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Geological environment of the Cigar Lake uranium deposit

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Received June 17, 1992

Revision accepted February 12, 1993

The Cigar Lake uranium deposit occurs within the Athabasca Basin of northern Saskatchewan, Canada. Like other major uranium deposits of the basin, it is located at the unconformity separating Helikian sandstones of the Athabasca Group from Aphebian metasediments and plutonic rocks of the Wollaston Group. The Athabasca Group was deposited in an intra-continental sedimentary basin that was filled by fluvial terrestrial quartz sandstones and conglomerates. The group appears undeformed and its actual maximum thickness is about 1500 m. On the eastern side of the basin, the detrital units correspond to the Manitou Falls Formations where most of the uranium deposits are located. The Lower Pelitic unit of the Wollaston Group, which lies directly on the Archean basement, is considered to be the most favourable horizon for uranium mineralization. During the Hudsonian orogeny (1800–1900 Ma), the group underwent polyphase deformation and upper amphibolite facies metamorphism. The Hudsonian orogeny was followed by a long period of erosion and weathering and the development of a paleoweathering profile.

On the Waterbury Lake property, the Manitou Falls Formation is 250–500 m thick and corresponds to units MFd, MFc, and MFb. The conglomeratic MFb unit hosts the Cigar Lake deposit. However, the basal conglomerate is absent at the deposit, wedging out against an east–west, 20 m high, pre-Athabasca basement ridge, on top of which is located the orebody.

Two major lithostructural domains are present in the metamorphic basement of the property: (1) a southern area composed mainly of pelitic metasediments (Wollaston Domain) and (2) a northern area with large lensoid granitic domes (Mudjatik Domain). The Cigar Lake east–west pelitic basin, which contains the deposit, is located in the transitional zone between the two domains. The metamorphic basement rocks in the basin consist mainly of graphitic metapelitic gneisses and calc-silicate gneisses, which are inferred to be part of the Lower Pelitic unit. Graphite- and pyrite-rich “augen gneisses,” an unusual facies within the graphitic metapelitic gneisses, occur primarily below the Cigar Lake orebody.

The mineralogy and geochemistry of the graphitic metapelitic gneisses suggest that they were originally shales. The abundance of magnesium in the intercalated carbonates layers indicates an evaporitic origin.

The structural framework is dominated by large northeast–southwest lineaments and wide east–west mylonitic corridors. These mylonites, which contain the augen gneisses, are considered to be the most favourable features for the concentration of uranium mineralization.

Despite the presence of the orebody, large areas of the Waterbury Lake property remain totally unexplored and open for new discoveries.

Le gisement d'uranium de Cigar Lake est situé dans le bassin d'Athabasca, au nord de la Saskatchewan, Canada. Il se développe, comme pour la plupart des gisements voisins, au contact entre les grès hélikiens du Groupe d'Athabasca et les métasédiments aphébiens et les roches plutoniques du Groupe de Wollaston. Le Groupe d'Athabasca a été déposé dans un bassin sédimentaire intracontinental qui a été comblé par des grès quartziques et des conglomérats fluviaux terrigènes. Ce groupe n'est pas déformé et son épaisseur maximum actuelle est d'environ 1500 m. Sur le côté oriental du bassin, les unités détritiques correspondent à la Formation de Manitou Falls qui renferme la majorité des gisements d'uranium. L'unité pélitique inférieure du Groupe de Wollaston qui repose directement sur le socle archéen, est considérée comme l'horizon le plus favorable pour la localisation des gisements uranifères. Durant l'orogénèse hudsonienne (1800–1900 Ma), le groupe est affecté par une déformation polyphasée et un métamorphisme régional dans le faciès amphibolite supérieur. L'orogénèse hudsonienne a été suivie d'une longue période d'érosion et d'altération de surface avec le développement d'un régolithe bien préservé.

Sur la propriété de Waterbury Lake, la Formation de Manitou Falls, d'une épaisseur de 250 à 500 m, est représentée par les unités MFd, MFc et MFb. L'unité conglomératique MFb renferme le gisement. Cependant, sous le gisement il y a absence du conglomérat basal. Ce dernier disparaît en coin contre une ride de socle d'âge anté-Athabasca, d'une hauteur de 20 m, et sur laquelle repose le gisement.

Deux importants domaines lithostructuraux sont présents dans le socle métamorphique de la propriété : (1) une région au sud dominée par les métasédiments pélitiques (Domaine de Wollaston) et (2) une région au nord qui inclut de grands dômes granitiques lenticulaires (Domaine de Mudjatik). Le bassin pélitique est–ouest de Cigar Lake, lequel contient le gisement, est localisé dans la zone de transition entre ces deux domaines. Les roches du socle métamorphique dans le bassin sont formées principalement de gneiss métapélitiques graphitiques et de gneiss calcosilicatés, que l'on croit appartenir à l'unité pélitique inférieure. Les « gneiss ocellés » riches en graphite et pyrite, un faciès peu commun dans les gneiss métapélitiques graphitiques, apparaissent le plus fréquemment sous le corps minéralisé de Cigar Lake.

La minéralogie et la géochimie des gneiss métapélitiques graphitiques suggèrent qu'à l'origine ils étaient des shales. L'abondance de magnésium dans les lits de carbonates intercalés, témoigne d'une origine évaporitique.

Le canevas tectonique est dominé par de grands linéaments de direction nord-est – sud-ouest et de larges corridors mylonitiques orientés est–ouest. Ces mylonites qui renferment les gneiss ocellés, sont interprétées comme les zones structurales les plus favorables à la concentration de minéralisations uranifères.

Malgré la présence du gisement, de très larges secteurs de la propriété de Waterbury Lake demeurent totalement inexplorés et ouverts à de nouvelles découvertes.

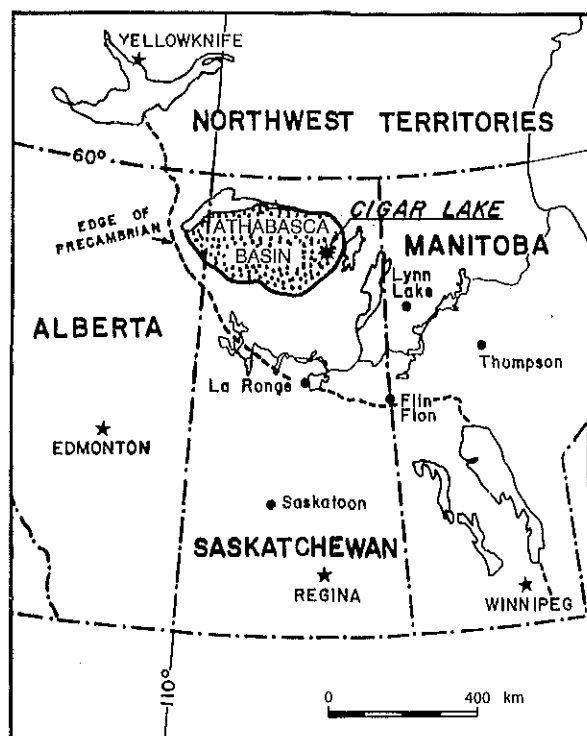


FIG. 1. Location of the Athabasca Basin.

Introduction

The Cigar Lake uranium deposit is located on the Waterbury Lake property near the eastern rim of the Athabasca sedimentary basin, northern Saskatchewan, Canada (Figs. 1–3). The deposit, which is devoid of any direct surface expression, lies at a depth of 410–450 m below surface. It was discovered through drilling of an electromagnetic conductor identified by airborne INPUT (induce pulse transient system) and ground DEEP (an in-house ground electromagnetic system used by the company Crone Geophysics) electromagnetic surveys.

The geological environment of the Cigar Lake deposit is comparable to that of the other major uranium deposits of the basin. It is situated at the unconformity between Archean and Proterozoic metasediments of the Wollaston Group and detrital units of the unmetamorphosed Helikian Athabasca Group. It occurs in the sandstones, immediately above the unconformity, although minor mineralization is present up to 300 m above the unconformity (perched mineralization), and in veins in the underlying basement. On the property, the Athabasca Group (Manitou Falls Formation) is between 250 and 500 m thick and consists of predominant quartz sandstones with conglomerate layers locally developed, particularly at the base of the group. The basement rocks comprise graphitic, biotite–cordierite pelitic gneisses, diopsidic calc-silicate gneisses, and granitoid segregations derived from anatexis of the surrounding rocks. The pelitic gneisses, where they underlie the orebody, are augen textured. The deposit is surrounded by a large hydrothermal alteration zone extending upwards about 400 m into the Athabasca Group sandstones and some 100 m into the basement. In the basement rocks, the alteration zone is superimposed on a preexisting lateritic weathering profile.

Regional geology

Athabasca Group

The Athabasca Basin, which covers approximately 100 000 km², mainly in Saskatchewan (Figs. 1, 4), is filled with red-

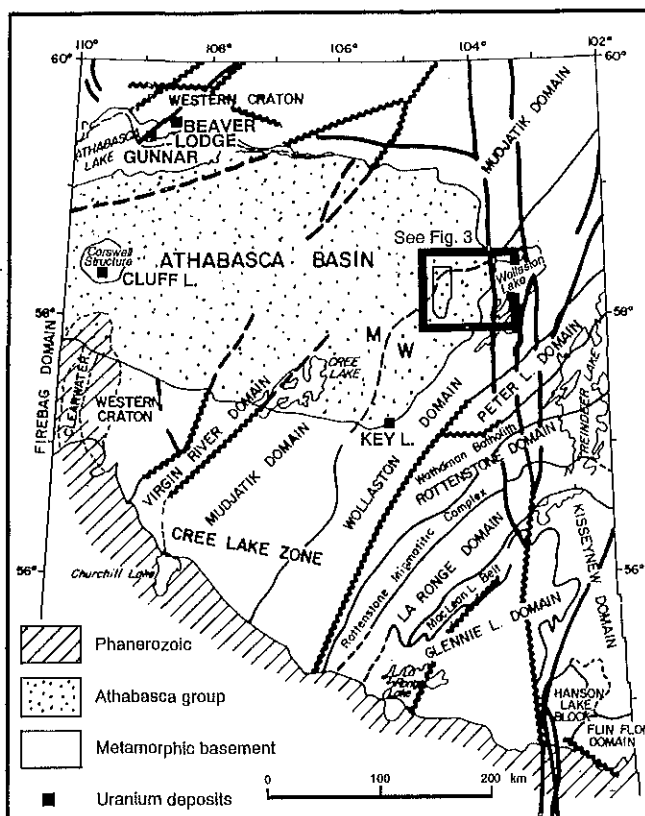


FIG. 2. General geology of northern Saskatchewan.

bed sandstones, conglomerates, minor shales, and dolomites of the Middle Proterozoic Athabasca Group. In the centre of the basin (Rumpel Lake drill hole), the sediments are about 1500 m thick, but the Athabasca Group forms only the lower portion of a deeply buried sedimentary sequence. Its thickness must have certainly been in excess of the actual preserved sections and Pagel (1975a, 1975b), on the basis of fluid inclusion studies, estimated the thickness of the original complete stratigraphic pile to have been 4–5 km. This is in agreement with the results of clay mineral studies indicating deep burial (Hoeve et al. 1981).

Ramaekers (1979a, 1980, 1981) proposed that the Athabasca Group was deposited in a tectonically active sedimentary basin located on a continental margin, the development of which was initiated by the formation of northeast–southwest-trending subbasins controlled by major Hudsonian faults in the metamorphic basement. These subbasins were quickly filled with detrital sediments and subsequently coalesced to form the larger Athabasca Basin. In contrast with this unstable continental margin model proposed by Ramaekers, the depositional environment envisaged by Hoeve and Quirt (1984) is that of an intracontinental basin filled by fluvial terrestrial sandstone and having only intermittent contact with the open sea (Wolverine Point and Tuna Point formations). Basement faults were certainly active during the early stages of sedimentation and in some areas controlled later basin development. But apart from faulting, the Athabasca Group appears undeformed and is largely resting at the initial shallow dips of sedimentation (MacDonald 1987). On the eastern side of the basin, the basal part of the stratigraphic column corresponds to the Manitou Falls Formation, which unconformably overlies a deeply weathered lateritic surface (regolith) developed on Archean and Proterozoic metamorphosed rocks. The Manitou

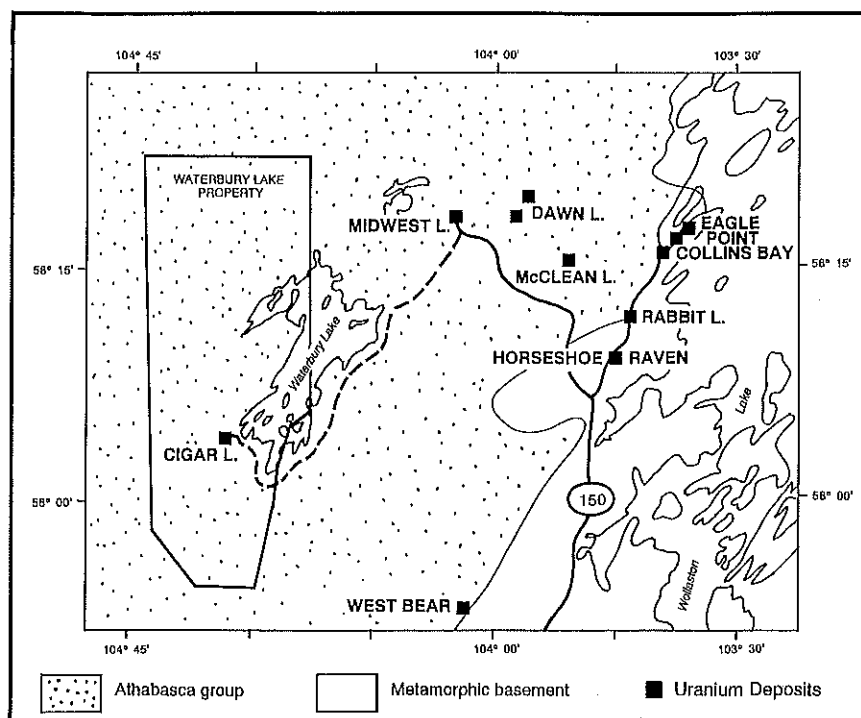


FIG. 3. Location of uranium deposits, eastern rim of the Athabasca Basin.

Falls Formation is the unit in which most of the uranium deposits are located. It is classically subdivided (Ramaekers 1979a) into four members (MFa, MFb, MFc, MFD), comprising coarse fluvial conglomerate and pebbly sandstone (MFa + MFb) overlain by sandy, braided-stream and wadi deposits (MFc + MFD) which were deposited from the east.

The Athabasca sediments have been variably dated at 1484 ± 55 and 1459 ± 4 Ma by the $^{40}\text{Ar}/^{39}\text{Ar}$ method (Bray et al. 1987), and at 1340 ± 50 Ma (Ramaekers and Dunn 1977), 1428 ± 30 Ma (Ramaekers 1979b), 1450 ± 30 Ma (Armstrong and Ramaekers 1985), 1513 ± 24 Ma (Bell 1981), using the Rb–Sr method. Hoeve and Quirt (1984) consider the 1450 Ma age obtained on tuffs of the Wolverine Point Formation to be the best estimate. K–Ar diagenetic ages determined on authigenic illites are much younger, in the range of 1350–1050 Ma (Clauer et al. 1985; Wilson et al. 1987).

