Preliminary Report on the Origin of Uranium Occurrences in the Horton Group of the Windsor Area, Nova Scotia

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Abstract

There are numerous uranium occurrences in basin fill units of the Maritimes Basin, and in the adjacent crystalline basement rocks in Atlantic Canada. The exploration model applied to the sandstone-hosted uranium occurrences was that of a uranium roll front, similar to the deposits of Texas and the western United States. The recognition of deeply weathered granitoids below the unconformity of the Horton Group on the South Mountain Batholith, however, suggests that a genetic link to regolith-related unconformity deposits, such as the Athabaska Basin of Saskatchewan, may also be applicable. Although there is no doubt of the presence of roll fronts in Horton Group sandstone, the source of uranium within the system may be related to weathered horizons beneath the Horton Group rocks and not exclusively the result of diagenetic change in the sandstone.

In the area near Windsor, Nova Scotia, there are numerous uranium occurrences with the most notable being at Three Mile Plains where Saarberg Interplan Canada Ltd. drilled numerous diamond-drill holes from 1978 to 1981. Significant uranium is restricted to the Glass Sand unit of the Horton Bluff Formation and the base of the Cheverie Formation. The uranium occurrences can be divided into two types: (1) carbon- and pyrite-related quartz-sandstone type and (2) hematite arkosic-sandstone type. Although this paper deals primarily with uranium and associated elements from occurrences in the Windsor area, the regional nature of the pre-Carboniferous weathering episode and the areal extent of the Horton Group strata throughout eastern Canada would seem to imply that suitable environments for uranium mineralization might have existed throughout the Maritimes Basin. This may be of particular note in areas that have numerous uranium occurrences in granitoid basement rocks adjacent to the Carboniferous basin fill.

Introduction

The presence of anomalous levels of uranium, radium and radon in the Carboniferous Horton Group and underlying basement rocks of Atlantic Canada has been known for many years (Fig. 1). In the late 1970s and early 1980s numerous companies conducted extensive uranium exploration programs in eastern Canada. Even though there were successful results from this exploration, public pressure in 1982 forced a moratorium on all exploration and prospecting for the commodity in Nova Scotia. The exploration model applied to the sandstone-hosted occurrences was that of a uranium roll front, similar to the deposits found in Texas and the western United States. The recognition of deeply weathered granitoids below the unconformity of the Horton Group on the South Mountain Batholith (O'Beirne-Ryan and Zentilli, 2003), however, suggests that a genetic link to regolith-related unconformity deposits such as the Athabaska Basin of Saskatchewan may also be applicable. There is no doubt of the presence of roll fronts in the Horton Group sandstone, but the source of uranium in the system may be related to weathered horizons beneath the Horton Group rocks and not exclusively the result of diagenetic change in the sandstones.

Granitoid rocks of the South Mountain Batholith in Nova Scotia contain numerous uranium deposits and occurrences (Fig. 1). These

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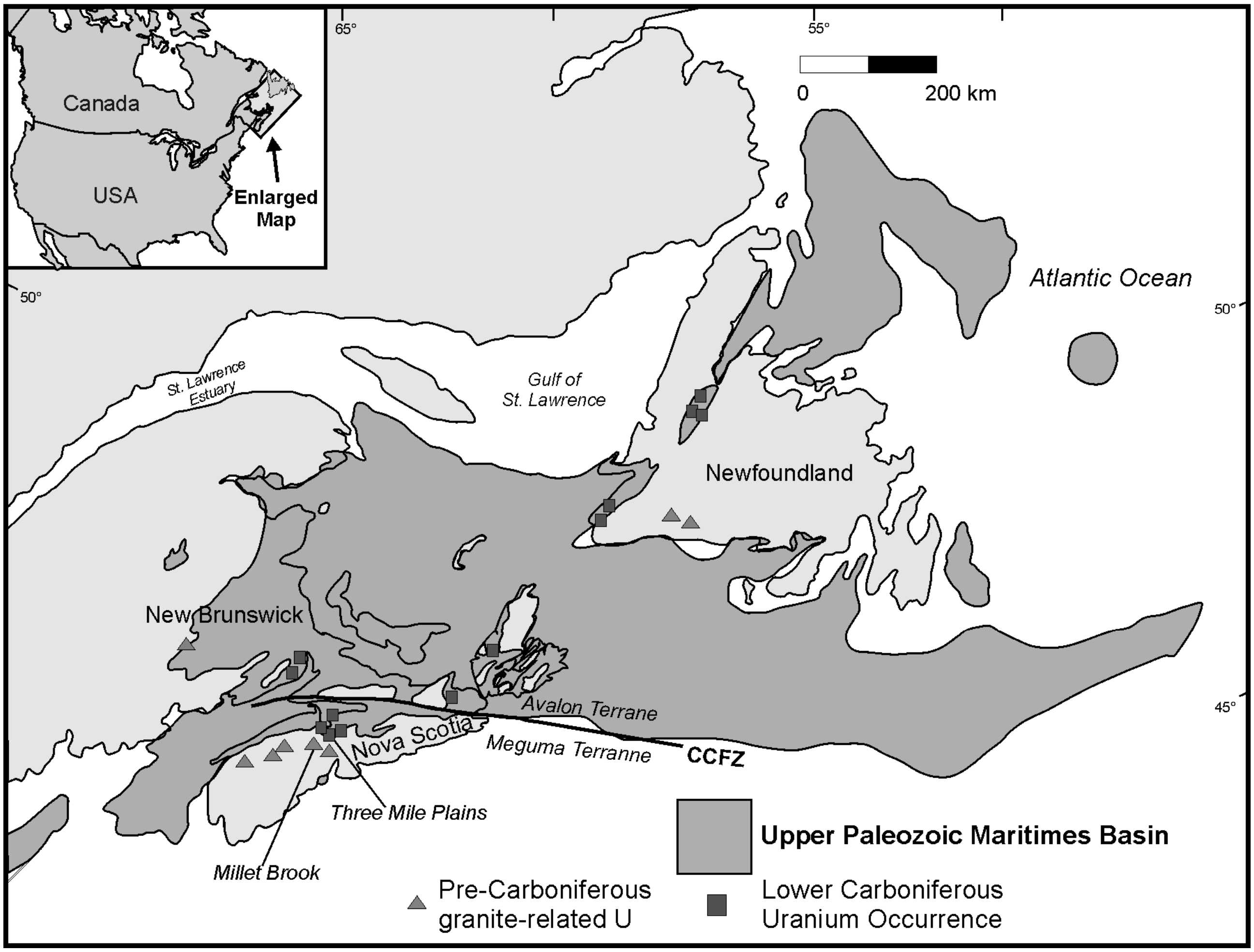

Figure 1. Location of uranium occurrences in Mississippian strata of the Maritimes Basin and in the adjacent basement rocks.

deposits are interpreted as having been formed due to fluid migration in the late stages of granitoid emplacement and occur within shear and fracture zones of altered rocks, either in the granitoids or as peribatholithic occurrences in the metasedimentary Meguma Group country rocks (MacDonald, 2001). The Millet Brook deposit, Hants County, is the largest (450 000 kg of U_3O_8) and best documented uranium deposit in the South Mountain Batholith and in the Maritime Provinces. The deposit also contains copper and silver. The dominant uranium-bearing mineral in the granitoid-hosted ore zones (veins) below 50 m is pitchblende (MacDonald, 2001). In the uppermost 50 m of the Millet Brook deposit uranium occurs as the U-phosphate minerals torbernite, autunite and Pb-meta-autunite (MacDonald, 2001). MacDonald (2001) suggests that this upper mineral assemblage is the result of a surface weathering process. Other minerals present in the upper zone include bornite, covellite, chalcocite, proustite, hematite, kaolin, and illite-smectite. All of these associated minerals are consistent with low-temperature surface weathering processes. Similar occurrences of uranium are found in other Devono-Carboniferous granitic plutons elsewhere in the Maritime Provinces and in Newfoundland (Fig. 1).

