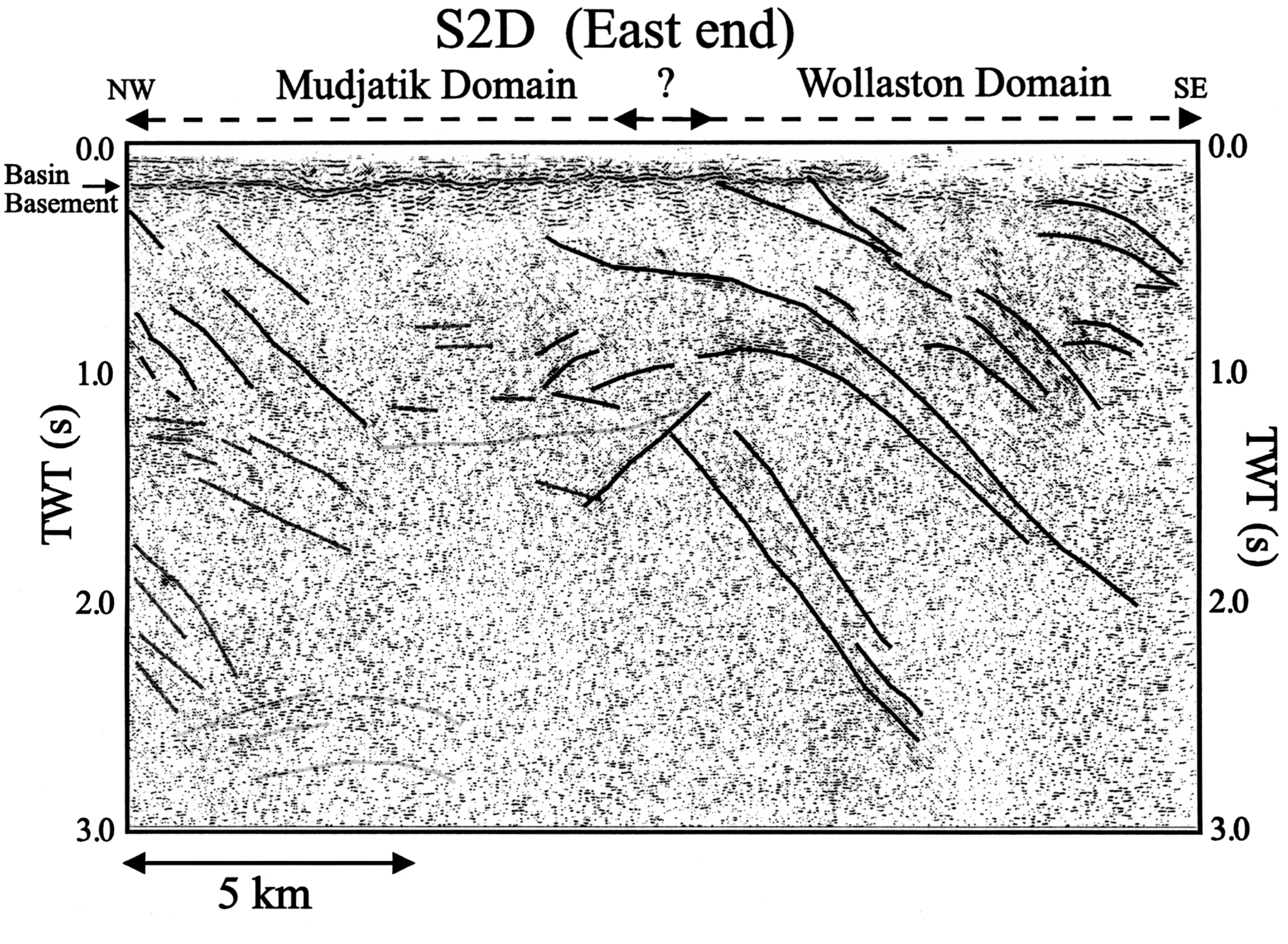

Figure 9: *Eastern 18-km segment of the high resolution seismic survey. Dark lines indicate reflections with dip greater than 30°. Processing of this section included all 480 traces of the individual field records. Muting was modified but the processing operations were same as indicated in association with Figure 6.*

In the Mudjatik domain, several east-dipping fault zones are mapped with considerable depth extent (Figure 9). Many of these faults can be traced to the sandstone contact and a number of them appear to penetrate through the basin rocks. A second set of slightly weaker, more gently dipping, or nearly horizontal patterns of reflectivity can also be recognized below 1.00 s (TWT) in this domain. These reflections appear to be images of older structures since some of them are offset by the east-dipping faults. Signal-to-noise ratios are high throughout the section indicating effective imaging of complex structures to a depth of 9000 m.