However, these ages determined for different parts of the Athabasca Group have to be related to the intense thermal activity associated with the diabase dyke intrusions, which are partially responsible for the uranium mineralization. Armstrong and Ramaekers (1985) report Rb–Sr ages of 1310 ± 70 and 1160 ± 40 Ma for diabase dykes crosscutting Athabasca sediments. On the western side of the basin in Alberta, fluorapatites from the Upper Wolverine Point and Fair Point formations have been analysed for U and Pb. Surprisingly, the data yield old ages in the range of 1650–1700 Ma (Cumming and Kristic 1987). Fluorapatite formation occurred early in the depositional history of these units.

Crystalline basement

The Precambrian shield of northern Saskatchewan is composed of Archean and Lower Proterozoic rocks that have been variably affected by the Hudsonian orogenesis (1800–1850 Ma). Evolution continued through several tectono-metamorphic episodes until the neo-Helikian (1500–1350 Ma), at which

time the postmetamorphic, sedimentary Athabasca Basin was formed.

The pre-Athabasca formations are classically divided into three large lithostructural units (Fig. 2): the Western Craton, the Cree Lake Zone, and the Reindeer Lake Zone (Lewry and Sibbald 1977). The Cree Lake Zone, present in the eastern part of the Athabasca Basin, is interpreted as a region of miogeosynclinal Aphebian sedimentation. It has undergone intense Hudsonian orogenesis marked by high-grade metamorphism and accompanying ductile interaction of the Archean cratonic basement and the Aphebian supracrustal formations (Sibbald 1985). The Cree Lake mobile zone has been itself divided into three domains: Mudjatik Domain, Virgin River Domain, and Wollaston Domain (Lewry and Sibbald 1977).

The Mudjatik Domain consists of felsic granitoid gneisses, which are considered to be Archean, with supracrustal rocks including metapelites, amphibolites, and local iron formations arranged in thin discontinuous arcuate belts. Three major deformation events have been recognized (Lewry and Sibbald 1977), defining regional-scale dome and basin interference patterns. Metamorphic grades are in the amphibolite–granulite facies transition. Retrogressive effects are generally weakly developed (Sibbald 1983).

The Wollaston Domain comprises an Aphebian supracrustal succession, the Wollaston Group (Ray 1977), a sequence that is considered to be 3–4 km thick (Hoeve and Sibbald 1978). So far, four main lithostratigraphic units have been distinguished (Lewry and Sibbald 1980). The coarse clastic basal unit (Quartzite Unit) (Fig. 5) comprises mature quartzitic to arkosic metasediments, basal quartz conglomerate, and semi-pelitic to pelitic muscovite and biotite schists. It is underlain in some places by a sequence of immature meta-arkoses. To the west, it is generally not identified. The second unit is dominantly pelitic and typically graphitic. It contains interlayers of quartzitic psammites, calc-silicates, and locally marbles. The Lower Pelitic unit lies directly on the Archean

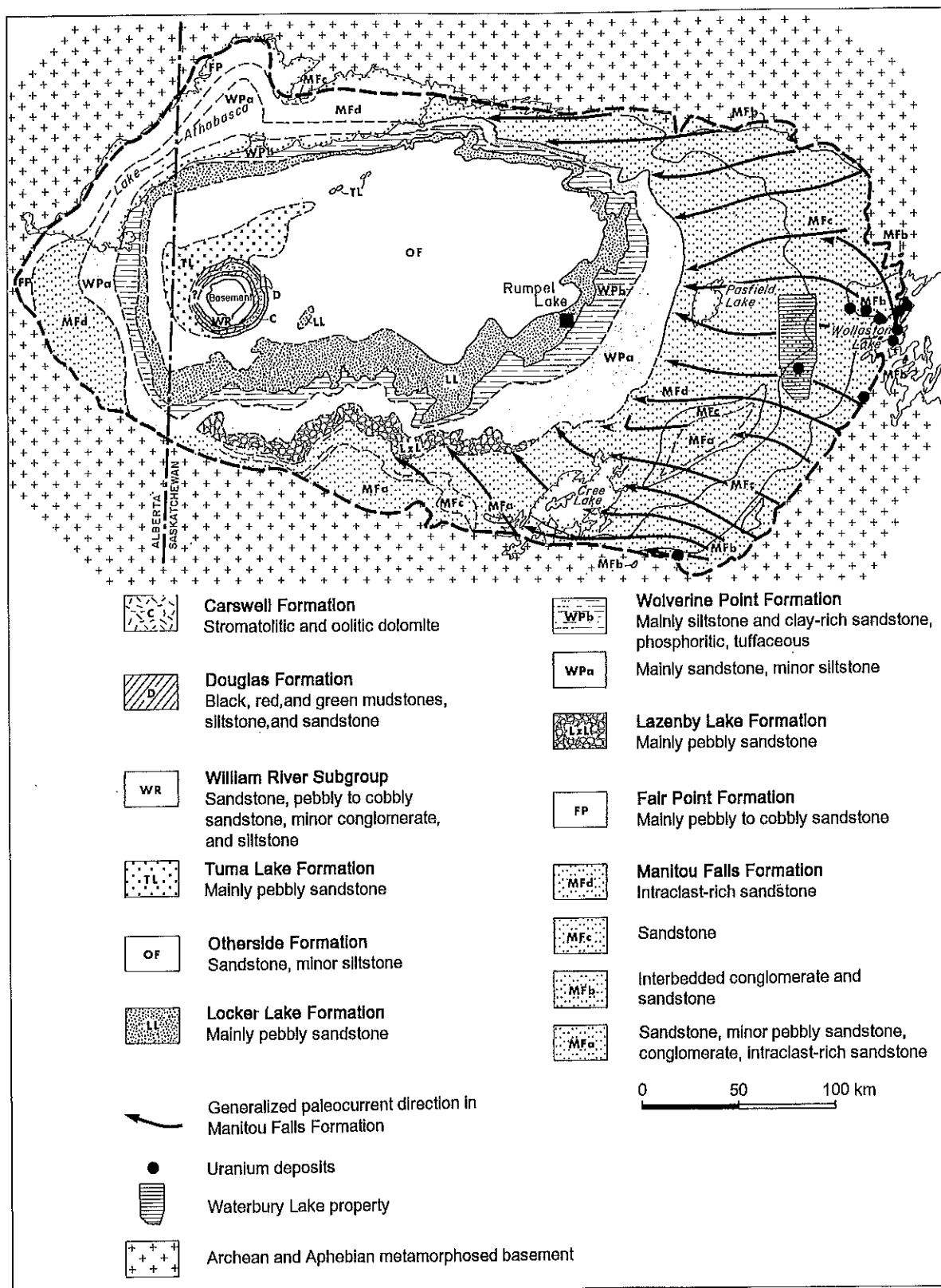


FIG. 4. Geology of the Athabasca Basin (modified from Ramaekers 1980; Wilson 1985).

basement throughout most of the Wollaston and Mudjatik domains. It is considered to be the most favourable horizon for the location of uranium deposits. The pelitic unit is succeeded by a thick and extensive, monotonous sequence of calcareous and noncalcareous meta-arkoses, interlayered with subor-

dinate calc-silicate, carbonate, and pelitic-semipelitic meta-sediments. Finally, the stratigraphic column ends with an upper amphibolite-quartzite unit characterized by these two rock types with interlayered calcareous sediments and graphitic pelites. This unit (Hidden Bay assemblage) is only reported in

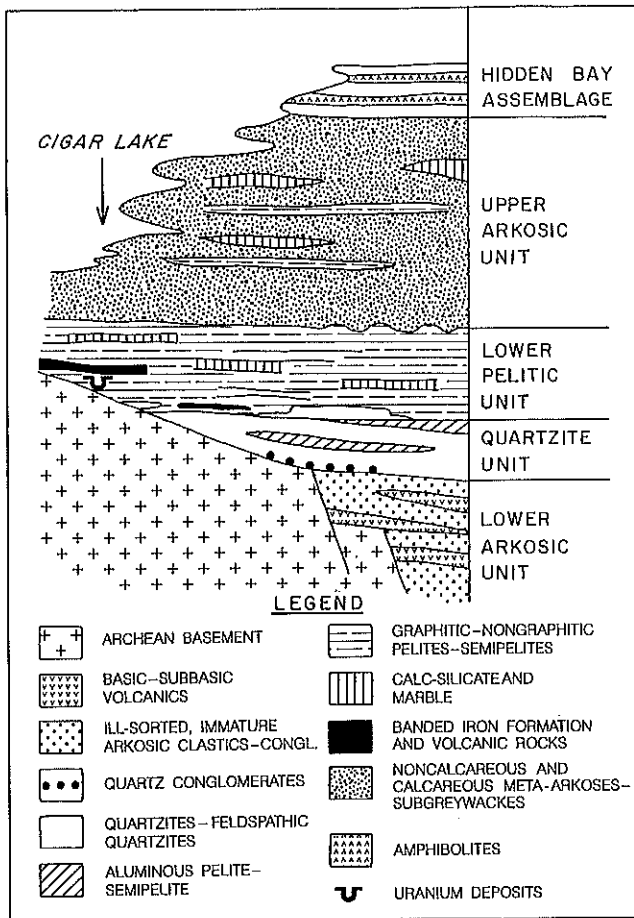


FIG. 5. Generalized stratigraphic relations in the Wollaston Group (modified from Lewry and Sibbald 1980). The right of the column is applicable to the eastern Wollaston Domain, the left to the western Wollaston and Mudjatik domains.

the Wollaston Lake area (Sibbald 1983).

During the Hudsonian orogeny, the Wollaston Group underwent polyphase deformation and low- to intermediate-pressure, upper amphibolite facies metamorphism. Three main deformational events have been recognized (Sibbald 1985). Folding during the second event produced northeast-southeast-elongated domes and basins. Hudsonian magmatic activity is marked by concordant and discordant granitic to pegmatitic lenses, veins, and bodies of quartz-feldspathic composition.

Rb-Sr whole-rock and U-Pb zircon methods give ages of 2636 ± 37 Ma (Worden et al. 1985), 2594 ± 70 Ma (Wanless and Loveridge 1978), and 2494 ± 38 Ma (Ray and Wanless 1980) for rocks from the granitic domes, whereas younger granitic intrusions of the Wollaston Domain yield an Rb-Sr age of 1765 ± 30 Ma (Bell and MacDonald 1982).

The Hudsonian orogeny was followed by a long period of erosion and intense lateritic weathering, as indicated by the presence of a regional altered zone (regolith), which is well preserved everywhere under the Athabasca Group (MacDonald 1980). Development of the regolith was initiated at least 1633 ± 30 Ma ago (Fahrig et al. 1978).

Exploration drilling summary

From 1981 to 1987, 217 holes were drilled on the Waterbury Lake property. They include (Fig. 6) the following:

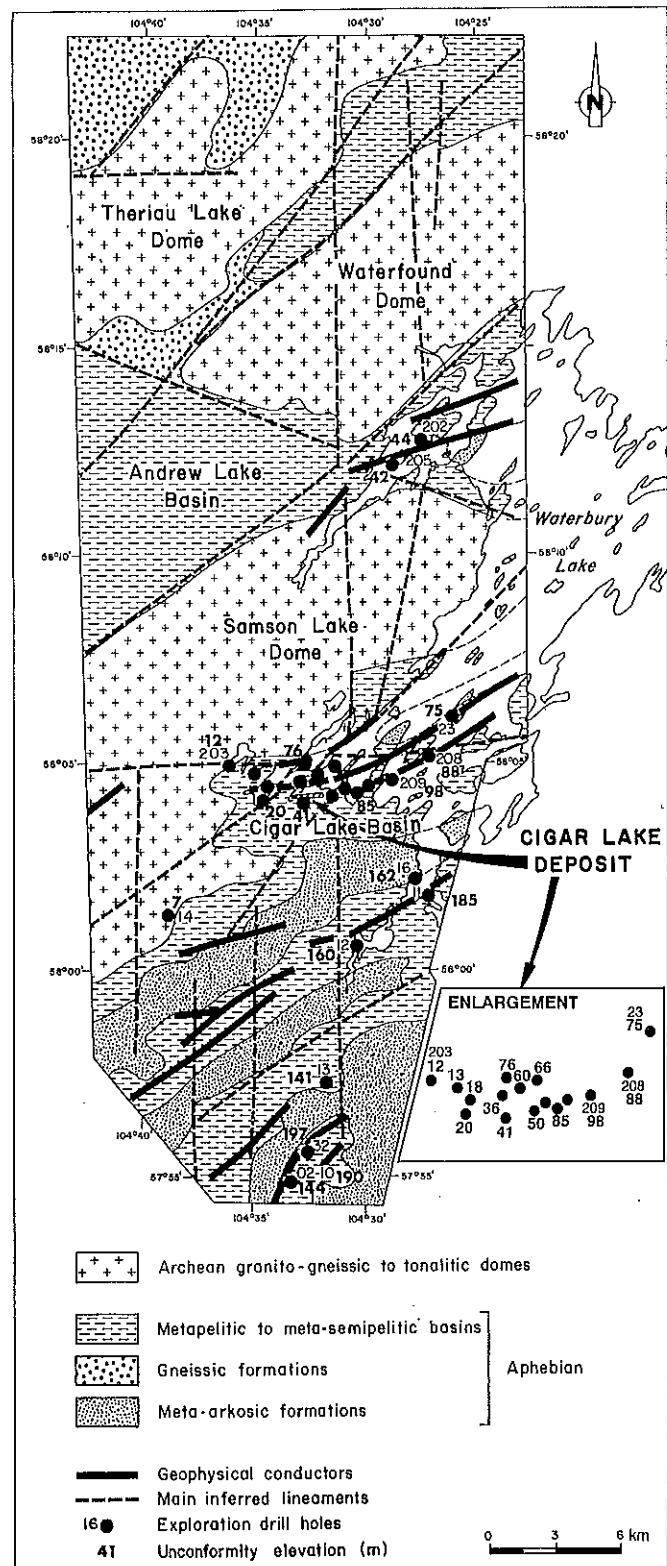


FIG. 6. Generalized geological map of the Waterbury Lake property with location of the drill holes.

(1) Regional exploration drilling (17 drill holes) located south of the property along the Whitford River and north east of Lake Waterbury (Kelly Bay). Weak uranium mineralization was intersected in the basement of one hole in the Whitford River area. (2) Drilling to test geophysical targets around the

Cigar Lake orebody (43 drill holes). This programme established the presence of additional mineralization in a small pod (Tibia Lake pod) containing a few hundred tonnes of low-grade (0.3–0.4 %) uranium mineralization at the unconformity (currently regarded as uneconomical). (3) Drilling strictly related to the Cigar Lake orebody. In all, 177 drill holes have been completed, of which 119 were mineralized.

In 1986, a shallow hole drilling programme (38 holes) was performed along the northeastern extension of the Cigar Lake conductor. The holes were drilled through the overburden to bedrock to sample sandstone for a geochemical study. During the same year, 16 shallow geotechnical holes for an environmental study were also drilled around the Cigar Lake orebody. Thirteen of these intersected the bedrock.