Weathering of the South Mountain Batholith (SMB) to a depth of 10 m with an average of 1 ppm depletion of the uranium contained within these uranium deposits and their uranium-bearing granitoid host prior to (and subsequent to) the deposition of the Horton Group sedimentary rocks would liberate approximately 190 000 000 kg of uranium[2]. The uranium liberated by weathering of the granitic region must have been incorporated in the surface water and subsequently entered, as uranium-enriched groundwater, into the permeable sandstone and conglomerate aquifers of the Horton Group and/or younger permeable Carboniferous strata.

Most of the known unconformity-type uranium deposits are associated with Precambrian rocks in the McArthur Basin of Australia and the Athabaska Basin of Saskatchewan. These deposits are located at or near the base of sedimentary basins overlying Precambrian unconformities. The basin fill strata are dominated by sandstone and the uranium deposits are associated with graphite-rich faulted basement rocks (shear zones). Maynard (1983) suggests that ultimately almost all uranium concentrated is derived from rocks with granitic composition. The role of regoliths in relation to uranium mineralization in the Athabaska Basin has been debated over the years; however, the proximity of weathered mantles below these giant unconformity uranium deposits strongly suggests that there is some genetic connection.

Maynard *et al.* (1995) have also suggested a genetic relationship between weathered, hydrothermally altered granites (regolith) and the gold and uranium deposits found in the Witwatersrand Basin. There has also been controversy about the nature of the Witwatersrand deposits, similar to the Athabaska Basin deposits, as to whether these South African deposits were paleoplacers or related to metamorphic fluids (Phillips and Myers, 1989). Sutton *et al.* (1990) argued that source area weathering was the main contributing factor to the Witwatersrand deposits rather than metamorphism. Maynard *et al.* (1995) cite the mineralogically supermature nature of the sandstone and conglomerate, the stratigraphic continuity of the units, and the absence Fe-Ti oxide grains as evidence for a placer origin for the gold and uranium.

O'Beirne-Ryan and Zentilli (2003) and Ryan *et al.* (2005) have suggested that some of the mineralogically mature sands and sandstones of the Cretaceous and Carboniferous are probably related to the erosion of weathering profiles developed on the granitoid and metamorphic rocks in Nova Scotia and elsewhere in the northern Appalachians. O'Beirne-Ryan and Zentilli (2003) provide evidence for pre-Carboniferous, pre-Triassic and pre-Pliestocene ages of saprolite development in southern Nova Scotia (Fig. 2). This paper will in part examine the implications of these pre-Carboniferous saprolites for uranium enrichment in the Horton Group of Nova Scotia in particular, and equivalent strata in the Maritimes Basin as a whole.

General Geology

The rocks and saprolites referred to in this paper are located primarily in southern Nova Scotia. Southern Nova Scotia forms the Meguma Terrane of the northern portion of the Appalachian Orogen. The Appalachian Mountains stretch from Newfoundland to the southern United States. The Meguma Terrane is thought to be an allochthonous fragment accreted onto the eastern margin of the North American continent and represents the final stage of continent building in eastern North America. The terrane is characterized by a thick sequence of Cambro-Ordovician metasedimentary slate and quartzite referred to as the Meguma Group. Meguma Group strata are host to numerous mesothermal gold deposits associated principally with quartz veins. The Meguma Group is locally overlain by Silurian metasedimentary and volcanic sequences. The Meguma Group rocks have been intruded by Late Devonian granitoids of the South Mountain Batholith (Williams, 1995).

Approximately one third of the Meguma Zone is underlain by peraluminous granitic rocks ranging in composition from granodiorite to leucogranite (MacDonald *et al.,* 1992). The South Mountain Batholith is the largest igneous mass in the Appalachian Orogen and consist of 13 separate plutons. Texture varies from megacrystic, coarse-grained rocks to medium-grained equigranular and very fine-grained units. The plutons can be grouped

[2]Area of the SMB = 7300 km^2 or 7.3 x 10^{10} m^2 x specific gravity $\frac{\sim 2.6\ t}{m^3}$ x 10 m depth = 1.89 x 10^{11} t @ 1 ppm or

$$\frac{1\ gU}{t} \times \frac{1\ kg}{1000\ g} = 1.9 \times 10^{8}\ kg\ U$$

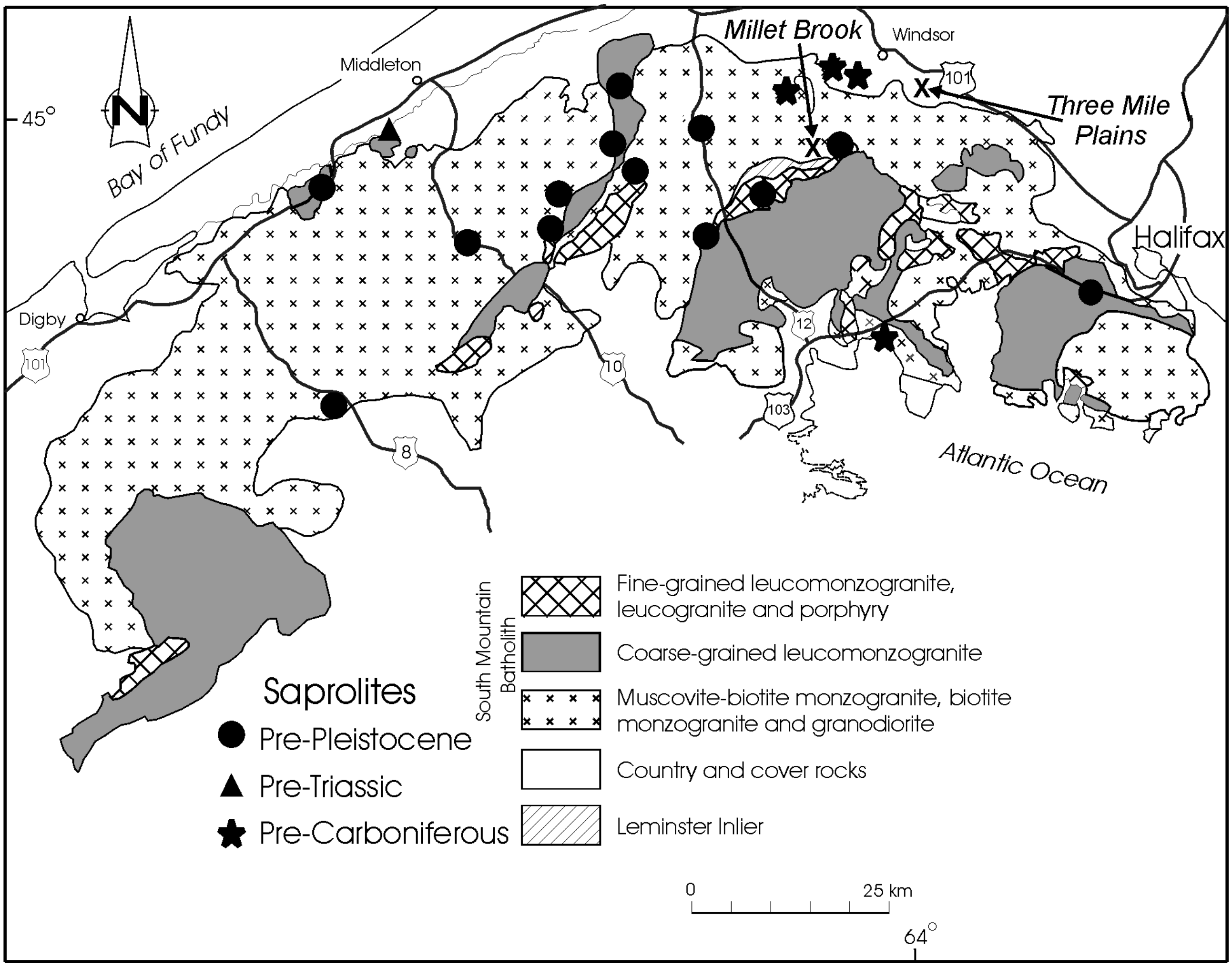

Figure 2. Simplified geology map of the South Mountain Batholith and location of the Millet Brook and Three Mile Plains occurrences in relation to saprolites (after Ryan *et al.,* 2005).

together into two main stages of intrusion: (1) an older, mostly granodiorite and monzogranite stage and (2) a younger, mostly monzogranite, leucomonzogranite and leucogranite stage (MacDonald *et al.*, 1992) (Fig. 2). Although there is a complex history of intrusion within the batholith, geochronological evidence indicates that both stage 1 and 2 plutons were intruded and crystallized during a short time interval ca. 380 Ma (MacDonald *et al.,* 1992).