SUMMARY AND CONCLUSIONS

This short experimental high-resolution survey effectively imaged the floor of the eastern margin of the Athabasca basin. The seismic signatures outline a complex geologic environment beneath the sedimentary fill. The basement is offset by a number of mainly southeast-dipping dense sets of imbricate faults. Some of these fracture zones ascend into the overlying sandstone strata, attesting to continued tectonic activity throughout the existence of this intracratonic structure. The basement seismic signatures are intricate wave-forms which change in character laterally. These changes in reflectivity are partly associated with variations in depth of weathering and thickness of the paleoregolith.

The distinct seismic reflections which are associated with the basement unconformity, the regolith and the related fault zones in the basin, define the primary structural elements that control the ore deposits of the region. Most of the faults that intersect the basement penetrate to significant depth. Detailed regional mapping of these structural patterns could provide the additional data needed for a better understanding of the relationships between the ore deposits and the tectonic evolution of the area. An understanding of the relationship between the regional tectonic framework and the location of the ore deposits could also help to recognize new exploration targets in the basin. The subsurface seismic signatures of the Mudjatik and the Wollaston domains appear to be distinct, indicating a somewhat different thermotectonic history of the two regions of the Cree Lake zone.

A properly designed seismic reflection program appears to be able to provide comprehensive geological information about the subsurface from shallow to significant depths in the Athabasca basin. The results are encouraging for the use of the technique to extend exploration beneath or within the basin to depths greater than previously attempted. Although difficult near-surface geologic settings, in some parts of the basin, may lead to the observation of complicated signals, appropriately designed data acquisition and signal enhancement procedures can produce clear images of the subsurface in the basin. There are several favourable geologic conditions which suggest that the seismic reflection technique can be effectively adapted for subsurface mapping purposes within the Athabasca basin.

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REFERENCES

Annesley, I.R., and Madore, C., 1989, The Wollaston Group and its underlying Archean basement in Saskatchewan, Saskatchewan Geol. Surv., Misc. Report 89-4, 87-91.

Annesley, I.R., Madore, C., Shi, R., and Krogh, T.E., 1996, U-Pb geochronology and thermotectonic history of the Wollaston domain in the Wollaston Lake area, Hearne Province, Saskatchewan, Geol. Assoc. of Canada-Min. Assoc of Canada Ann. Meeting, Winnipeg, Abstract, 21, A-4.

Baudemont, D., and Fedorowich, J., 1996, Structural control of uranium mineralization at the Dominique-Peter deposit, Saskatchewan, Canada, Economic Geology, **91**, 855-874.

Crowell, J.C., 1974, Origin of late Cenozoic basins in southern California, *in* Dickson, W.R., ed., Society of Economic Geologists and Mineralogists, Spec. Pub. 22, 190-204.

Fahring, W.F., and Loveridge, W.D., 1981, Rb-Sr isochrone age of weathered Pre-Athabasca formation basement gneiss, northern Saskatchewan, Geol. Surv. Can., Paper 81-1C, 127-129.

Fouques, J.P., Fowler, M., Knipping, H.D., and Schimman, K., 1986, The Cigar Lake uranium deposit: discovery and general characteristics, Evans, E.L., ed. Uranium deposits of Canada, Canadian Inst. Min. and Metallurgy, Spec. Vol. 33. 218-229.

Hajnal, Z., and Reilkoff, B.R., 1980, Reflection data processing in the Athabasca basin, 50th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1387-1415.

Hajnal, Z., Stauffer, M.R., and King, M.S., 1983, Petrophysics of the Athabasca basin near the Midwest Lake uranium deposit, *in* Cameron, E.M. ed., Uranium exploration in Athabasca basin, Saskatchewan, Canada, Geol. Surv. Can. Paper 82-11, 303-310.

Hobson, G.D., and MacAuley, H.A., 1969, A seismic reconnaissance survey of the Athabasca formation, Alberta and Saskatchewan, Geol. Survey of Canada, Paper 69-18, 35-47.

Hoeve, J., and Sibbald, T.I.I., 1978, On the genesis of Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada, Econ. Geol., 73, 1450-1473. *in* Parslow, G.R., ed., Uranium exploration techniques, Sask. Geol. Soc., Special Pub., 4, 297-322.

Hoeve, J., and Quirt, D., 1984, Uranium mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the Middle-Proterozoic Athabasca basin, Saskatchewan Canada, Saskatchewan Res. Council, Pub., R-855-2-B, 190 pp.