Neutron–neutron and natural gamma logging was completed in each hole, with additional ST 22-2T probing in mineralized holes.

General basement geology of the Waterbury Lake property

The large Waterbury Lake property (3880 km²) is entirely covered with glacial drift and sandstone of the Manitou Falls Formation. Thicknesses of these two formations range from 250 m at the eastern boundary to 500 m at the western boundary. The geological interpretation of the sub-Athabasca basement is therefore essentially based on examination of the geophysical signatures obtained from electromagnetic and magnetic airborne surveys flown over the entire property. Data are confirmed by drill hole information, where available. Most of the drill holes are, however, located above narrow geophysical conductors and thereby provide limited geological information. Large areas of the Waterbury Lake property thus remain totally unexplored.

Lithology

Based on distinctive magnetic–electromagnetic responses, several formations can be distinguished (Fig. 6). Areas of strong magnetic response, lacking conductivity anomalies, correspond to large bodies of interpreted granitic gneisses (Theriau Lake dome, Waterfound dome, Samson Lake dome), interspersed with supracrustal belts with rather uniform, weak magnetic responses and numerous geophysical conductors. Local magnetic highs within the supracrustal belts may represent interlayered magnetite meta-arkoses or Hudsonian anatectic granites. The magnetic anomaly pattern on the property suggests the presence of two major lithostructural domains (Fouques et al. 1986): a southern area with well-defined northeast–southwest linear and magnetic anomalies characteristic of the Wollaston Domain; and a northern area (north of the Cigar Lake orebody comprising curvilinear anomalies indicative of the Mudjatik style of deformation).

The granito-gneissic domes display lensoid shapes that appear to be structurally controlled. Drill hole 14, located on the south margin of the Samson Lake dome (Fig. 6), intersected biotite–amphibole tonalitic gneisses at the bottom of the hole, followed by homogeneous tonalites. These tonalitic rocks are considered to be Archean in age due to their resemblance to similar facies found in surrounding properties. A Rb–Sr isochron of 2613 ± 93 Ma has been obtained from granitoid gneisses flanking the Midwest Lake deposit to the west (Worden et al. 1985). In the case of drill hole 14, the contact of the tonalitic facies with the overlying fine-grained metapelitic sequence appears transitional without major shearing. The tonalites are light-grey, medium-grained, equigranu-

lar to weakly foliated rocks. Plagioclase (70%) is the major component; quartz (15–20%), biotite (5–10%), amphibole (1–5%) and rare pyroxene are also present.

The 14 exploration drill holes (02–13, 16, and 32) completed south of the permit (Fig. 6) intersected psammopelitic and psammitic gneisses and pelitic gneisses interlayered with medium-grained meta-arkoses and calc-silicates. Metaquartzites have not been observed in the succession. Pelitic to semi-pelitic metasediments, probably corresponding to the lower pelitic unit of the Aphebian Wollaston Group succession, are well represented. The pelitic gneisses are usually dark grey to dark green in colour and range from fine to medium grained. Gneissic layering is poorly to well defined. The gneisses are composed of quartz, plagioclase, K-feldspar, biotite, and cordierite, locally with garnet, sillimanite, graphite, and pyrite. The psammopelitic gneisses correspond to homogeneous or heterogeneous, fine- to medium-grained varieties, with colours ranging from grey to pinkish grey. Lit-par-lit leucocratic layers are locally well developed. Gradational contacts with other lithofacies, such as pelitic gneisses, meta-arkoses, and calc-silicates, have been observed. The psammopelitic gneisses are essentially quartzo-feldspathic rocks with biotite (5–20%) and locally some amphibole, garnet, and magnetite. More siliceous coarser grained facies with lighter colours are called psammitic gneisses. Calc-silicate rocks make up only a small part of the regional stratigraphic succession. However, they are well represented in some drill holes (9–12). They are highly variable in texture and composition. In drill hole 11, dark-green, massive calc-silicate facies with peculiar textures have been interpreted by local geologists as possible stromatolitic formations. They consist of variable amounts of plagioclase, diopside, amphibole, biotite, K-feldspar, quartz, calcite, sphene, and graphite.

Interpretation of aeromagnetic surveys farther north places the Cigar Lake deposit in an east–west pelitic basin (Fig. 6). This basin includes primarily graphitic pelitic gneisses with calc-silicate intercalations, which are presumed to be part of the Lower Pelitic unit of the Wollaston Group. On a larger scale, the area is located in the transitional zone between the Wollaston Domain and the Mudjatik Domain (Fouques et al. 1986), represented to the northwest by the Samson Lake granite dome.

Finally, two holes (202 and 205) were drilled on the north side of the Samson Lake dome. They intersected quartzo-feldspathic, medium-grained gneisses with garnet (5–10%) and sillimanite (up to 10%), and fine-grained plagioclasic pelitic gneisses with abundant garnet (10–25%). These facies, which contain very little graphite, are quite different from those observed in the Cigar Lake basin. The presence of high-grade metamorphic minerals is more typical of the Mudjatik Domain.

Structure

Three main generations of structural lineaments have been recognized on the Waterbury Lake property. East–west and northeast–southwest directions are the most obvious (Fig. 6). They seem to correspond to structures of Archean age, which control the Archean domes and give them their lensoid shapes. They have been reactivated during the Hudsonian orogeny and exhibit ductile deformational features (mylonitization and blastomylonitization). The Cigar Lake deposit is located within one of these east–west-trending structural corridors. The north–south lineaments observed on magnetic maps and

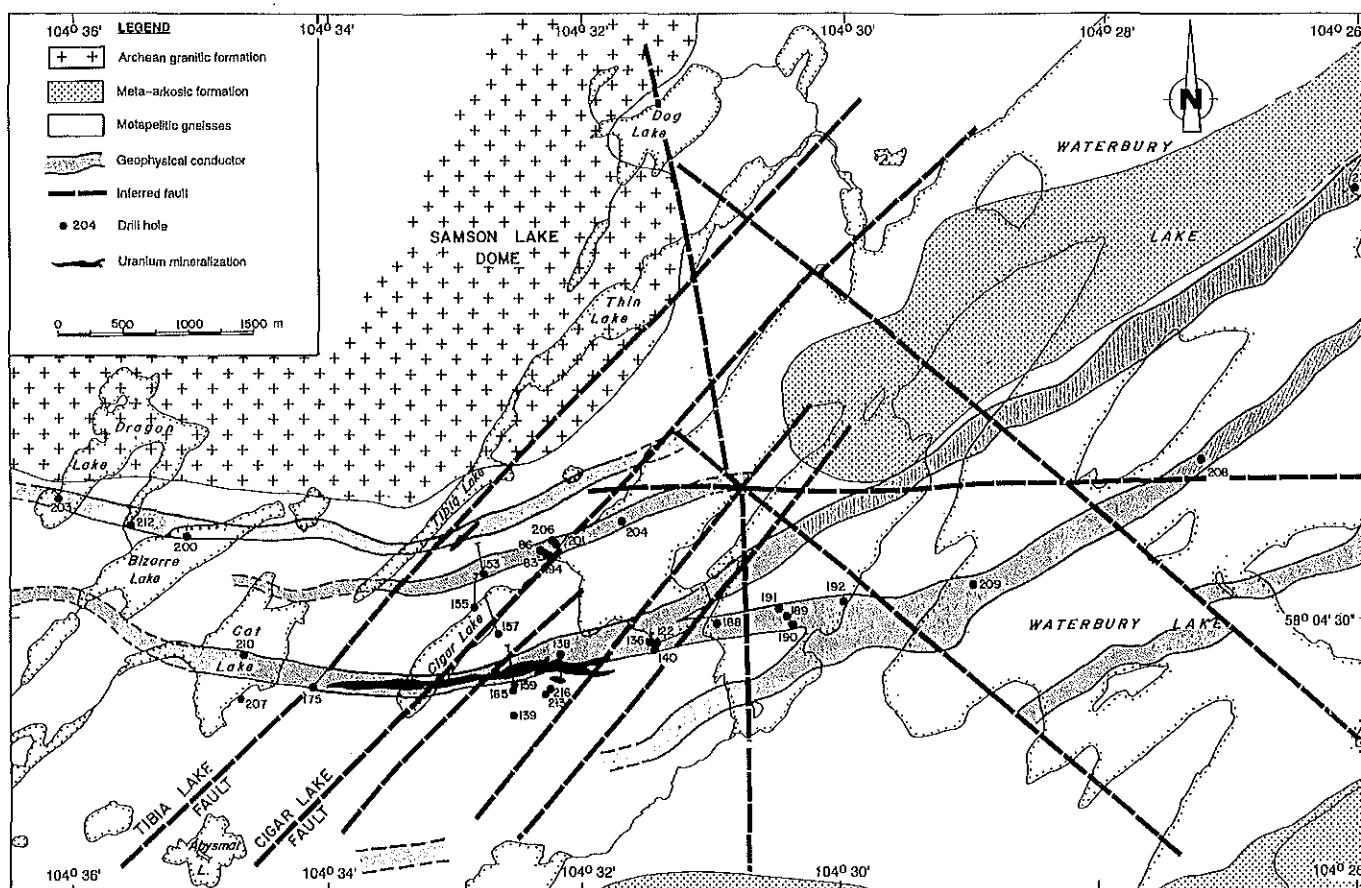


FIG. 7. Geophysical interpretation of the basement formations in the Cigar Lake basin (modified from Fouques et al. 1986).

Landsat images are well represented, especially in the southern part of the property. They probably correspond to late faulting, which may be responsible for the differences observed in the elevation of the unconformity between the southeast part of the permit (140–197 m asl) and the Cigar lake basin (20–98 m asl).

Geology of the Cigar Lake basin

The Cigar Lake basin is an east–west elongated structure that is bordered to the north by the Samson Lake granitic dome (Fig. 7). It opens towards the east and the northwest, where magnetic observations suggest the presence of arkosic meta-sedimentary belts. Similar units occur along the southern border of the basin. Towards the west, the basin appears to terminate in a complicated area, which may correspond to a large east–west mylonitic zone crosscutting the Samson Lake dome and containing pelitic remnants. Around the Cigar Lake orebody, exploration drilling within an area of roughly 10×2 km was carried out to investigate the main Cigar Lake conductor, four other parallel geophysical conductors, and the weakly mineralized Tibia Lake pod (Fig. 7). Large areas of the basin are unexplored.

Surficial sediments

In the Cigar Lake basin, elevations range from 454 m (Waterbury Lake surface) to 529 m, the highest point in the Tibia Lake area, providing locally steep relief. Ground moraine up to 55 m thick is the dominant surficial deposit. Typically it consists of poorly sorted sand and gravel with abundant

boulders of various sizes. Sandstone boulders from the Manitou Falls Formation are ubiquitous and basement boulders are common. The till is covered in parts of the area by eskers, kame, and outwash deposits, which in turn are locally covered by lacustrine sand, clay, lakes, and muskegs. Regionally, the last major ice movement was from the northeast. This is illustrated in the bedrock elevation map above the Cigar Lake basin (Fig. 8). However, the glacial surface is variable, with a general increase of the elevation from the east (400–410 m asl) to the west (480–490 m asl). A wide east–west paleo-channel is present north of the surface projection of the orebody.

Athabasca Group

Stratigraphic units

The thickness of the Manitou Falls Formation of the Athabasca Group ranges from 260 m south and east of the Cigar Lake orebody to a maximum of 498 m in drill hole 14 on the west border.

Detailed core logging has been carried out by Ramaekers (1986) in a few regional drill holes and in drill holes located around the deposit where the Athabasca Group sandstone is approximately 400 m thick. Using maximum grain size and pebble content, Ramaekers was able to separate three main stratigraphic units, which correspond to units MFd, MFc, MFb of the Manitou Falls Formation, and to define four marker beds (M1, M2, M3, M4) recognizable through the whole study area.

Unit MFd, at the top of the sandstone sequence (Fig. 9), is

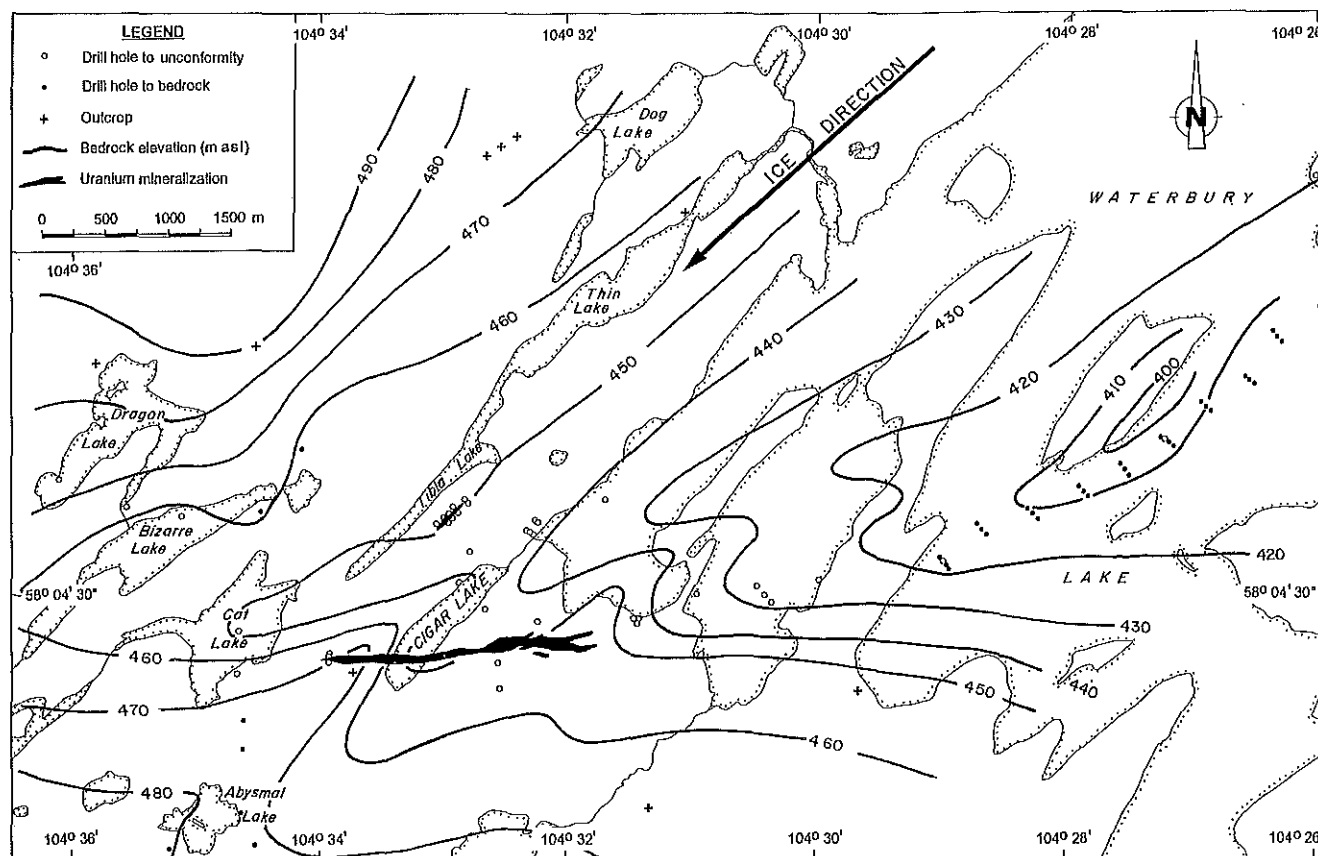


FIG. 8. Elevation of bedrock surface, Cigar Lake basin.

present in all holes except those in the eastern half of the Waterbury Lake property, where it has been removed by erosion. It is represented by an homogeneous fine- to medium-grained sandstone with uncommon coarser laminations and silty horizons. It is characterized by the occurrence of white to light-yellow, centimetre-size clay chips. The marker M1 corresponds to the base of unit MFd and is marked by the disappearance of the clay intraclast-rich beds. Its recognition is difficult due to the fine-grained texture of the formation. This unit is everywhere affected by a strong surficial bleaching and limonitization, resulting in typical white to yellow colours.