At many localities these metamorphic and crystalline basement rocks are unconformably overlain by Carboniferous sedimentary rocks and by Triassic clastic sedimentary strata. Locally poorly consolidated Cretaceous strata also occur. The most common surface units in southern Nova Scotia are unconsolidated Pleistocene glacial tills (Finck and Stea, 1995).

The Carboniferous strata stitch together the Meguma Terrane and the Avalon Terrane to the north and form the Nova Scotian portion of the Maritimes Basin (Fig. 1). Van de Poll and Ryan (1985) suggest that the Maritimes Basin should not be thought of as a single, post-orogenic Permo-Carboniferous basin, but rather as a “composite basin” consisting of a group of interconnected fault-block basins and horsts, which at various times shared similar subsidence rates and strata.

Stratigraphy

The general stratigraphy of the Maritimes Basin (Fig. 3) consists of a late Devonian redbed and volcanic sequence referred to as the Fountain Lake

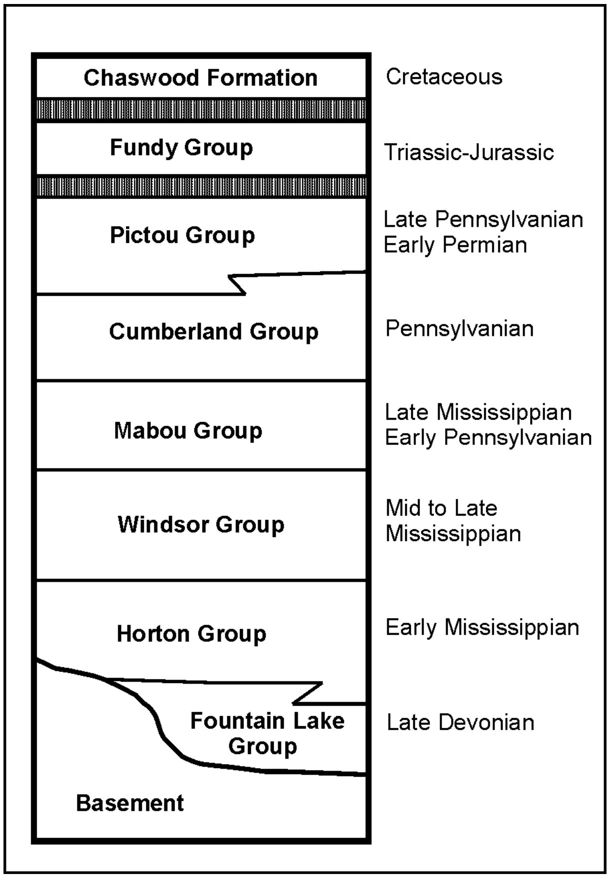

Figure 3. General stratigraphy of the Maritimes Basin.

Group, Mississippian clastic fluvial-lacustrine rocks of the Horton Group, a Mississippian marine evaporite, clastic-carbonate sequence of the Windsor Group, fine terrestrial clastics of the Mabou Group, coal measures of the Cumberland Group, and late Carboniferous to Permian redbeds of the Pictou Group. In the area surrounding the Bay of Fundy there was also a Jurassic-Triassic sedimentary basin (Fundy Group) in which sandstone, shale, basalt and minor limestone were deposited. During the Cretaceous, fluvial quartz sand and kaolin of the Chaswood Formation (Stea and Pullan, 2001) were deposited throughout the Maritimes, but only a few outliers have been preserved.

Although the Fountain Lake Group underlies the Horton Group in some areas, in most areas the Horton Group strata overlie pre-Carboniferous basement rocks. In particular, in the type area of the Horton Group near Windsor, Nova Scotia, the Horton overlies Meguma Group metasediments or granitoids of the South Mountain Batholith. This area also has numerous uranium occurrences in the Horton Group strata and, therefore, these rocks are the focus of this study.

Horton Group

Horton Group rocks of the Maritimes Basin are host to the best-documented uranium occurrences. There have been a multitude of formation names applied to the various Horton Group units in the different regions of the Maritimes Basin. This paper will use nomenclature from the type area (Bell, 1929) (Fig. 4).

Lower Horton Bluff Formation

The unit is an overall fining-upward sequence of the Horton Group dominated by basin margin conglomerate and a sandstone-dominated, more basinward facies. The unit is compositionally dependent on the adjacent basement rock source areas. For example, in areas underlain by the Meguma Group rocks of southern Nova Scotia the basal conglomerates of the Horton Group are composed primarily of quartz-pebble conglomerate derived from quartz veins that are ubiquitous in the Meguma Group, whereas in areas flanked by granitic basement rocks the basal conglomerate is usually on arkosic granite-pebble conglomerate. The upper parts of the unit are sandstone-dominated with carbonaceous quartz-rich litharenite and arkose inter-cross stratified with subordinate grey siltstone and organic-rich shale. The finer grained rocks locally contain abundant plant debris. These strata are interpreted to have been deposited as locally derived alluvial fans along the basin margins that grade laterally and vertically into low sinuosity streams (primarily braided). A lacustrine influence in the unit is more evident toward the top of the sequence, suggesting that the streams ultimately emptied into a large inland lake in the central portions of the basin with sandstone deposition occurring in distributary channels and lacustrine deltas.

Middle and Upper Horton Bluff Formation

This sequence of the Horton Group is a grey, mainly fine-grained coarsening-upward succession of rocks. The rocks include grey to black organic-

	Type Area Bell 1929	Type Area Martel and Gibling 1996		Cape Breton	New Brunswick	Newfoundland
Upper Horton Group Upper coarse facies sequence	Cheverie	Cheverie Fm.	Cheverie Formation	Ainslie	Moncton	Spout Falls
Middle Horton Group Fine Lacustrine Facies sequence	Upper Horton Bluff Middle Horton Bluff	Horton Bluff Formation	Hurd Creek Member Blue Beach Member Curry Brook Member	Strathlorne	Albert	Frairs Cove Snakes Bight
Lower Horton Group Lower coarse facies Sequence	Lower Horton Bluff		Harding Brook Member	Craignish	Memramcook	Kennels Brook

Figure 4. Correlation of the Horton Group in Atlantic Canada.

rich shale, mudrocks, oil shale, siltstone and sandstone with thin carbonates and rare evaporites. Sandstone generally makes up less than 10% of the succession and sandstone layers are more numerous and thicker near the top of the coarsening-upward sequence. Plant debris, fish scales and ostracods are locally very abundant. The thickness of the unit varies throughout the Maritimes Basin from a few tens of metres near basin margin overlap areas to in excess of 1200 m elsewhere. The mean thickness of the unit is approximately 800 m, based on observation of numerous seismic profiles throughout the Maritimes Basin. This unit includes the black albertite-bearing shale and quartz-rich sandstone of the Albert Formation in New Brunswick which, respectively, are the source and reservoir rocks of the small but long-producing oil and gas field at Stoney Creek, and the recent discoveries in the Sussex area. In the lower parts of the succession the sandstone beds rarely exceed 1.2 m in thickness. In the Upper Horton Bluff Formation, however, multistoried-multilateral channel sandstone bodies can attain thicknesses up to approximately 30 m. Sandstones within the unit are usually quartz-rich and exhibit significant porosity and permeability.