King, M.S., Stauffer, M.R., Yang, H.J.P., and Hajnal, Z., 1988, Elastic-waves and related properties of clastic rocks from the Athabasca basin, western Canada, Can. J. Explor. Geophysics, **24**, 110-116.

Kotzer, T.G., Kyser, T.K., and Irving, E., 1992, Paleomagnetism, and the evolution of fluids in the Proterozoic Athabasca basin, northern Saskatchewan, Canada, Can. J. Earth Sci., **29**, 1474-1491.

Lewry, J.F., and Collerson, K.D., 1990, The Trans-Hudson Orogen: Extent, Subdivision, and Problems, *in* Lewry, J.F. and Stauffer, M.R., eds., The Early-Proterozoic Trans-Hudson Orogen, Geol. Assoc. Can., Paper 37, 1-14.

Lewry, J.F., and Sibbald, T.I.I., 1980, Thermotectonic evolution of the Churchill Province in northern Saskatchewan, Canada, Can. J. Earth Sci., **68**, 45-82.

Lucas, S.B., Green, A., Hajnal, Z., White, D., Lewry, J., Ashton, K., Weber, W., and Clowes, R., 1993, Deep seismic profile across a Proterozoic collision zone: surprises at depth, Nature, **363**, 339-342.

Machado, N., 1990, Timing of collisional events in the Trans-Hudson Orogen: evidence from U-Pb geochronology for the New Quebec Orogen, the Thompson belt, and the Reindeer zone (Manitoba and Saskatchewan), *in* Lewry, J.F. and Stauffer, M.R., eds., The Early-Proterozoic Trans-Hudson Orogen, Geol. Assoc. Can., Paper 37, 433-441.

Madore, C., and Annesley, I.R., 1993, Metamorphic pressure-temperature conditions of the basal Aphebian Wollaston Group, Hearne Province, Northern Saskatchewan, Geol. Assoc. of Canada-Mineral Assoc. of Canada Ann. Meeting Abstract 18, A-65.

Overton, A., 1977, Seismic determination of basement depths, Athabasca basin, Geol. Surv. Can., Rept. of Activities Part C, Geol. Surv. Can., Paper 77-1C, 19-25.

Pagel, M., Poty, B., and Sheppard, S.M.F., 1980, Contributions to some Saskatchewan uranium deposits mainly from fluid inclusions and isotopic data, *in* Ferguson, S. and Goleby, A., eds., Uranium in the Pine Creek geosyncline, Inter. Atom. Energ. Agen., Vienna, 639-654.

Ramaekers, P., 1979, Stratigraphy of the Athabasca basin, In summary of investigations, Sask. Geol. Surv., Misc. Report, 79-10, 154-160.

Ramaekers, P., 1981, Hudsonian and Helikian basins of Athabasca region, northern Saskatchewan, Geol. Surv. Can., Paper 81-20, 219-232.

Ramaekers, P., and Dunn, C.E., 1977, Geology and geochemistry of the eastern margin of the Athabasca basin,

Ramaekers, P., and Hartling, A.A., 1979, Structural geology and intrusive events of the Athabasca basin and their bearing on uranium mineralization, *in* Parslow, G.R., ed., Uranium exploration techniques, Sask. Geol. Soc., Special Pub., 4, 221-234.

Schreiner, B.T., 1983, Quaternary geology of the NEA/IAEA test area, *in* Cameron, E.M. ed., Uranium exploration in Athabasca basin, Saskatchewan, Canada, Geol. Surv. Can. Paper 82-11, 27-32.

Scott, F., 1983, Midwest Lake uranium discovery, *in* Cameron, E.M., ed., Uranium exploration in Athabasca basin, Saskatchewan, Canada, Geol. Surv. Can. Paper 82-11, 41-50.

Sibbald, T.I.I., 1983, Geology of the crystalline basement, NEA/IAEA test area, *in* Cameron, E.M., ed., Uranium exploration in Athabasca basin, Saskatchewan, Canada, Geol. Surv. Can. Paper 82-11, 1-14.

Sibbald, T.I.I., 1986, Overview of the Precambrian geology and aspects of the metallogenesis of northern Saskatchewan, *in* Gilboy, C.F. and Vigrass, L.W., eds., Economic minerals of Saskatchewan, Sask. Geol. Soc., Spec. Pub. 8, 1-16.

Steel, R.J., 1976, Devonian basins of western Norway-Sedimentary response to tectonism and varying tectonic context, Tectonophysics, 36, 207-224.

Tremblay, L.P., 1982, Geology of the uranium deposits related to the sub-Athabasca unconformity, Saskatchewan, Geol. Surv. Canada, Paper 81-20, 1-55.

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