The MFc unit is generally represented by medium- to coarse-grained sandstone with microconglomeratic layers, containing rounded quartz pebbles in the 2–6 mm range. The silty horizons are more frequent than in the MFd unit, and the matrix is generally slightly richer in clay. Cross-bedding and slump structures are common. Unit MFc can be distinguished from overlying unit MFd by the appearance of the first microconglomeratic layer as well as by the disappearance of clay chips.

Unit MFb is the coarsest member of the Manitou Falls Formation. It is represented by medium- to coarse-grained sandstone with gritty and locally conglomeratic layers, passing into a succession of grit and conglomerate. The top of unit MFb is marked by a prominent increase in the pebble content and by the first appearance of bedded conglomerate thicker than 2 cm. This is a reliable marker (M2) present in every drill hole. Marker M3 corresponds to the top of a conglomerate subunit 40–50 m above the unconformity; it is characterized by an increase in the maximum pebble size to the 16–32 mm

range. To date, it has proved to be the most useful marker bed in the Manitou Falls Formation because it is expressed by both a change in grain size and pebble content. Finally, M4 corresponds to the top of a basal conglomeratic subunit, often very coarse (pebbles up to 64 mm and over), with a marked increase in pebble content to 50% or even more. It is generally 5–15 m thick. Hematite is ubiquitous throughout units MFc and MFb, imparting purple, red, and pink colours to the rocks. Liesegang rings are frequent.

On drill core, the boundaries between the units are commonly gradational, reflecting the extreme variability in lithology of fluvial sandstone. Hence limits are somewhat arbitrary on geological logs, with a 5–50 m wide zone of uncertainty. To help in the definition of more precise limits, natural gamma and neutron–neutron probes were systematically run in the drill holes. In the quartzitic sandstone of the Manitou Falls Formation, radioactivity is related mainly to the presence of heavy minerals such as zircon and monazite. These minerals are well represented in the basal MFb unit, where they are concentrated as millimetre-scale seams in the conglomeratic layers. The neutron response depends mainly on the porosity and clay content of rocks. It is affected by tectonism and alteration.

Typical natural gamma and neutron–neutron profiles from drill hole 139 are presented in Fig. 9. This hole is located 400 m south of the orebody (Fig. 7), far enough away not to be affected by hydrothermal alteration or faulting related to the deposit. Unit MFd is characterized by a low radioactivity background and a neutron response decreasing downward. The boundary between units MFd and MFc is well marked as

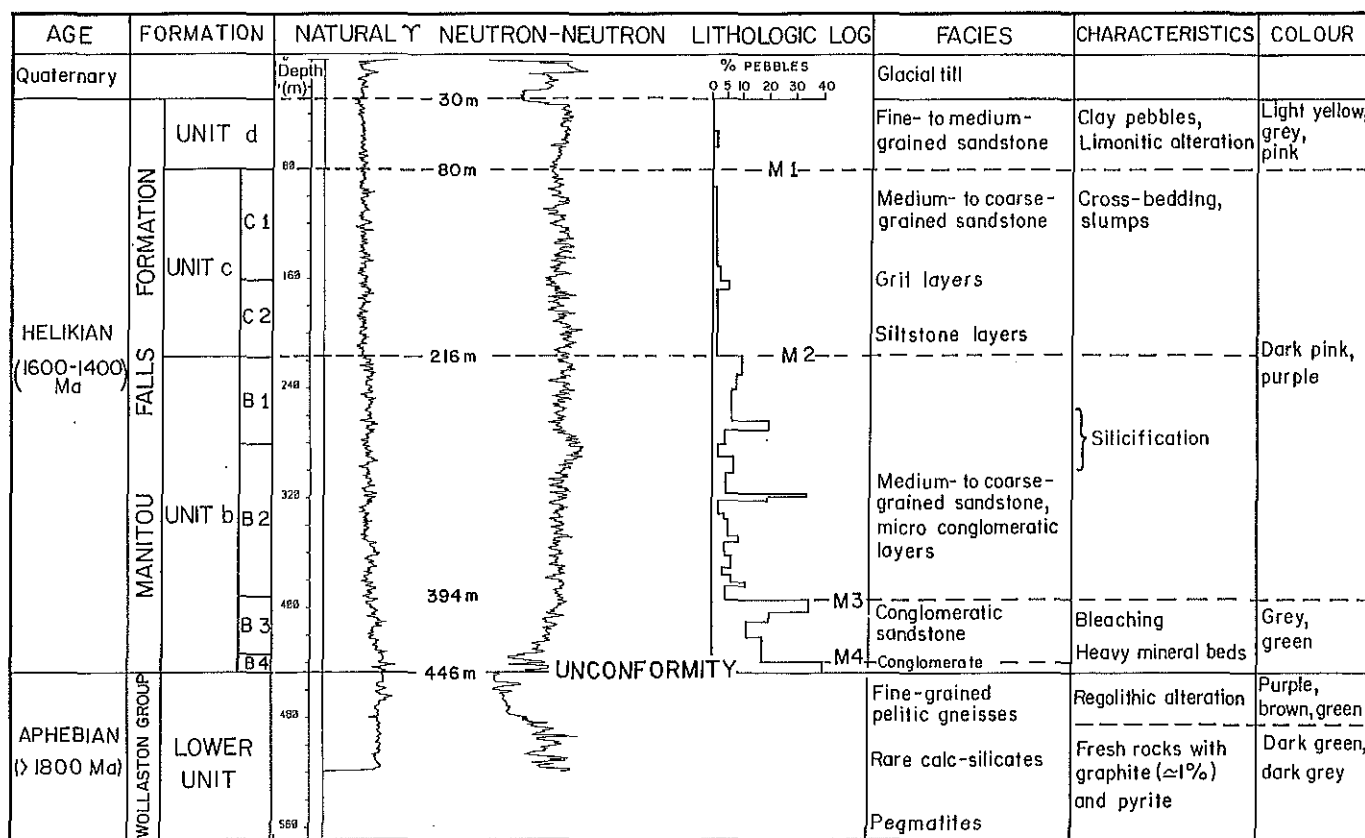


FIG. 9. Lithostratigraphy in the Cigar Lake area from drill hole 139.

an inflection point on the neutron profile. Unit MFc exhibits a higher radioactivity, which is related to the greater number of microconglomeratic layers. On the neutron log, at least two subunits (MFc1 and MFc2), corresponding to large sedimentary cycles, may be distinguished. The boundary between units MFc and MFb is recognizable by the sharp increase in the radioactive background, corresponding to the appearance of conglomeratic layers. Based on neutron observations, four distinct units (MFb1, MFb2, MFb3, MFb4) have been recognized in MFb, their limits being defined by neutron lows. MFb3 and MFb4 are particularly well delineated and correspond to marker beds M3 and M4. MFb3 is a negative sequence above the MFb4 positive sequence. These units above are in accordance with Ramaekers' lithologic units.

Tectono-stratigraphic analysis of the Cigar Lake basin

Natural gamma logs and neutron-neutron logs display the same patterns in every drill hole on the Waterbury Lake property, allowing stratigraphic units and marker horizons to be mapped on a regional scale. Major faults can also be located between widely spaced drill holes, and changes in depth-to-basement due to faulting, presandstone topographic highs, and paleoslopes can be determined.

To illustrate these observations, an east-west longitudinal stratigraphic cross section along the Cigar Lake basin is presented in Fig. 10. This 11 km long section is subparallel to the regional paleocurrent direction. Paleocurrent measurements in near-surface core (unit MFd) show the same southwesterly pattern ($260-265^\circ$) that is evident in the rare outcrops near Cigar Lake (Ramaekers 1986) and is compatible with the regional pattern (Fig. 4). Also, on the east side of the Atha-

basca Basin, the regional gradient at the unconformity is estimated to be about 9 m/km towards the west. Thicknesses of stratigraphic units are shown in Fig. 10. Unit MFd and part of subunit MFc1 have been removed by erosion on the east between holes 188 and 23. The thinnest sequence above basement in the Cigar Lake area is 318 m in hole 209; in contrast, 461 m of sediments is present in drill hole 203. MFc2, which is the first complete subunit in every drill hole, and MFb1 and MFb2 show almost no variation in thickness over the basin. MFb3 and MFb4, the basal conglomeratic subunits, are of consistent thickness in the east, but thicken in the two most western drill holes (210 and 203). This is apparently the only significant variation in these subunits over the Cigar Lake basin. The progressive increase in thickness of the conglomeratic subunits towards the centre of the basin is possible only if some subsidence occurred during sedimentation. The syn-sedimentary structures that rejuvenated the source areas appear to be located proximal to paleodepressions where there is a rapid and significant increase in the thickness of the MFb3-MFb4 subunits.

The topography of the sub-Athabasca unconformity indicates a relatively flat surface with minor relief. Along the Cigar Lake basin, however, significant displacements of the unconformity surface have taken place (Fig. 10). The main tectonic feature suggested from the stratigraphic data is the 36 m step between holes 188 and 140. In this case, the whole stratigraphic column has been displaced, and this is considered to be due to postdepositional sandstone faulting. Another offset of the unconformity (16 m) occurs between holes 192 and 209, affecting only the MFb3 and MFb4 members. It does not affect the MFc-MFb contact and appears to be related to

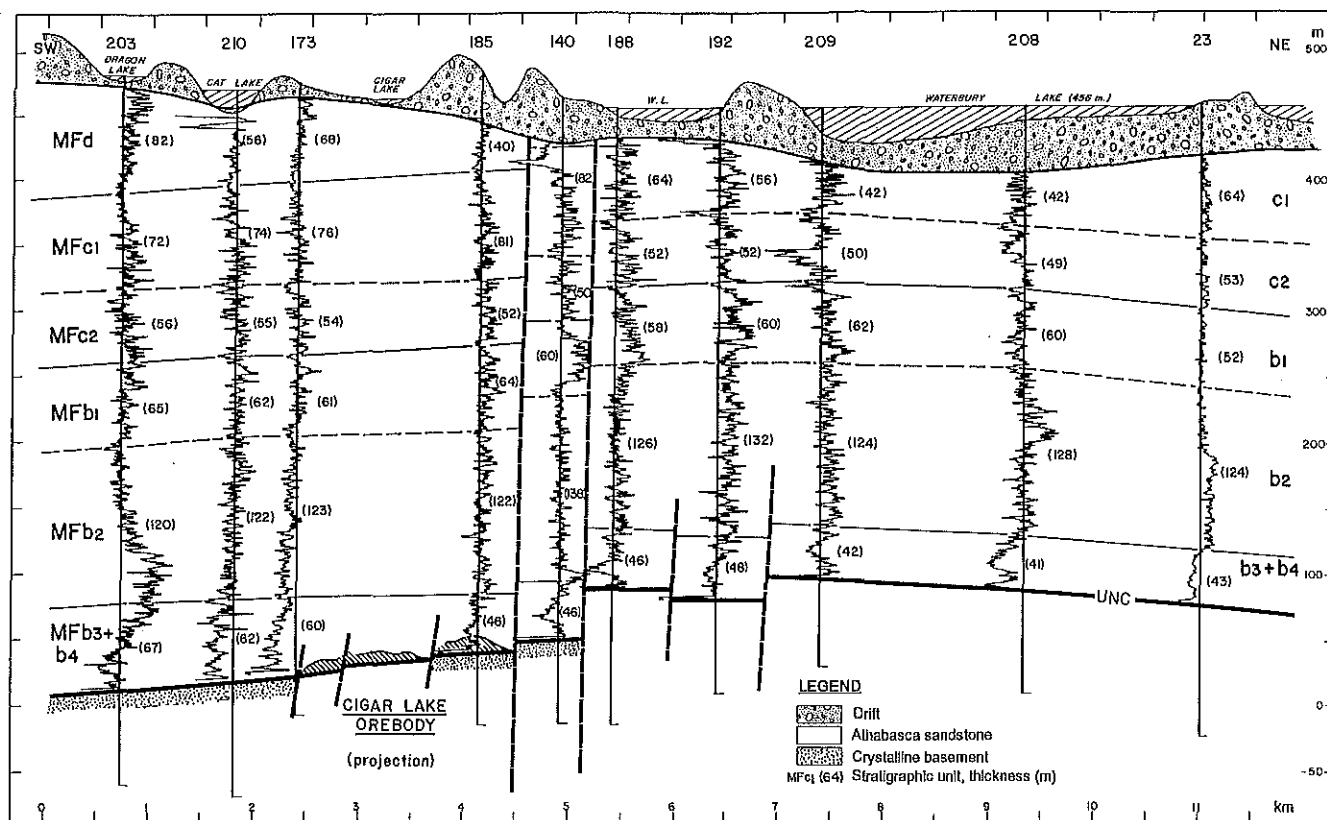


FIG. 10. Regional east-west cross section through the Cigar Lake basin.

faulting during deposition of the basal conglomeratic units. Finally, local faulting is inferred between drill holes 173 and 140, in relation to the emplacement of the orebody, but this does not affect the MFb-MFc contact. The basement unconformity between holes 188 and 23, dips towards the east, which may be explained by regional block tilting.

Petrography of the Athabasca sandstones

The Athabasca Group sandstones are classified as quartz arenites (Ramaekers 1983). They are composed mainly of poorly sorted quartz grains within a clay matrix. Relict grains of altered biotite, feldspar, and lithic fragments are rare. The main component is detrital quartz, which occurs as sub-rounded to well-rounded monocrystalline grains of a range of sizes. Quartz overgrowths are common, especially in silicified areas, where it may represent the only cement. Hematitic rims are frequently observed between the quartz grains and the secondary overgrowths. Biotite flakes are strongly distorted by compaction and are replaced by clay.

The interstitial clay content of the sandstones and conglomerates ranges from 2 to 20%. Clay occurs as a fine-grained, recrystallized, interstitial matrix associated with hematite and consists of kaolinite and minor illite. Illite is primarily present as fine-grained replacements of kaolinite (Hoeve and Quirt 1984).

Heavy minerals are widespread in the sandstone, and are particularly common in the MFb conglomeratic unit, where they occur as detrital, millimetre-thick black seams. In some drill holes, black heavy mineral layers may be up to 10 cm thick in the basal conglomerates. They consist of Fe-Ti oxides, rutile, zircon, monazite, tourmaline, and phosphates. The principal opaque mineral is hematite, formed by the oxi-

dation of ilmenite, rutile, and magnetite. Zircons and rare monazite grains are rounded and brown in colour. Tourmaline occurs as detrital fragments of a range of colours. Colourless overgrowths of dravite are optically identical to the hydrothermal dravite described in alteration haloes around other uranium deposits of the Athabasca Basin. Very small, light-green to light-brown, subeuhedral phosphatic grains are locally present in trace quantities.