The presence of fresh water fish, plant debris and thin pedogenic carbonates suggest that the fine-grained beds were deposited in a lacustrine environment. The presence of thin horizons with glauconite grains, marine-affinity bivalves, arenaceous foraminifera, crinoids and one specimen of trilobite, however, suggest that there was a distal marine influence within the sequence at various times (Ryan, 1998). The fine-grained unit is, therefore, interpreted to represent lacustrine sedimentation in a large inland lake that covered most of the Horton-aged Maritimes Basin, which had distal marine influences. Sedimentation in lacustrine sandstone deltas, distributary channels, and beach sand areas occurred marginal to, and interfingering with, the lake sediments. Lake sediments were subsequently incised by meandering and low sinuosity streams. The presence of multicolored shale near the top of the sequence attests to the general drying up of the inland lake (Ryan, 1998).

Thickness variations of the unit in the basin are probably caused by two factors. The first factor is that there was significant irregularity on the surface of the basin after deposition of the lower Horton Group (inferred from tops of formation contour maps). The surface is interpreted as reflecting the underlying basement's structural features. It has been demonstrated that within the type area of the Horton Group the middle unit accumulates in the depressions and that thickness of the unit thins dramatically over basement ridges draped by thin lower Horton sediments. The net result is a general smoothing out of contours to the top of the formation for subsequent Horton units (Ryan, 1998). The second factor controlling the thickness of the unit is that the upper contact of the unit is almost always an angular unconformity with the overlying Cheverie Formation, suggesting that the degree of tilting of older Horton strata and the amount of subsequent erosion also contributed to the thickness variations. The occurrence of low-angle thrusts and bedding-plane displacements in this unit are common in most sub-basins and consequently thicknesses are often overestimated. The carbonaceous nature of fine-grained layers in the sandstone-dominated Horton Group strata makes them a preferential focal point for compression-related tectonic dislocations.

Cheverie Formation

The uppermost sequence of the Horton Group corresponds to a sudden shift from relative tectonic quiet of lake sedimentation in the middle unit to rapid coarse-grained sedimentation in braided streams and alluvial fans related to uplift of the adjacent basement areas and rapid subsidence of the basin. Thick arkosic sandstone-dominated successions are typical of the Cheverie Formation, especially where the basin is flanked by granitic basement areas. Basin margin conglomerates are common and locally very thick. The strata deposited in the overbank environment during this interval are typically organic-poor and are usually green or red, contrasting with the grey fine-grained strata prevalent in the lower and middle Horton units. The succession forms a generally fining-upward sequence, whereas the proportion of sandstone to mudrock decreases up section. The more central portions of the basin or sub-basin appear to have a thinner sandstone-dominated sequence at the base of the unit and grade upward into a mainly fine-grained sequence of predominately red siltstone and mudrock.

Locally there are younger successions of conglomerate, sandstone, siltstone, shale and minor limestone (and rarely gypsum) overlying the Cheverie Formation. In these cases deposition continued to occur in unfilled basinal depressions prior to Windsor Group deposition, with only minor erosion taking place along the unconformable contact with the basal Windsor Group.

Correlation of the Horton Group

Regional correlation of the Horton Group lithostratigraphy is pinned on two strong marker horizons: (1) the widespread lacustrine strata of the middle Horton (including the Middle Horton Bluff, Albert, Strathlorne, Snakes Bight-Frair's Cove; Fig. 4), and (2) the basal Windsor carbonate representing the basin-wide transgression of the Windsor Sea. These horizons are lithologically distinct and widespread. Utting *et al.* (1989) further suggest that these horizons are good chronostratigraphic markers on the basis of palynology.

It should be noted that the although the Horton Group can be viewed as a second-order sequence or an allocycle in the sequence stratigraphy or tectonostratigraphic sense, there are problems with interpreting the strata in this way. Varying degrees of angularity along unconformities in seismic profiles can lead to inclusion of formations in sequences to which they do not belong stratigraphically. Sequence boundaries are useful on a local scale but have little regional significance. Contacts may appear to be conformable on a local scale but on a regional scale there is often a disconformity and even an angular unconformity at these contacts. In cases of conflicting evidence between seismic-based sequence stratigraphy and stratigraphy based on outcrop and paleontological evidence, it is prudent to accept the exposed stratigraphy over the interpretive geophysics.

The two markers form the most convincing correlation ties throughout the basin and, therefore, the units between them must be correlative. Comparison of the various local formations show a remarkable consistency of the overall succession across the basin. The tripartite subdivision of the Horton Group is tenable, although local variations of lithology are to be expected given the variations in the local source areas. In many areas in the basin there is an angular unconformity between the middle and the upper Horton Group and also with the underlying pre-Horton Devonian strata. Martel (1990) and Hamblin and Rust (1989) also noted the consistency of the three-stage stratigraphy of the Horton Group in the Maritimes Basin.

Uranium Occurrences

In the area near Windsor there are numerous uranium occurrences. The most notable is found at Three Mile Plains, where Saarberg Interplan Canada Ltd. drilled numerous diamond-drill holes (Fig. 5). Significant uranium enrichment is restricted to two horizons: (1) the Glass Sand unit of the Upper Horton Bluff Formation and (2) the base of the Cheverie Formation. The uranium enrichment can be divided into two types: (1) carbon- and pyrite-related quartz sandstone type and (2) hematite arkosic sandstone type.

Carbon-Pyrite Quartz Sandstone Type (Horton Bluff Formation)

The Glass Sand unit occurs near the top of the sandstone-dominated upper section of the Upper Horton Bluff Formation (Bell,1929) (Hurd Creek Member of the Horton Bluff Formation of Martel and Gibling, 1996; Fig. 4). The unit is dominated by quartz-rich sandstone. The sandstone varies from very coarse grained to fine grained. The porosity of the sandstone ranges from 9-15% with permeabilities between 5 and 250 md. The most abundant bedforms are low-angle forsets and shallow trough cross-stratification. Multilateral, multistoried channel sequences form sandstone sheets up to 30 m thick. The bases of the individual channels are often made up of coarse pebbly quartz sandstone that has abundant plant detritus as lag material. Feldspar is rare but locally occurs as K-feldspar that has been almost completely kaolinized. Micas are noticeably absent in the sandstone. Thin interbeds of grey cross-laminated siltstone and shale (overbank deposits) occur within the sandstone bodies, which are underlain and overlain by lacustrine grey shale and siltstone. The environment of deposition for the unit is interpreted to be distributary channels within a lacustrine delta setting (Ryan, 1998). Ryan *et al.* (2005) suggest that the quartz-rich nature of the sandstone is the result of a monominerallic source area rather than a unique environment of deposition. Ryan *et al.* (2005) postulate that the Glass Sand unit is made up of detritus derived from