The crystalline basement

Most geological data on the basement of the Cigar Lake basin has come from the drilling of geophysical conductors. These are associated with a particular type of lithology, since conductors generally indicate the presence of graphitic formations. Geological information elsewhere in the basin is therefore limited.

Lithology and petrography

Metamorphic basement rocks in the Cigar Lake basin consist essentially of graphitic metapelitic gneisses with intercalations of calc-silicate gneisses and rare meta-arkoses. These rocks are locally crosscut or invaded by leucocratic veins and lenses of pegmatite and quartzo-feldspathic anatectic rocks.

On the basis of their grain size and textures, the graphitic gneisses have been subdivided into three units of unequal abundance: (1) fine-grained metapelitic gneisses; (2) medium- to coarse-grained metapelitic gneisses; and (3) augen-textured metapelitic gneisses (referred to as "augen gneisses" in the Waterbury Lake project).

Fine-grained metapelitic gneisses are the main basement rock in the study area. They are homogeneous, massive, dark-grey to dark-green, fine-grained (0.2–1 mm) rocks, with

poorly defined to well-defined layering. Migmatization commonly occurs as lit-par-lit veinlets parallel to the early fabric of the rocks, or as a diffuse, more leucocratic and coarser grained component. Graphite and pyrite are generally present.

The fine-grained metapelitic gneisses are often fresh outside mineralized zones and below the regolith. They display a typical granolepidoblastic texture, with biotite and graphite oriented along the metamorphic foliation. Their mineralogical composition is simple and uniform, comprising quartz (15–25%), K-feldspar and plagioclase (40–70%), biotite (10–20%), cordierite (5–15%), graphite (up to 3%), and sulphides (up to 2%). Plagioclase may be the only feldspar. Garnet and sillimanite are present locally. Accessory minerals include apatite, monazite, zircon, ilmenite, rutile, and tourmaline. Petrographically, these rocks are biotite–cordierite, quartzofeldspathic gneisses.

Medium- and coarse-grained metapelitic gneisses are a transitional facies between the fine-grained gneisses and “augen gneisses” in the Cigar Lake conductor. They are also well represented in the other geophysical conductors of the basin. In several cases, they appear to be remobilized finer grained facies with local augen textures. Graphite and pyrite are always present in these rocks.

The augen gneisses are the most peculiar basement facies in the Cigar Lake area. The term “augen gneiss” reflects the presence of K-feldspar and cordierite porphyroblasts (3–20 mm) elongated along the metamorphic foliation. The foliation is defined by graphitic–biotitic layers. Graphite and pyrite are consistently present. These rocks have a restricted distribution; they occur as a 50–100 m wide horizon at least 2 km long, located primarily below the Cigar Lake orebody (Fig. 10). A few thin horizons have also been observed along the Cigar Lake conductor towards the east, and to the north along the Tibia Lake and Long Year bay conductors. Augen gneisses below the orebody are always strongly altered, even up to 100 m away from the unconformity, and display a typical green colouration. They are also altered everywhere else they have been found in the Cigar Lake basin.

The primary mineralogical composition of the augen gneisses is similar to that of the fine-grained metapelitic gneisses, although the relative abundance of the constituent minerals may differ. For instance, in the augen gneisses, cordierite (15–30%) and graphite (2–10%) are more abundant and feldspars (20–40%) and biotite (5–10%) less abundant than in the metapelitic gneisses. Porphyroblasts of cordierite and K-feldspar, ranging from 3 to 20 mm in size, occur in approximately equal proportions and constitute up to 20% of the rock. They form dark green nodules with polygonal to fusiform shapes, which contrast sharply with the fine- to medium-grained, light-green matrix. In thin sections the texture is porphyroblastic granolepidoblastic: discontinuous layers of graphite and biotite mould around the porphyroblasts. In general, the porphyroblasts are elongated within the foliation. In some cases, inclusions in the porphyroblasts are aligned at 10–30° to the foliation, indicating that the porphyroblasts formed early and were rotated and elongated during the development of the regional foliation. The augen gneisses can be classified as biotite–cordierite quartzofeldspathic gneisses with abundant graphite and pyrite.

Calc-silicate gneisses make up only a small part of the stratigraphic succession. They occur as thin (0.1–1 m) layers and larger lenses or massive units (5–25 m) intercalated with the fine-grained metapelitic gneisses. They are common south and

west of the Cigar Lake orebody and in the Dragon Lake – Bizarre Lake conductors (Fig. 7). Facies transitional between calc-silicate gneisses and fine-grained gneisses are common and generally have gradational contacts. In these rocks, dark tourmaline is abundant and garnet common. Calc-silicate gneisses have a wide range of colours, textures, and grain size.

Macroscopically, four main groups have been distinguished: (1) banded calc-silicates; (2) massive calc-silicates; (3) “satiny” calc-silicates; and (4) granoblastic calc-silicates. Banded calc-silicates are characterized by thin irregular layers of variable colour and grain size. Fine-grained dark layers contain plagioclase and (or) microcline, quartz and pyroxene. Pink to red layers tend to be coarser-grained and microcline rich. The white layers are rich in dolomite. Accessory minerals include zircon, monazite, apatite, anatase, graphite, and rare sulphide. Massive calc-silicates have a dark-green colouration and contain only pyroxene. “Satiny” calc-silicates are green coloured and have a granolepidoblastic texture. The major constituent is plagioclase (albite–oligoclase) with a typical polygonal texture. Anthophyllite, tremolite, diopside, and phlogopite constitute 15–30% of the mineral assemblage. Accessory minerals are also abundant and include sphene, apatite, zircon, monazite, tourmaline, anatase, and opaque minerals. Granoblastic calc-silicates differ from the preceding types by their light colour, lack of foliation, and their homogeneous grain size. Plagioclase is the main constituent and it is associated with diopside. Sphene and tourmaline are particularly abundant, apatite appears as large xenomorphic crystals, and allanite may be present. In contrast, amphiboles and micas are generally absent.

Mobilizates and pegmatites are widespread and have great morphologic and granulometric diversity. They occur in the form of leucocratic and quartzofeldspathic veinlets, vein lenses, or irregular bodies, which are concordant or discordant with the foliation. In fact, metapelitic rocks showing no remobilization are uncommon. The term mobilizate is used to describe facies that are obviously the result of anatexis of the enclosing metapelitic rock units. Two generations are recognized. The early generation occurs as diffuse or lit-par-lit veinlets parallel to the early fabric of the rocks, and the younger generation as coarser grained heterogranular facies locally crosscutting the early segregations. The term pegmatite is used when the degree of mobilization is sufficient to produce well-developed, uniform, coarse-grained facies that crosscut the surrounding rocks. Mobilizates are extremely heterogeneous in grain size and mineralogy, depending on the degree of remobilization. They are quartzofeldspathic rocks, consisting of 70–100% quartz, plagioclase, and K-feldspar. They also contain cordierite, sillimanite, garnet, biotite, graphite, and sulphides. Tourmaline is generally present as brown automorphic crystals. Pegmatites have a simpler and more uniform mineralogy dominated by quartz, K-feldspar, and plagioclase with small amounts (1–5%) of biotite and tourmaline.

Metamorphic conditions in the Cigar Lake basin can be estimated using the mineralogical assemblages. The metapelitic gneisses are characterized by (1) the absence of primary muscovite; (2) the presence of sillimanite and cordierite (and locally garnet in calc-silicate metapelitic gneisses); prismatic sillimanite, which is usually characteristic of the katazone, has been observed only in drill holes at Tibia Lake; (3) an abundance of potassium feldspar; and (4) the presence of biotite, graphite, and pyrite. In addition, anatectic quartzofeldspathic mobilizates, pegmatites, and migmatitic structures are wide-

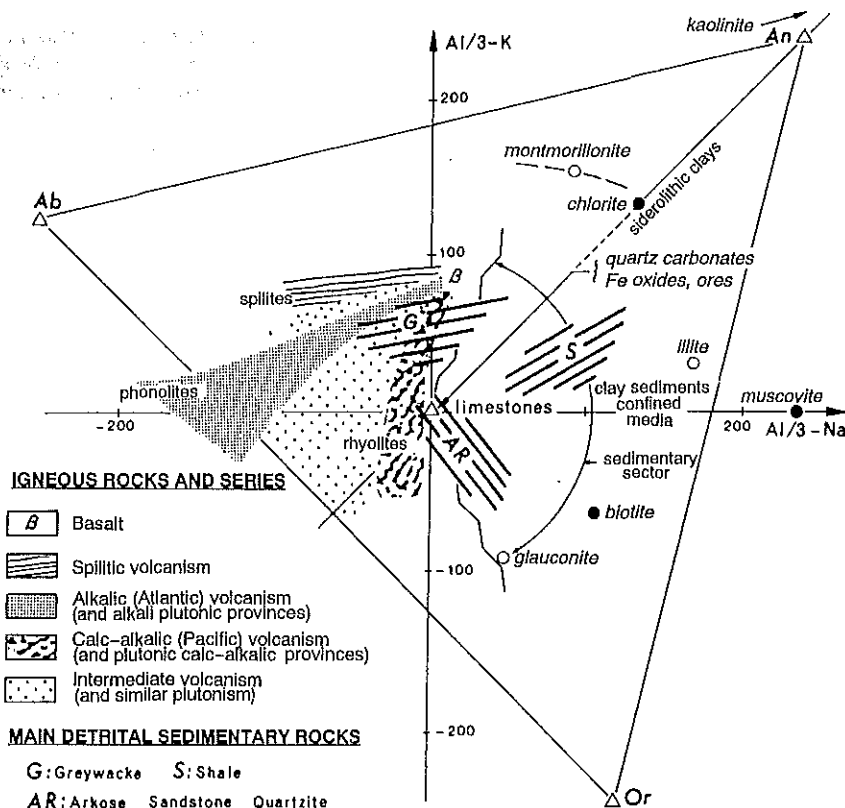


FIG. 11. General distribution of metasedimentary rocks and minerals in an $Al/3 - Na$ versus $Al/3 - K$ diagram (de La Roche 1965).

spread. These observations suggest that the metapelitic rocks reached the upper amphibolite grade during Hudsonian regional metamorphism. The metamorphic conditions are estimated to be $T = 700-750^{\circ}\text{C}$ and $P = 3-5$ kbar (1 kbar = 100 MPa).

Alteration

Alteration of the crystalline basement rocks is of three distinct types: retrograde alteration, which is associated with the late stages of the Hudsonian orogeny; alteration associated with the development of a pre-Athabasca paleoweathering profile; and hydrothermal alteration, which is restricted to the uranium mineralization and extends up into the Athabasca sandstone, above the deposit.

Retrograde metamorphic alteration, which is of limited occurrence, is characterized by sericitization and chloritization of cordierite, sillimanite, biotite, pyroxene, amphibole, and feldspars (Bruneton 1987; Halter 1988), giving a homogeneous green colour to most of the rocks. Conditions of crystallization of muscovite correspond to the greenschist facies (Halter 1988).

A characteristic paleoweathering profile, called the regolith, is developed in the uppermost basement rocks. The regolith in the Cigar Lake basin and throughout the Waterbury Lake property is similar to that described elsewhere in the Athabasca Basin (Hoeve and Sibbald 1978; MacDonald 1980, 1985). It ranges up to 40–50 m in thickness and comprises four characteristic zones: (1) a light-yellow, thin (0.1–1 m) "bleached zone," which is present only in a few drill holes; (2) a distinctive hematitic "red zone"; (3) a "red-green transitional zone"; and (4) a "green zone" grading downwards into fresh rocks.

The transition between the red zone and the green zone is

a basin-wide redox boundary separating oxidized Athabasca red-bed sandstones above the unconformity from reduced basement rocks below (Hoeve and Quirt 1984). As has been observed in surrounding properties, differences in the thickness of the regolith are primarily due to variations in rock types (MacDonald 1980; Ibrahim and Woo 1985; Mellinger 1985). For example, calc-silicates, quartzo-feldspathic gneisses, and pegmatites are more deeply weathered than graphitic gneisses. This is a function of greater content of graphite and pyrite in the latter rocks. The thickness of the red and red-green zones ranges from 0.5 to 25 m in the Cigar Lake basin and is least well developed in the graphitic metapelitic facies (0.5–10 m).

The regolith has generally been interpreted as a paleoweathering profile formed prior to the deposition of the Athabasca Group and preserved from erosion by the Athabasca cover. Its similarity to parts of present-day lateritic profiles suggests that it formed under a tropical to subtropical climatic regime (MacDonald 1980). There is still some controversy concerning the origin of the "bleached" zone locally present at the top of the profile. According to MacDonald (1980), it is a product of regional circulation of brines from sandstones. However, Halter (1988), noticing the absence of this zone in drill holes distant from the Cigar Lake orebody, considered it to be the distal expression of brines accompanying the mineralization.

As noted previously, the regolith began to develop prior to 1632 ± 30 Ma (Fahrig and Loveridge 1981). This Rb–Sr isochron age is close to ages of 1610 ± 20 and 1560 ± 20 Ma recently obtained by Pagel et al. (1993) using the Rb–Sr method on metapelitic facies.

Adjacent to the Cigar Lake deposit, strong hydrothermal

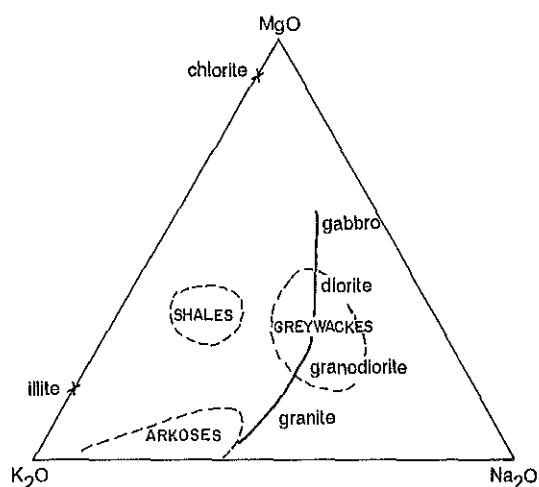


FIG. 12. General distribution of metasedimentary rocks and minerals in a MgO, K₂O, Na₂O diagram (silico-aluminate diagram, de La Roche 1965).

TABLE 1. Major element analyses for fine- to medium-grained metapelites

Sample no. ^a :	1	2	3	4	5	6
Hole no.:	35	165	139	139	139	139
Depth (m):	—	—	448	450	466	513
No. of analyses:	7	2	1	1	1	1
SiO ₂ (wt. %)	61.54	61.37	69.12	45.07	60.17	58.34
Al ₂ O ₃	16.88	16.27	17.39	32.37	20.15	16.01
Fe ₂ O ₃	7.19	5.83	1.09	1.69	1.46	6.89
MnO	0.05	0.03	0.01	0.01	0.01	0.06
MgO	4.19	3.65	3.41	4.42	7.32	4.91
CaO	0.75	1.12	0.11	0.19	0.27	1.72
Na ₂ O	0.73	3.16	0.01	0.05	0.04	1.01
K ₂ O	4.55	4.63	3.05	7.33	2.39	5.42
TiO ₂	0.81	0.74	0.62	1.35	0.81	0.77
P ₂ O ₅	0.20	0.14	0.07	0.21	0.07	0.14
LOI ^b	3.09	2.61	4.41	6.10	6.45	3.22
Total	99.87	99.55	99.28	98.79	99.14	98.49
Sulphur	0.04	0.35	0.05	0.06	0.01	1.62

^a1, 2, fresh facies; 3, regional alteration (bleached zone); 4, regional alteration (red zone); 5, green alteration; 6, fresh facies. Samples 3–6 are from the same drill hole.

^bLOI, loss on ignition.

alteration, which is synchronous with mineralization, has totally obliterated earlier alteration (Bruneton 1987). The most striking feature in the field is the disappearance of the red and brown hematitic colours below the orebody. A typical whitish to pale green colouration appears within rocks affected by hydrothermal alteration because of the abundance of illite–muscovite. Effects of hydrothermal alteration have been sporadically observed in drill holes along the Cigar Lake conductor towards the east, with its intensity progressively decreasing, and finally disappearing a few kilometres away from the orebody.

Geochemistry: Introduction

In most geochemical studies involving metamorphic rocks, it is inferred (usually correctly) that the global chemical composition does not drastically change during metamorphism, that is, metamorphism is an essentially isochemical process.

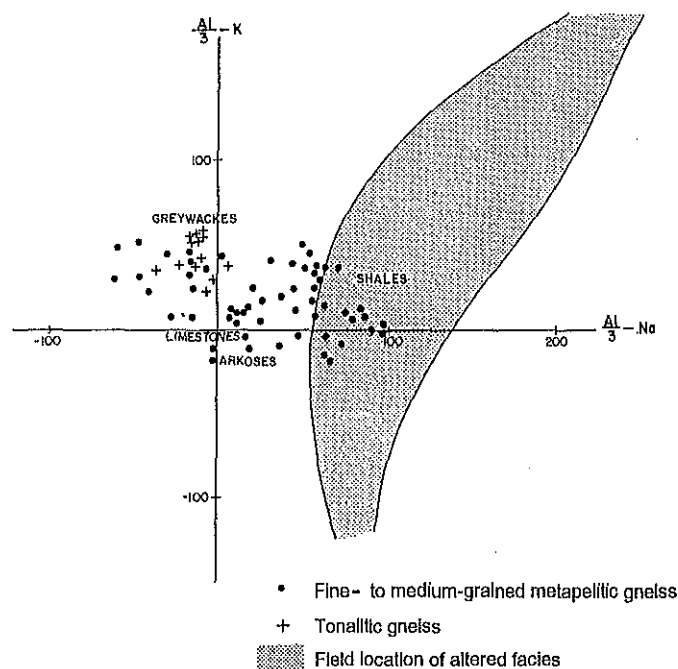


FIG. 13. Location of fine- to medium-grained metapelitic gneisses in an Al/3 - Na, Al/3 - K diagram.

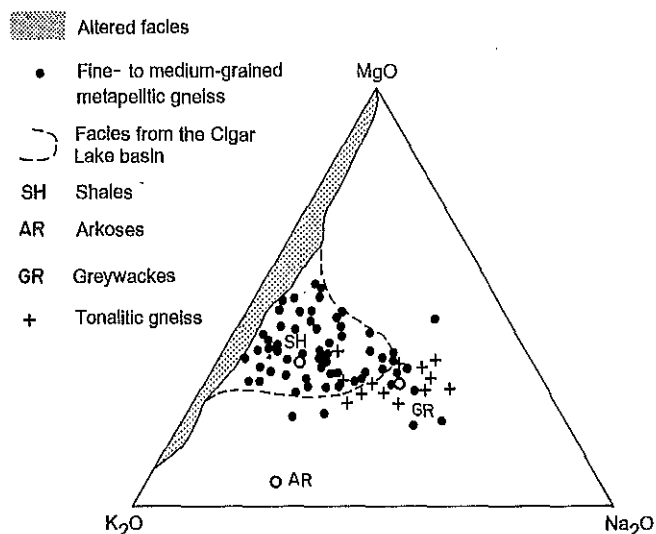


FIG. 14. Location of fine- to medium-grained metapelitic gneisses in the silico-aluminate diagram.

However, in some cases, metasomatism also has taken place, for example, within zones of hydrothermal alteration related to mineralization. Such metasomatism is clearly observed near the Cigar Lake deposit.

Numerous geochemical diagrams have been developed for determining the origin of metamorphic rocks, particularly metasediments. Two different types of diagrams are used here to display the chemical composition and variation of basement rocks in the Cigar Lake basin: (1) Al/3-K, Al/3-Na (aluminium diagram; de La Roche 1968); and (2) MgO, K₂O, Na₂O (silico-aluminate diagram; de La Roche 1965). The first diagram (Fig. 11) takes advantage of the discriminating behaviour of aluminium towards potassium and sodium, and is often

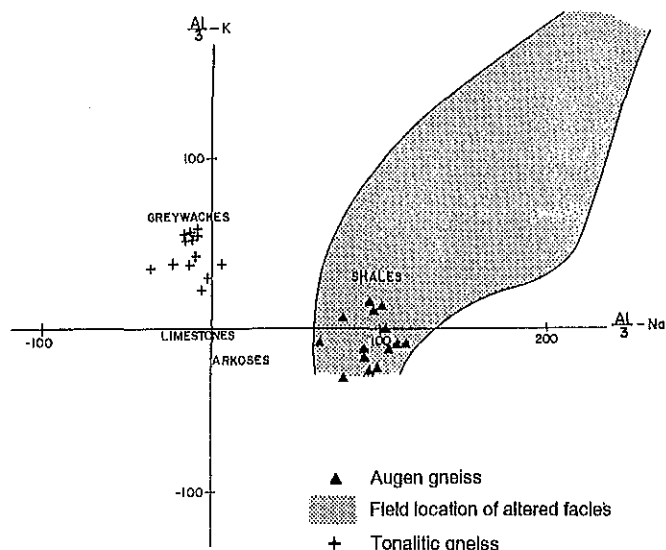


FIG. 15. Location of augen gneisses in an $Al/3 - Na$, $Al/3 - K$ diagram.

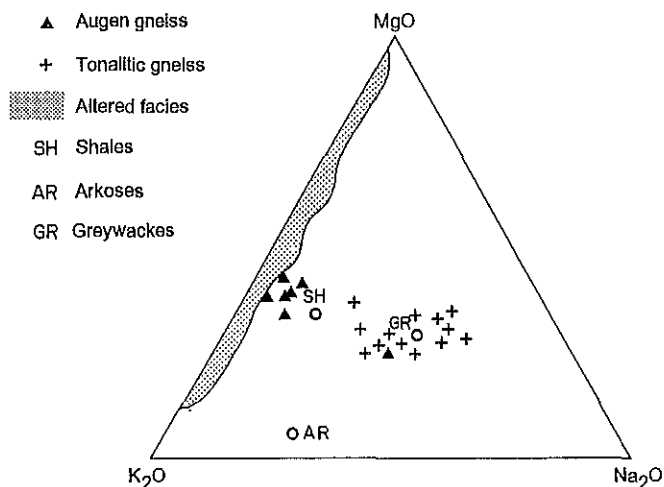


FIG. 16. Location of augen gneisses in the silico-aluminate diagram.

used to display the maturity of sediments. Variations of K and Na separate clay minerals (kaolinite, illite, chlorite) from silico-aluminate minerals (mainly feldspars). Quartz, carbonates, and iron oxides plot towards the origin of the diagram. Sedimentary and igneous domains are distinct, as are different types of sedimentary rocks (arkose, shale, and greywacke). Alteration processes are also well defined, Al_2O_3 and Na_2O being very sensitive elements. In the silico-aluminate diagram, the domains of arkose, shale, and greywacke are generally distinct (Fig. 12); in addition, alteration processes can be discriminated.

Geochemistry: Results

About 1000 basement samples have been analysed for major elements, S, and selected trace elements, including U, Pb, Ni, Co, Cu, Zn, and Mo. Fine-grained metapelitic gneiss is the dominant basement rock in the Cigar Lake basin. Table 1 summarizes the chemical composition of selected facies. Fresh fine-grained metapelitic gneiss (Table 1, samples 1, 2, 6) contains 58–62 wt. % SiO_2 and is rich in Fe_2O_3 and MgO , com-

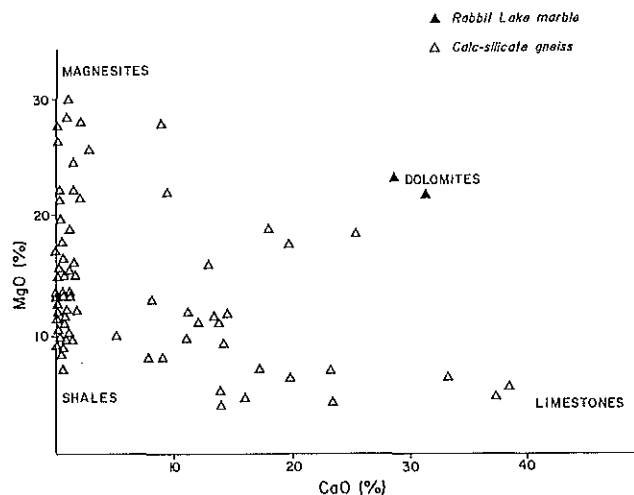


FIG. 17. Location of calc-silicate gneisses in a MgO , CaO diagram.

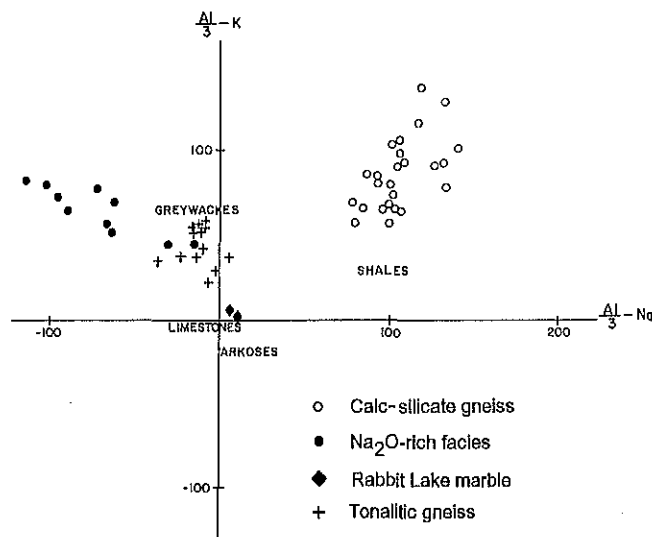


FIG. 18. Location of calc-silicate gneisses in an $Al/3 - Na$, $Al/3 - K$ diagram.

TABLE 2. Major element analyses for "augen gneisses"

Sample no. ^a :	1	2	3	4
Hole no.:	139	20	4	6
No. of analyses:	2	5	2	10
SiO_2 (wt. %)	59.04	63.74	60.47	62.75
Al_2O_3	16.52	15.52	15.74	15.50
Fe_2O_3	6.62	5.08	4.98	4.06
MnO	0.02	0.02	0.02	0.01
MgO	3.45	3.76	6.29	5.08
CaO	0.57	0.45	1.09	0.30
Na_2O	0.80	0.86	0.05	0.15
K_2O	4.58	5.29	2.94	3.68
TiO_2	0.81	0.66	0.80	0.81
P_2O_5	0.09	0.14	0.11	0.11
LOI ^b	5.73	3.91	5.98	6.53
Total	98.23	99.43	98.42	99.09
Sulphur	1.58	1.45	0.12	0.21

^a1, 2, weakly altered facies from the Cigar Lake basin; 3, 4, weakly altered facies from regional drill holes.

^bLOI, loss on ignition.

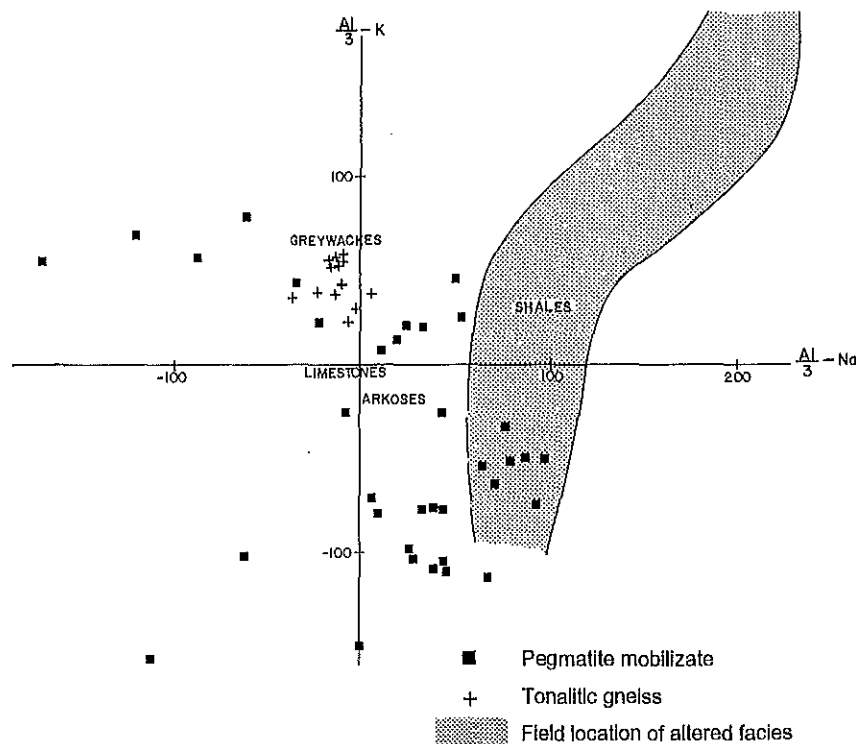
FIG. 19. Location of pegmatites and mobilizates in an $Al/3 - Na$, $Al/3 - K$ diagram.

TABLE 3. Major element analyses for calc-silicate gneisses

Sample no. ^a :	1	2	3	4	5	6	7	8	9
Hole no.:	—	11	11	164	164	164	164	164	164
Depth (m):	—	314	315	475	484	490	492	505	508
No. of analyses:	2	1	1	1	1	1	1	1	1
SiO ₂ (wt. %)	3.44	21.98	16.17	42.22	23.44	45.66	45.67	43.75	52.08
Al ₂ O ₃	0.99	4.29	3.43	19.30	3.07	9.74	7.34	7.96	18.56
Fe ₂ O ₃	0.78	2.86	3.00	6.09	3.66	3.37	3.29	3.68	3.64
MnO	0.04	0.26	0.28	0.01	0.24	0.06	0.09	0.12	0.01
MgO	22.25	5.59	18.68	21.93	18.04	9.97	9.26	4.42	15.45
CaO	29.85	39.22	24.75	0.21	18.96	10.49	14.00	23.41	0.31
Na ₂ O	0.01	0.16	0.39	0.01	0.01	0.03	0.06	0.06	0.01
K ₂ O	0.13	1.49	0.82	0.05	0.05	4.24	3.47	2.72	1.64
TiO ₂	0.02	0.14	0.17	0.69	0.14	0.39	0.29	0.33	0.38
P ₂ O ₅	0.26	0.07	0.05	0.17	0.04	0.08	0.06	0.09	0.11
LOI ^b		24.10	21.50	9.69	31.66	14.20	15.20	22.50	7.49
Total		99.65	99.75	99.33	99.31	98.27	98.80	99.08	99.77
Sulphur		0.08	0.01	0.05	0.05	0.04	0.07	0.04	0.08

^a1, marbles from the Rabbit Lake open pit; 2, 3, massive calc-silicates from regional drill holes; 4–9, various calc-silicates from the same drill hole.