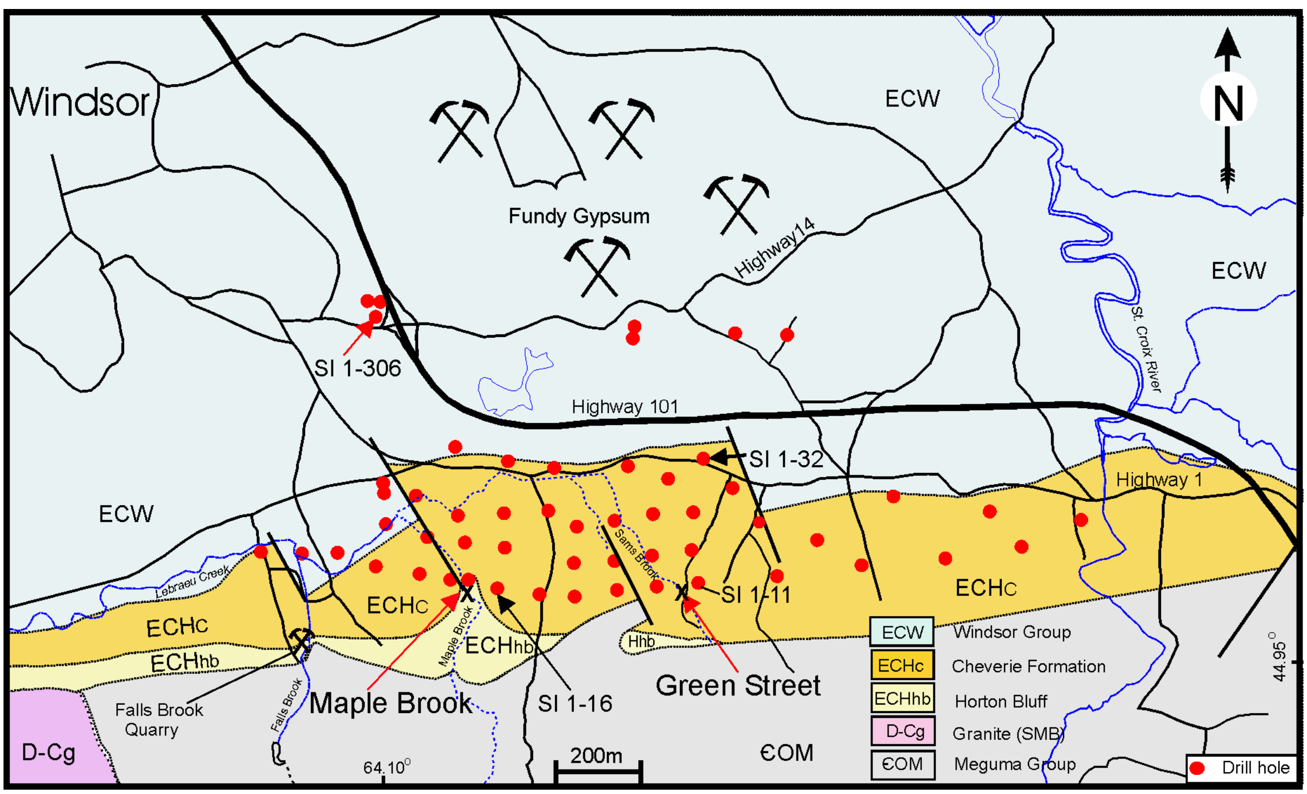

Figure 5. Geology map of the Three Mile Plains area near Windsor, Nova Scotia.

the upper levels of the pre-Carboniferous paleosaprolite in which the intensity of weathering resulted in only quartz-kaolinite remaining.

Uranium occurs in the Horton Bluff as very fine-grained uraninite enrichment associated with pyrite, which is inextricably related to carbon-rich horizons in the sandstone and shale. The presence of these reductants changes the valence state of the uranium to an insoluble U^{4+}state and deposits it at or near the reducing pyrite and/or carbon material. The uranium enrichment is related to reduction-oxidation fronts in the sandstone, but the paucity of iron-bearing minerals, and the re-reduction of the sandstones after uranium mineralization, obscures the classic red to grey boundaries often associated with this type of mineralization. There are, however, very subtle differences in the colour and carbon content of the oxidized versus the primary reduced sandstones. The oxidized sandstone appears to be bleached to a very light buff to light greyish-tan colour and only the larger plant fragments are preserved in the permeable sandstone. In contrast sandstone occurring down-dip in the drill core has abundant fine plant debris preserved in addition to large fragments, and is light- to medium-grey. Evidence for the redox front is often more clearly manifest in the nature of pyrite in the sandstone beds, with finer disseminated pyrite representing the re-reduced pyrite of the once reddened up-dip sandstone portion of the roll front, whereas the down-dip portions contain well-formed early diagenetic pyrite. Remobilization of some of the uranium by hydraulic redistribution is evident in some of the channel sequences, where the centre of the channel has less abundant uranium and the channel flanks have secondary up-channel flank rolls.

The best documented occurrence of the carbon-pyrite quartz-sandstone redox type is at Maple Brook in Three Mile Plains area (Fig. 5) where bedrock samples from trenches contained up to 555 ppm uranium. In Saarberg Interplan's drillhole SI 1-16, adjacent to the trench anomaly, it is apparent that the uranium is tied up primarily in organic-rich fine-grained shale above and below the sandstone, which contains lesser amounts of uranium (Fig. 6), indicating that the roll front has passed beyond this intersection. Gamma logs of this and adjacent drillholes exhibit the classic double spike anomalies up-dip of the roll fronts. There are only rare examples of the classic broad anomaly in the sandstone ahead of the roll front, in the remote seepage zone at this locality. The uranium is associated with smokey quartz and pyrite, but the grey colour of the sandstone makes identification of the smoky quartz horizons tedious. The uranium concentrations rarely exceed 500 ppm in these beds and are, therefore, probably sub-economic. The U-rich zones do have significant environmental implications. It should be noted that Morse and Harder (1979) found that the bedrock contained less uranium than predicted from radioactivity measurements, suggesting a strong disequilibrium. This is consistent with leaching of the uranium, leaving the radium series behind as the roll fronts migrate.

Hematite Arkosic Sandstone Type (Cheverie Formation)

Uranium occurrences in the Cheverie Formation are restricted to the lower, thick arkosic sandstone, siltstone and pebbly conglomerate. The arkosic sandstone is best described as granite wash, with feldspar representing up to 25% of the rock. The sandstones are multilateral, multistoried channel sandstone sheet bodies up to 20 m thick. Coarse sandstone generally exhibits only crude fining-upward cycles. The ratio of sandstone to siltstone or shale is approximately 8 to 1 in the Windsor area. The most abundant bedforms in sandstone are large scale (up to 10 m wide) trough crossbeds. The sandstones are variably micaceous with flakes of biotite and muscovite present. Carbon plant material is present but much less abundant than in sandstone of the middle Horton. The overbank siltstone and mudrock are generally red or green, although grey beds also occur. The green and grey fine-grained beds are often mottled with red. Rip-up clasts of the fine-grained overbank strata up to 5 cm in diameter are often incorporated into the arkosic sandstone units. The lower sandstone-dominated portion of the Cheverie Formation is interpreted as lower alluvial fan deposits from a braided stream (Ryan, 1998).

In the drillholes pyrite, and to a lesser extent marcasite, is common near the uranium-rich zones, but iron sulphides are rare in the coeval strata elsewhere. In outcrop at the Green Street uranium occurrence (Figs. 5 and 7) the sulphides have been