^bLOI, loss on ignition.

patible with its mineralogical composition. CaO is low, and Na₂O, although variable, is consistently lower than K₂O. S values may reach 2 wt.% in the pyrite-rich facies. In Figs. 13 and 14, most of the fresh, fine-grained metapelitic gneiss samples from the Cigar Lake basin plot in the shale field, although samples outside the basin tend to plot towards the greywacke field. Tonalitic granitic gneisses of inferred Archean age also plot close to the greywacke–granodiorite field (Na₂O-rich facies). It is inferred that the lowest fine-grained gneiss units originate through degradation of the Na₂O-rich tonalitic basement. Plagioclase is the main com-

ponent, locally associated with amphibole and pyroxene. Younger rocks display a higher K₂O content. Chemical data for altered facies from a typical regolithic profile are presented in Table 1 (samples 3, 4, 5). Sample 3 is from the upper silicified bleached zone, sample 4 is from the strongly argillized red zone, and sample 5 from the altered green zone. Pyrite and graphite are absent in these three samples.

Unaltered augen gneiss is rare on the Waterbury Lake property; thus its original chemical composition is unknown. A few reasonably fresh samples have been obtained from two drill holes (Table 2, samples 1, 2). They have compositions

TABLE 4. Major element analyses for pegmatites and mobilizates

Sample no. ^a :	1	2	3	4	5	6	7	8	9	10
Hole no.:	14	210	210	210	139	165	—	43	43	43
Depth (m):	609	456	476	529	520	510	—	486	516	545
No. of analyses:	1	1	1	1	1	1	39	1	1	1
SiO ₂ (wt. %)	57.56	72.74	74.65	70.21	77.10	71.64	71.45	72.64	70.35	73.41
Al ₂ O ₃	18.61	14.85	15.09	15.82	12.03	14.73	15.17	16.18	16.62	15.14
Fe ₂ O ₃	6.70	3.08	1.15	2.07	0.68	0.50	1.94	1.12	2.45	0.89
MnO	0.07	0.08	0.01	0.01	0.01	0.01	0.02			
MgO	3.60	0.70	1.75	2.02	0.37	0.39	3.12	0.97	2.37	2.10
CaO	2.38	0.78	0.22	0.91	0.41	0.06	0.41	0.14	0.20	0.21
Na ₂ O	3.78	0.03	0.02	2.20	1.17	1.73	0.18	0.11	0.08	0.14
K ₂ O	4.04	1.95	3.70	3.92	7.32	9.69	2.87	2.06	4.06	5.10
TiO ₂	0.70	0.14	0.13	0.21	0.06	0.04	0.32	0.19	0.10	0.11
P ₂ O ₅	0.23	0.58	0.15	0.14	0.08	0.13	0.07	0.12	0.13	0.13
LOI ^b	1.93	4.76	3.12	1.97	0.29	0.80	4.12	4.58	3.30	2.26
Total	99.60	99.63	99.99	99.48	99.53	99.72	99.76	98.13	99.66	99.49
Sulphur	0.07	0.01	1.51	0.01	0.05	0.07	0.37	0.43	0.04	0.02

^a1, tonalitic gneiss (Archean dome?); 2–4, mobilizates; 5–7, Cigar Lake pegmatites; 8–10, Tibia Lake pegmatitic facies.

^bLOI, loss on ignition.

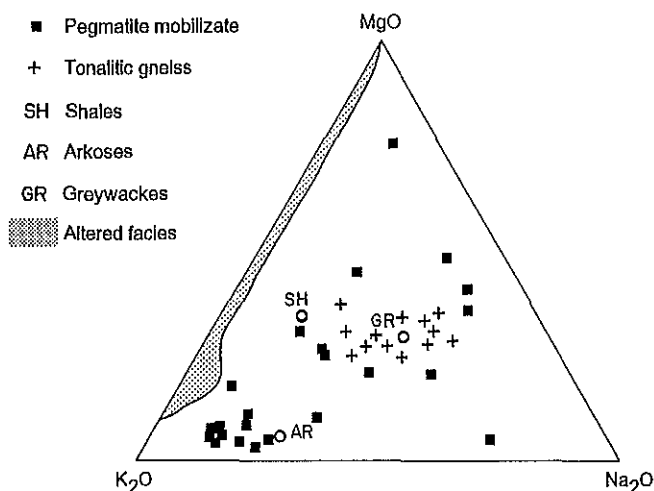


FIG. 20. Location of pegmatites and mobilizates in the silico-aluminate diagram.

similar to those of the fine-grained facies with, however, higher K₂O and S values and lower Na₂O and CaO values. Because of alteration, Na₂O and CaO never exceed 1 wt.%; the sulphur content is generally between 1 and 3 wt.%. The augen gneiss samples plot in tight clusters near the shale field in Figs. 15 and 16. There is however, apparently no trend towards the black shale field, with which uranium mineralization is commonly associated in other provinces.

Calc-silicate facies are chemically variable (Table 3). In fact, there are major differences between samples from a single drill hole (Table 3, samples 4–9). On a simple MgO versus CaO diagram (Fig. 17), calc-silicate gneiss samples show three trends away from a shale composition: (1) magnesite trend (MgO-rich rocks); (2) dolomite trend (MgO–CaO-rich rocks); and (3) limestone trend (CaO-rich rocks). MgO-rich facies with abundant black tourmaline are common around the Cigar Lake orebody. Most of the samples have antipathetic K₂O/Na₂O contents, suggesting a subdivision between Na₂O-

rich facies with albite, and K₂O-rich facies with microcline. Na₂O-rich facies are well defined in Fig. 18.

Mobilizates have, as expected, a wide range of compositions (Table 4, samples 2–4) and are widely scattered on the two geochemical diagrams (Figs. 19, 20). As mentioned above, they were produced by melting and anatexis of metapelitic rocks. Pegmatitic veins have high SiO₂ and very high K₂O (Table 4, samples 5–6). This is compatible with an origin from K₂O-rich intrusions of Hudsonian age.

Geochemistry: Discussion

The original chemical composition of metapelites in the eastern part of the Athabasca Basin is an interesting problem that remains unresolved. Metapelites are associated with most of the geophysical conductors and with several of the uranium deposits at the unconformity. They generally contain graphite and pyrite and, are considered by some to be a potential source of uranium and base metal. In any case, they act as reductants (C, S, Fe-rich units) for hydrothermal fluids.

Other noteworthy characteristics of the metapelites are the presence of cordierite ± sillimanite (Al-, Fe-, Mg-rich rocks) and the presence, generally, of two types of feldspars (plagioclase and K-feldspar). Abundant K-feldspar (15–30%) and biotite (5–15 %) imply high K₂O values.

The metapelites are interpreted as having originally been sediments that were deposited in a shallow, near-shore marine environment that was possibly restricted (Early Proterozoic intracontinental basin). The intercalated carbonate layers may represent algal bank accumulations, but the presence of tourmaline (B-rich formations) and the abundance of MgO favour an evaporitic origin. Calc-silicate rocks from a single drill hole have the chemical characteristics of limestone, dolomite, and evaporite, (Table 3, samples 3–9), suggesting platform-type sedimentation.

A particularly common source of graphite, especially in sedimentary rocks, is organic debris. During diagenesis and metamorphism, this debris is converted into increasingly crystalline and pure material, the end product being graphite.

The similarity between the chemical compositions of fine-

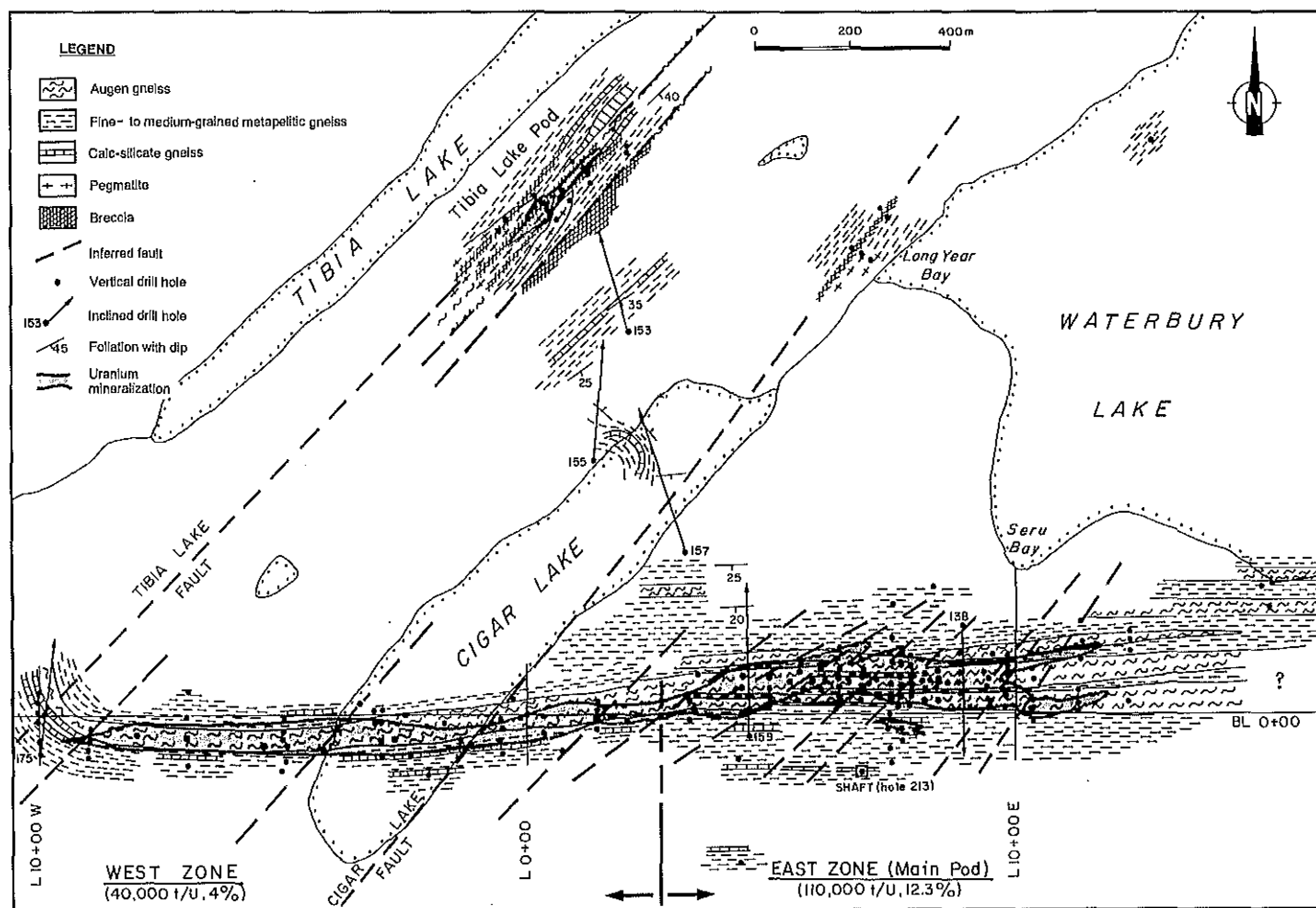


FIG. 21. Schematic geological map of the area around the Cigar Lake deposit.

grained metapelitic gneiss and augen-textured metapelitic gneiss supports the interpretation presented earlier that the augen gneisses are a tectonic derivative of the fine-grained metapelites. However, in general the augen gneisses contain more graphite, pyrite, and cordierite and less biotite than the metapelites. They are considered to be a more mature facies.

Augen gneisses are not unique to the Cigar Lake area, as was formerly thought. They have been observed in other areas of the Athabasca Basin, with and without associated mineralization. For example, in the nearby Close Lake property, the following typical augen gneiss facies have been described: (1) Pyrite- and graphite-rich augen gneiss. These rocks are green in colour, are weakly deformed, and contain no trace element anomalies even where there are large amounts of pyrite (2–10%). Regolith alteration is generally absent. (2) Augen gneiss without graphite and pyrite. In this case, a deep regolith alteration is present.

Structure

The structure of the Cigar Lake basin is dominated by large northeast–southwest lineaments visible on the aeromagnetic maps. These features are distinct from wide, east–west structural corridors, which could represent old Archean directions (Fouques et al. 1986). Sharper, but more discontinuous structures (faults?) striking north–south and northwest–southeast appear to be younger.

Oriented core from six inclined holes drilled across the

Cigar Lake basin provide more detailed structural information. Below and along the sides of the Cigar Lake orebody, the lithologic units form an east–west belt of mixed graphitic units dipping towards the south (Fig. 21). An axial-plane schistosity is strongly developed in the graphitic facies. Decimetre- metre- and decametre-scale folds are observed in the core. Irregular ptygmatic folds involving quartzofeldspathic leucosomes are present in fine-grained metapelitic gneisses, with the schistosity representing the axial plane. A major discontinuity (fault?) or change in foliation orientation (fold?) is noticeable at the west end of the deposit. Here, foliations trend almost north–south and dip steeply to the west. This discontinuity, which is associated with an important northeast-trending feature (Tibia Lake fault), could explain the absence of uranium mineralization to the west. In the Tibia Lake area, foliations trend mostly 045–060° and dip 40–80° southeast. The Tibia Lake brecciated zones seem to be approximately parallel to the regional foliation.

Results from hole 157, in the centre of the basin, are the most variable when compared with the other drill holes. A fairly complex structure was intersected and appears to correspond to a single fold axis plunging 45° at 050°.

The Cigar Lake – Tibia Lake area can thus be interpreted as a large open fold with an east–west limb hosting the Tibia Lake pod. However, deformation in the immediate vicinity of the Cigar Lake deposit is polyphase, comprising several folding events and later faulting.

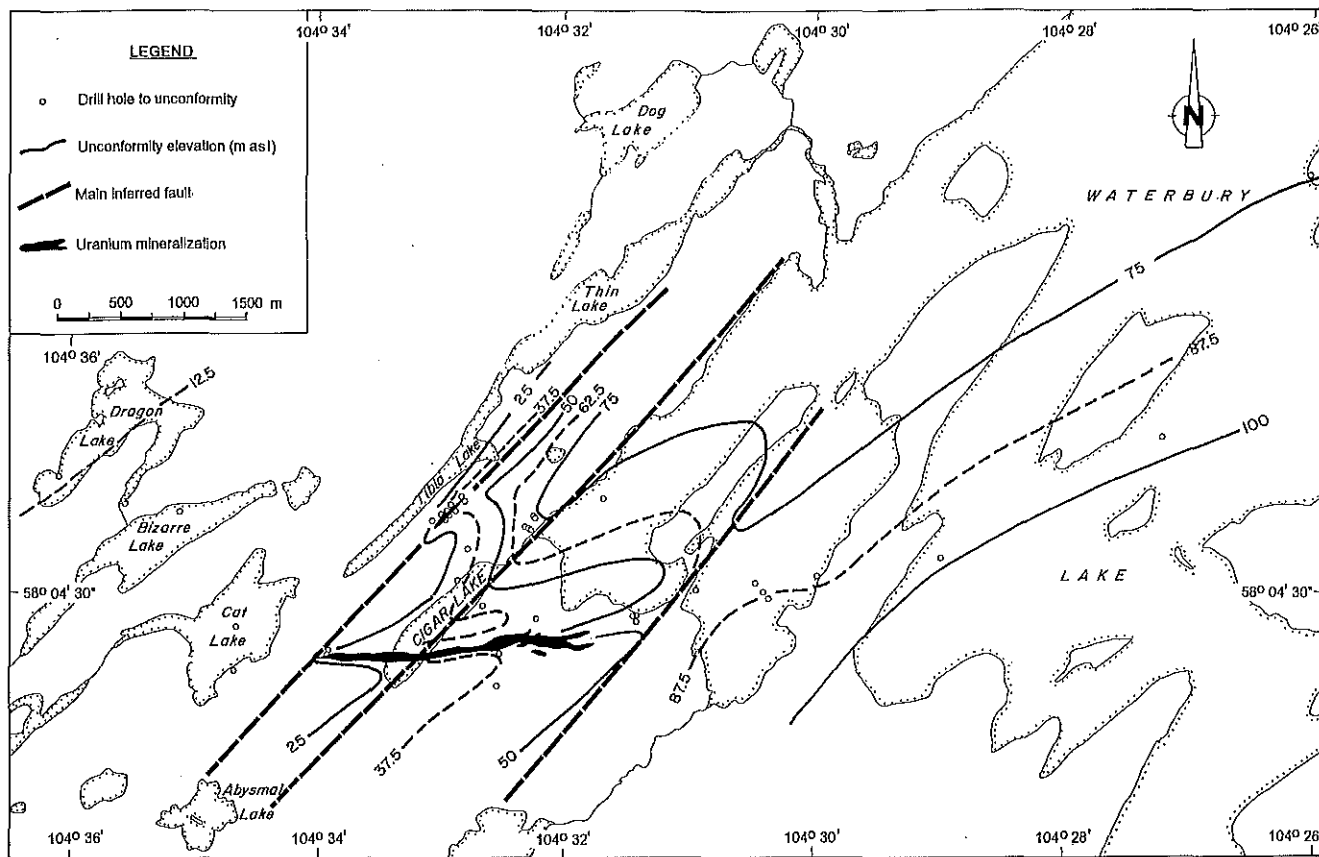


FIG. 22. Elevation of unconformity, Cigar Lake basin.

Two major fracture systems oriented $060^{\circ}/55^{\circ}$ SE and $090^{\circ}/60^{\circ}$ SE, are evident in the basement of the inclined drill holes. Similarly oriented fractures were observed in the sandstone of the Athabasca Formation. The dips, however, are somewhat steeper in the sandstone, suggesting some refraction at the boundary between the two rock types. These two sets of fractures correspond to the two principal structural directions within the region. Other fracture orientations ($020^{\circ}/30^{\circ}$ E, $005^{\circ}/50^{\circ}$ W, $135^{\circ}/30^{\circ}$ NE, $040^{\circ}/35^{\circ}$ SE, $160^{\circ}/70^{\circ}$ W) are only locally important.

The graphite-pyrite-rich augen gneisses may have formed through mylonitization. Ductile deformation, typical of deep crustal faults, transformed the initial metapelites into mylonites and blastomylonites. Recrystallization during deformation created rocks with large crystals. The porphyroblasts were progressively deformed, and graphite and biotite were segregated into parallel layers, creating a strong planar anisotropy. This mylonitization was contemporaneous with the regional metamorphism, and therefore is Hudsonian in age.

Figure 22 is an interpreted topographic map of the basement unconformity. The paleosurface progressively deepens towards the west or northwest. In the central part of the Cigar Lake basin, where most of the drilling information is concentrated, the isopleths appear to be quite disturbed, mainly by the northeast-southwest faults, producing local steps in the topography. These steps are oriented roughly parallel to Hudsonian structures in the crystalline basement.

The Cigar Lake deposit lies above a well-defined, east-west, topographic high. There is a strong correlation between the location of this ridge and the presence of both augen gneisses

and uranium mineralization (Fouques et al. 1986; Bruneton 1987). The topographic high is interpreted as a basement feature that was present before the deposition of the sandstone cover. The main evidence in support of this is the thinning of the Athabasca basal conglomerate toward the ridge (Fig. 23). The Tibia Lake mineralized pod is also located on top of a northeast-trending structural topographic high, which corresponds to a brecciated zone of regional extent.

Such pre-Athabasca basement "bumps" have been described at Dawn Lake (Clarke and Fogwill 1981), and McClean Lake (Wallis et al. 1983). It was suggested that these reliefs within the Athabasca basin would have exerted major control on fluid flows. The development of pelitic ridges may be compatible with the tropical weathering lateritic conditions, which characterized the pre-Athabasca land surface. Under such conditions, rocks rich in phyllosilicates would have a tendency to resist erosion (Sibbald and Quirt 1987).

Interpretation of the geological data

The basement rocks on the south flank of the Samson Lake dome (Dragon Lake, Bizarre Lake, Fig. 7) consist of a sequence of massive calc-silicate gneisses intercalated with meta-arkoses that grade to the north into fine-grained metapelitic gneisses containing small amounts of graphite and pyrite. Coarser grained facies and augen gneisses have not been observed. Large quartzo-feldspathic pegmatitic leucosomes are intercalated in the sequence or are intrusive into it.

Farther south (Cat Lake), two holes (207, 210) tested the possible extension of the Cigar Lake conductor, but no conductive material was intercepted. Instead, the basement units

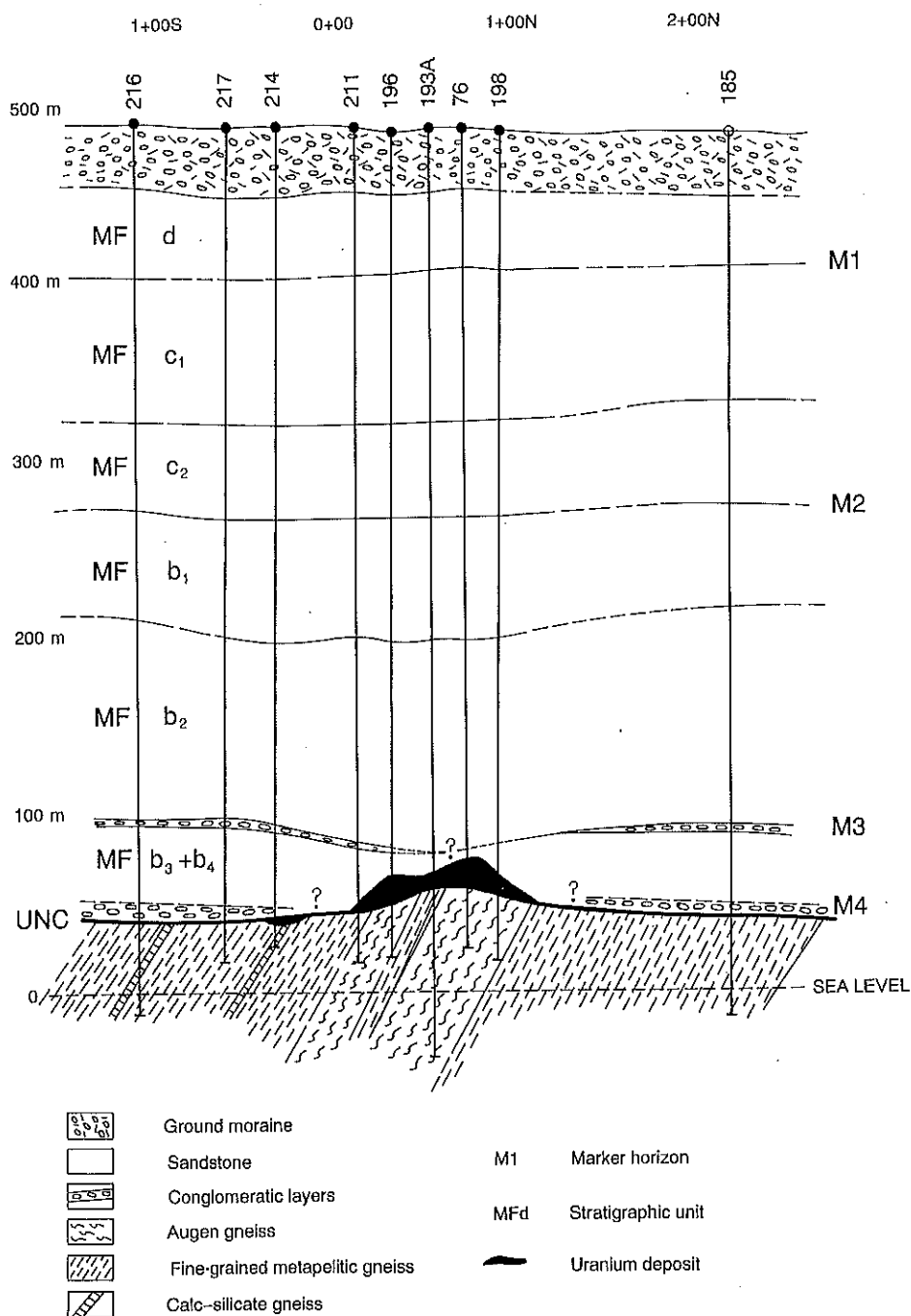


FIG. 23. Geological cross section, Cigar Lake deposit.

there consist of fine- to medium-grained anatectic granites intercalated with highly remobilized metapelitic remnants. The presence of abundant anatectic rocks and the absence of graphitic metapelitic gneisses suggest that the size of the metapelitic basin, as mapped from aeromagnetic data, is considerably smaller west of the orebody.

North of the basin (Tibia Lake, Long Year Bay), the basement lithologies are predominantly fine-grained metapelitic gneisses associated with medium- to coarse-grained pelitic gneisses, and rare augen gneisses and calc-silicate gneisses. Graphite and pyrite are ubiquitous in the pelitic formations. Pegmatite is the dominant lithology in the Tibia Lake area, occurring as homogeneous bodies several decametres wide.

These are probably related to increased remobilization near the Archean basement, which is interpreted from aeromagnetic data to lie immediately to the north. An usual and most interesting facies is strongly brecciated and mylonitized gneiss and pegmatite. Angular fragments of various sizes are embedded into a dark aphanitic chloritic matrix. This facies is more common in metapelitic gneisses than pegmatites. In one drill hole, sandstone fragments were found in the breccia, about 25 m below the unconformity. The breccia is inferred to be tectonic. It strikes $045^{\circ}-060^{\circ}$, parallel to the regional foliation, which may explain the interruption of the Cigar Lake deposit towards the west (Tibia Lake fault, Fig. 7). More important is the presence of uranium mineralization (Tibia Lake pod) asso-

ciated with the structure at the unconformity. Faulting is also well developed in the sandstone above the unconformity.

A fence of four inclined holes was drilled between the Cigar Lake orebody and the Tibia Lake pod to provide additional stratigraphic and lithologic information for this area. Basement rocks are very monotonous and composed mainly of fine-grained, weakly graphitic, metapelitic gneisses with limited intercalations of calc-silicates. Lithologies become coarser in hole 159, the closest to the Cigar Lake orebody, whereas hole 153 crosscuts breccias similar to those observed at Tibia Lake.

The eastern extension of the Cigar Lake conductor was the most promising geophysical target in the Cigar Lake basin, but the 10 exploration drill holes completed along the conductor did not reveal any uranium mineralisation. All the drill holes intersected various metapelitic gneisses. Graphite- and pyrite-rich augen gneisses are present in the western drill holes (140–192), but seem to disappear towards the east, graphite also becoming scarcer in the metapelitic gneisses. In situ remobilization of the metapelitic gneisses is locally strong and quartzo-feldspathic mobilizates are quite common.

Drill hole 23, the most northeast hole in the Cigar Lake basin, also intersected fine- to coarse-grained, weakly graphitic metapelitic gneisses, and bottomed out in fresh plagioclase gneisses containing abundant sillimanite. Facies in this hole are quite different from those observed elsewhere in the Cigar Lake basin and could indicate the proximity of meta-arkoses, inferred from geophysics (Fig. 7).

Finally, the geology of the area south of the orebody is known only from drill hole 139, located 400 m from the deposit. Fine- to medium-grained graphitic gneisses are dominant in this hole, with some augen gneisses, calc-silicate gneiss intercalations, and pegmatites.

Conclusions

The Cigar Lake deposit is considered to be the world's largest known high-grade uranium deposit. It is located at a depth of 420–450 m and is devoid of any direct surface expression. It was discovered in 1981 through drilling of an electromagnetic conductor. Like other major uranium deposits of the basin, it is spatially related to the unconformity separating Helikian sandstones of the Athabasca Group from Aphebian metasediments and plutonic rocks of the Wollaston Group.

Airborne and ground geophysical data in combination with neutron–neutron and natural gamma logs from drill holes are effective tools to delineate the main geological units.

On the Waterbury Lake property, the Athabasca Group is 250–500 m thick and consists of quartz sandstones with conglomerate layers corresponding to units MFd, MFc, and MFb of the Manitou Falls Formation. The metamorphic basement rocks comprise graphitic, biotite–cordierite pelitic gneisses, semipelitic gneisses, meta-arkoses, diopsidic calc-silicate gneisses, and granitoid segregations derived from anatexis of the surrounding rocks during the Hudsonian orogeny.

The Cigar Lake pelitic basin that contains the deposit is located in the transitional zone between the Wollaston Domain and the Mudjatik Domain. In the basin, the basement rocks consist mainly of graphitic metapelitic gneisses and calc-silicate gneisses. The mineralogy and geochemistry of the metapelitic gneisses suggest that they were originally shales. The calc-silicate gneisses may represent algal bank accumulations, but the abundance of magnesium indicates also an evaporitic origin for part of it. The sediments were deposited in an Early Proterozoic intracontinental basin in which shallow

marine conditions were prominent.

“Augen gneiss,” an unusual facies within the graphitic metapelitic gneisses, occurs only below the Cigar Lake orebody and along the Cigar Lake conductor. It contains more graphite and pyrite than the surrounding metapelitic facies. It is considered to be a more mature facies, but also a product of mylonitization along east–west tectonic corridors that were active during the Hudsonian regional metamorphism.

The unconformity surface and the sandstone pile have been affected by significant tectonic displacement. Particularly important is the northeast–southwest direction. Finally, the Cigar Lake deposit lies above a well-defined east–west topographic high. There is a strong correlation between the location of the ridge and the presence of both augen gneisses and uranium mineralization, suggesting that the ridge may have played a major control on the mineralizing fluid flows.

Acknowledgments

The author thanks the management of Cogema and its two partners of the Waterbury Lake project, CAMECO and Idemitsu, for permission to publish this paper. I am grateful to the two reviewers, C. Hallenstein and J. Smellie, for helpful comments on the early draft of the manuscript. The article was greatly improved by the review of J. Clague, former Editor of the Canadian Journal of Earth Sciences.

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