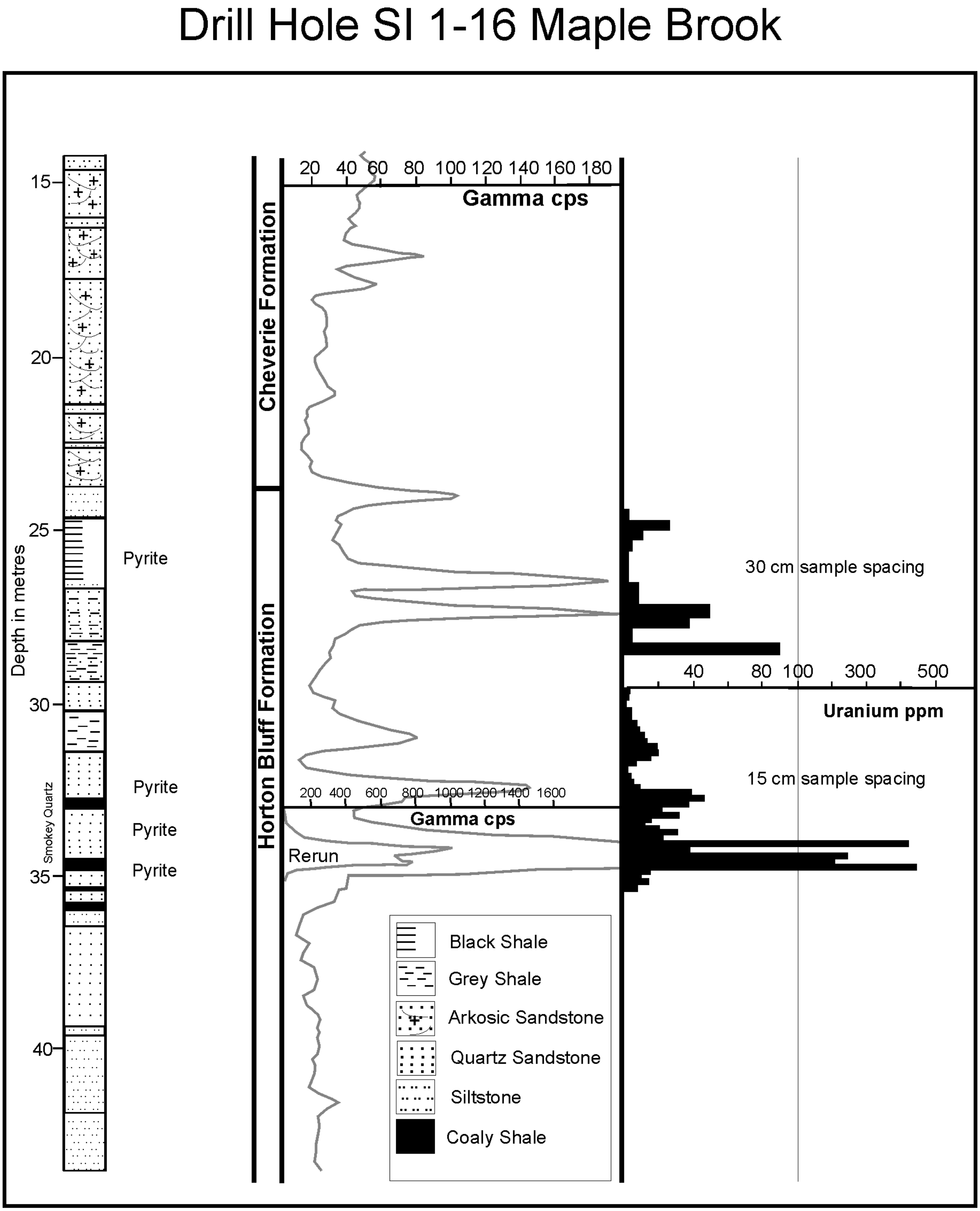

Figure 6. A portion of drillhole SI 1-16, drilled into the uranium occurrence at Maple Brook, Three Mile Plains. Note the double spike gamma anomalies associated with organic-rich fine-grained intervals.

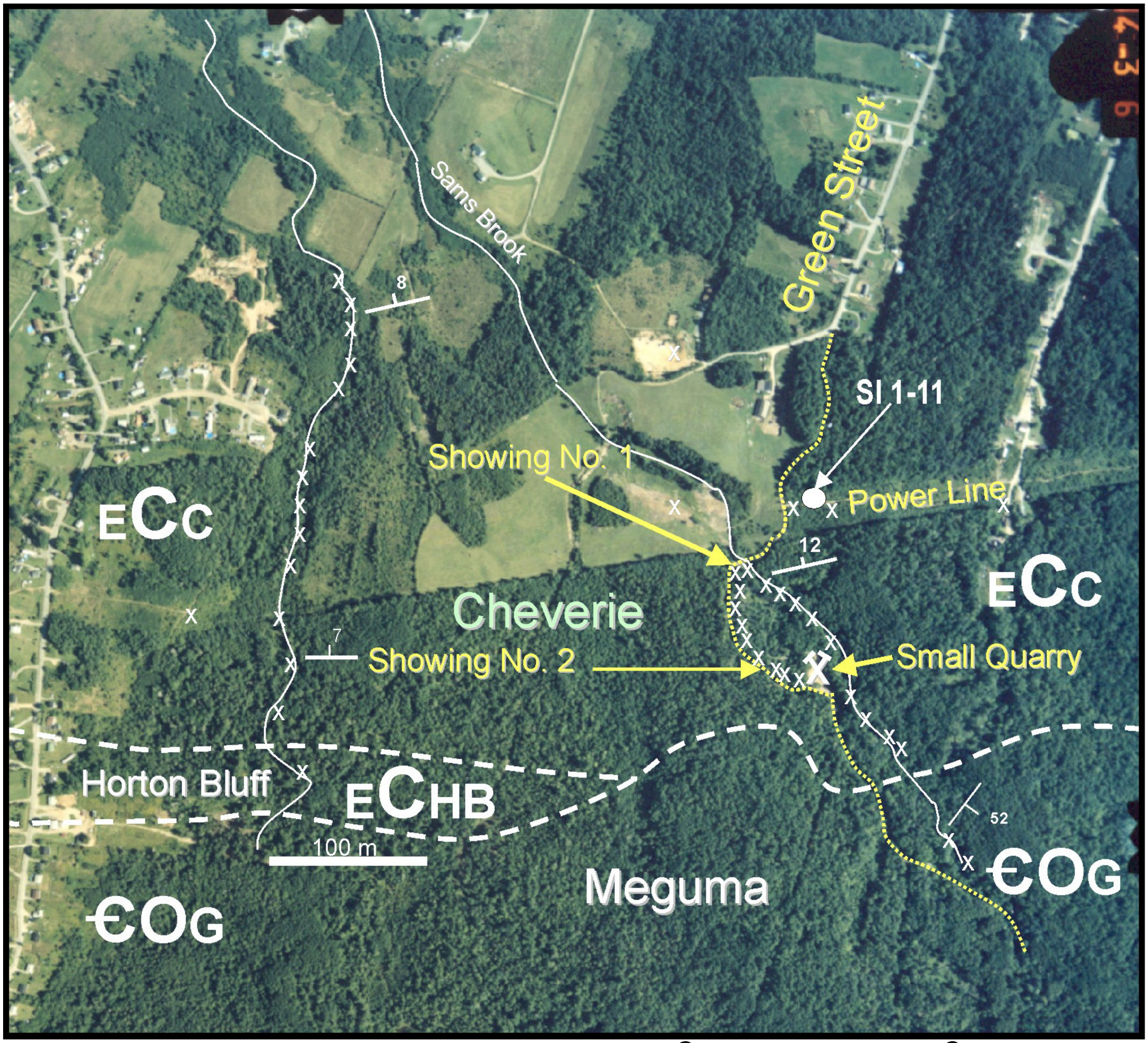

Figure 7. Detailed location of the Green Street uranium occurrence. ECC =Cheverie Formation; ECHB = Horton Bluff Formation; COG = Goldenville Formation.

oxidized and iron oxide staining is pervasive. The persistence of iron oxides near the uranium enrichment can also be observed in diamond-drill hole SI 1-11 (Fig. 8) adjacent to the Green Street occurrence (Fig. 7). Pyrite most often occurs as fine disseminated crystals in silty units, whereas marcasite and pyrite occur as larger amorphous blebs above and below the uranium-rich zones. Immediately adjacent to the uranium, hematization of the strata is common. In addition to hematite around the iron sulphides, biotite is also altered and iron released by weathering forms iron oxides that migrate at grain boundaries and along internal fracture surfaces. The presence of uranium enrichment associated with these hematized biotites is evident in the fission track distribution of the altered grains (Fig. 9).

In granitoid saprolites below the Horton unconformity, biotite is are completely weathered to clay within centimetres of the fresh granite. The arkosic nature of the Cheverie Formation, with its fresh K-feldspar and variably weathered biotite, and the completely weathered nature of the plagioclase feldspars, indicates the source area was only incipiently weathered, in contrast to the weathered source area of the Horton Bluff. K-

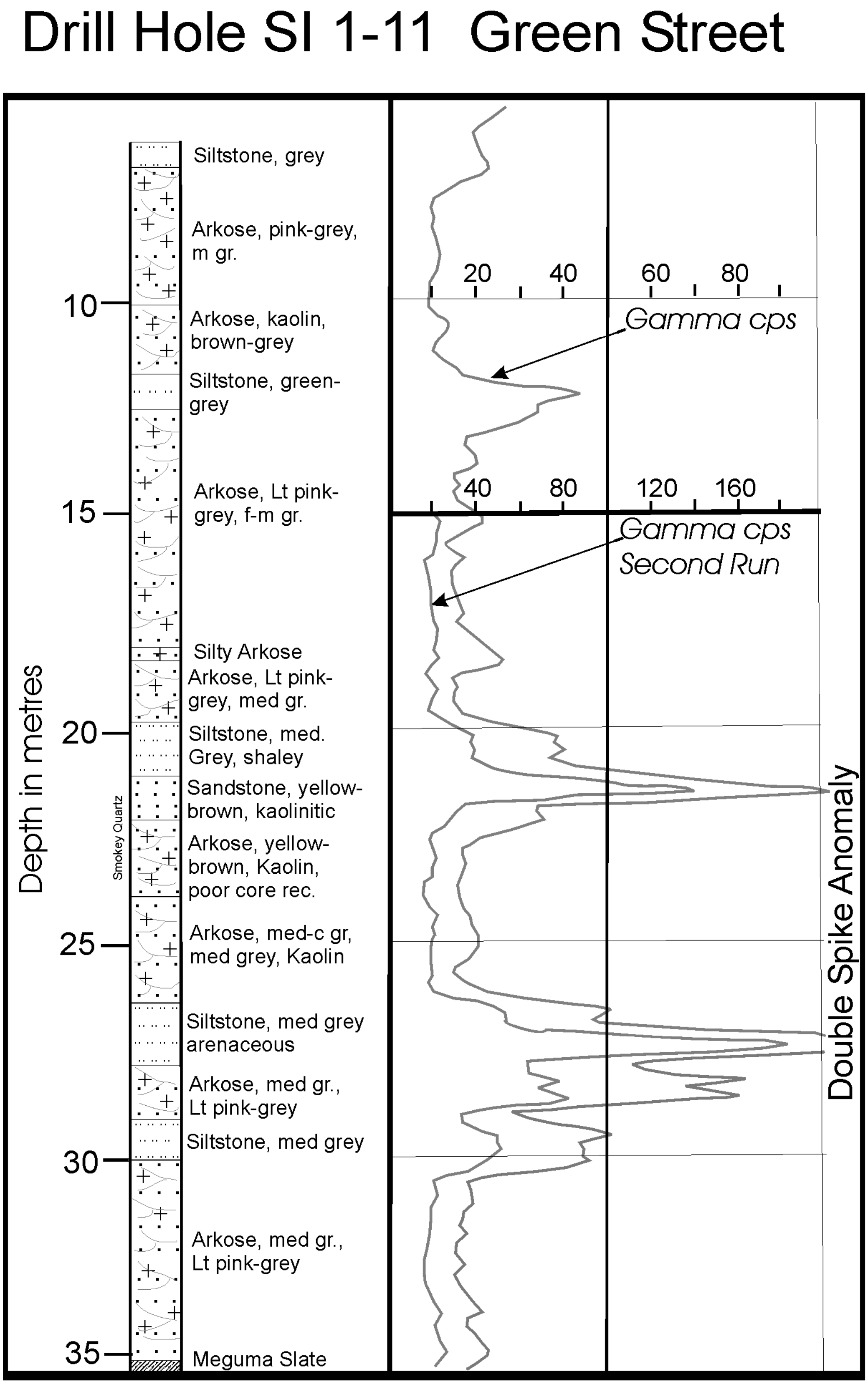

Figure 8. A portion of drillhole SI 1-11 at Green Street uranium occurrence. Note the classic double spike anomaly in the gamma log.

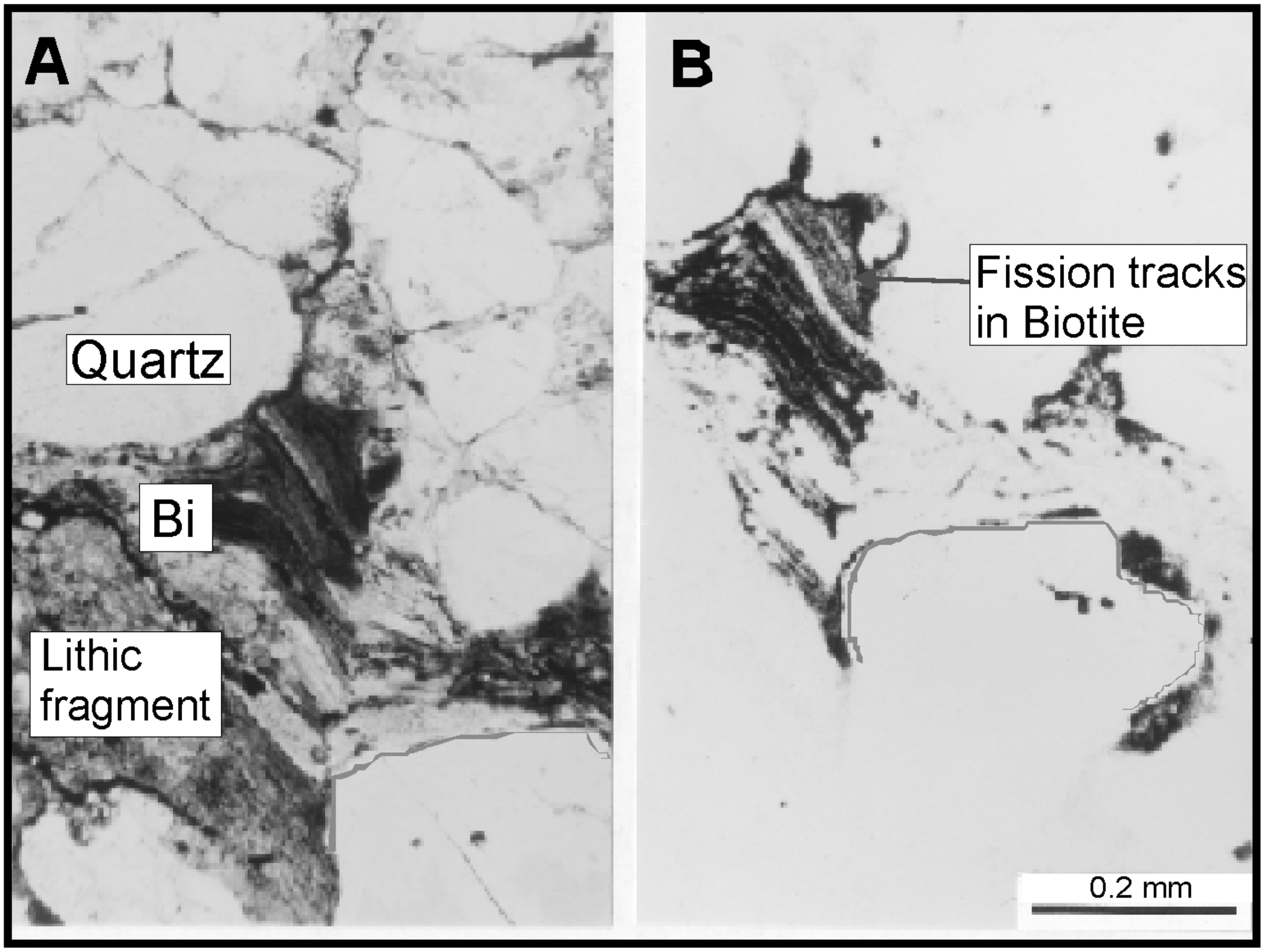

Figure 9. (A) Plain light photomicrograph of biotite in arkosic sandstone at the Green Street occurrence. The outline on grain boundary in A corresponds with the grain boundary on B. (B) Photomicrograph of the fission tracks created by irradiating sample A; the darkest areas represent the abundance of uranium. Note that the uranium is most abundant in the biotite grain and that it occurs along planes of weakness in the partially weathered biotite.

feldspar grains are reddened and quartz grains adjacent to the mineralized zones take on a smoky grey appearance. Above and below the mineralized sandstone, arkosic units have more abundant dolomitic cement, whereas within the mineralized zones carbonates occur primarily as thin dolomitic-calcite veins along fracture fills. It is unclear what relationship, if any, the carbonates have to the mineralization except that carbonate cements may lessen the permeability of the sandstone host rocks. Carbonates occur associated with the roll fronts in the Shirley Basin in Wyoming (Harshman, 1968), although a genetic link to the mineralization has not been clearly established. Although most of the fine-grained beds in the upper Cheverie Formation are usually green or red, siltstone near the mineralized horizons is usually grey. The grey colour of the siltstones probably indicates the presence of organic carbon that may have acted as a reductant.

The roll-front nature of uranium enrichment in sandstone is shown by the characteristic double spike gamma ray anomalies behind the roll front (Figs. 8 and 10). The presence of broad anomalies related to the proximal seepage zone in front of the reduction-oxidation boundary are present in drillhole SI 1-306 (Fig. 10). Gamma logs for this Saarberg Interplan drillhole exhibit excellent examples of these features in two stacked sandstone bodies within the same profile, a result of differential migration due to permeability variations (Fig. 10). At a depth of 245 m and at 251 m the double spike gamma anomaly signature, similar to that observed in drillhole SI 1-11

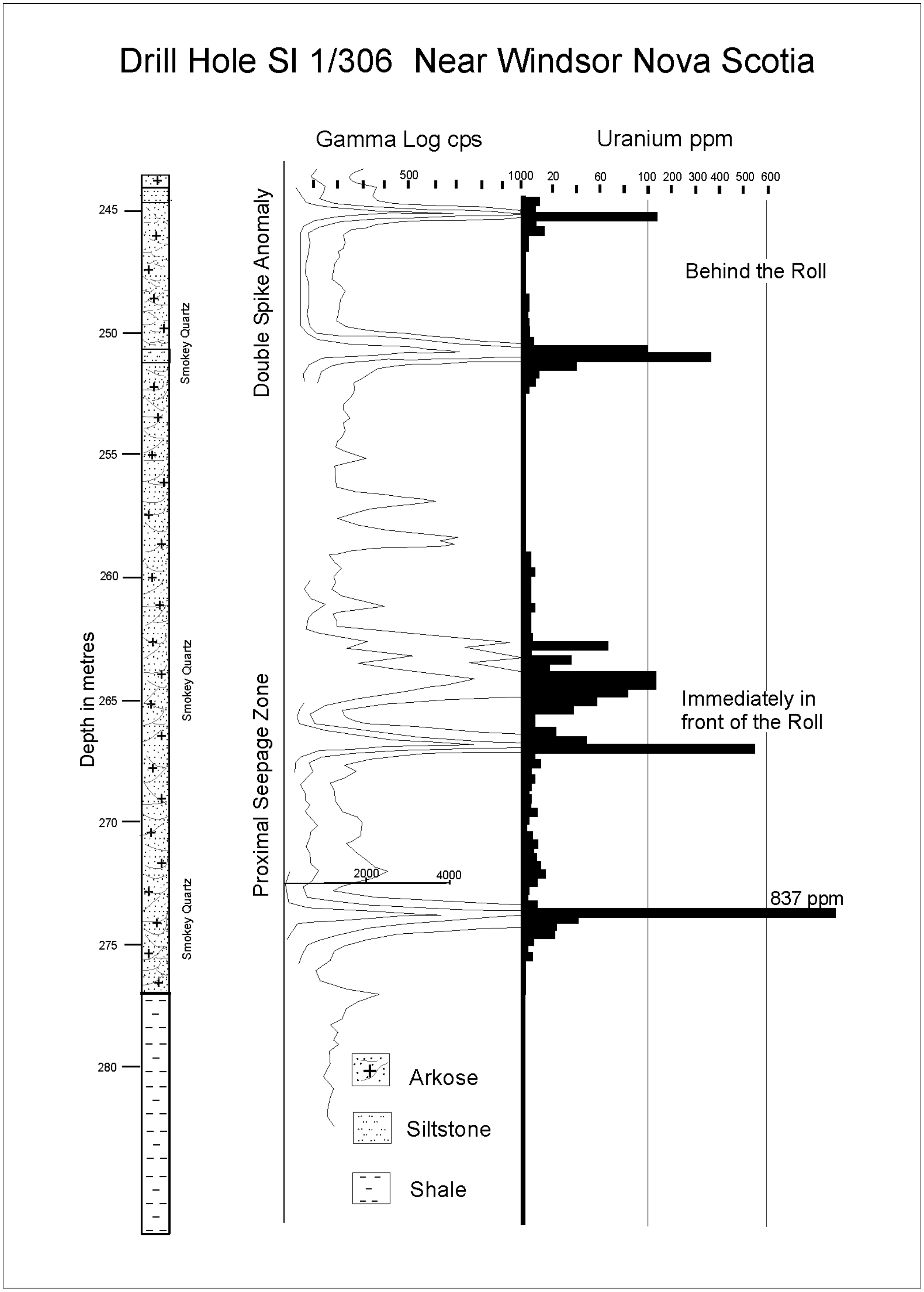

Figure 10. A portion of the log for Saarberg Interplan Canada's drillhole SI 1-306, near Windsor, Nova Scotia. Note that the upper mineralized intervals represent a classic (behind the roll front) double spike anomaly, whereas the lower mineralized interval has broad anomalies within the sandstone unit and represents a proximal seepage zone.

(Fig. 8), can be seen at the top and bottom of an arkosic sandstone interval. The peaks in SI 1-306 contain between 150 and 380 ppm uranium over 30 to 90 cm intervals, with minimal enrichment of uranium in the central portion of the sandstone unit (Fig. 10). These are interpreted to represent remnant mineralization left behind the roll front as tails, primarily at the contact with reducing fine-grained beds. At the interval between 263 m and 275 m there are multiple broad peaks on the gamma log that correspond to elevated uranium in the central portion of a sandstone unit rather than at its upper and lower extremities, as in the shallower double spike peaks (Fig. 10). There are several metres of sandstone ranging from 15 to 100 ppm uranium and 30 cm spikes between 520 to 837 ppm uranium. The interval is considered to represent a proximal seepage zone where the drillhole intersection penetrated immediately in front of the main portion of the roll front.

The classic colour boundaries between oxidized and reduced sandstones are not evident in the case of most arkosic sandstones. On close inspection, the oxidized portions of the sandstone are slightly more reddened with minor hematite and there is an intensification of the pinkish-red colour of the potassium feldspar as a result of irradiation caused by the passing uranium roll front. In many instances hematite has been re-reduced to form fine disseminated pyrite. In the case of drillhole SI 1-306, however, indications are that it is an active proximal roll and, therefore, the hematite remains unchanged. Drillhole SI 1-32 (Fig. 11) is down-dip from the Green Street occurrence and drillhole SI 1-11, and in this case uranium occurs in the middle portion of a thick sandstone unit (between 35 and 46 m). In addition, the logs exhibit a classic double spike anomaly in relation to the overlying and underlying fine-grained beds. SI 1-32 is interpreted as penetrating the sandstone just behind the roll front (Fig. 11). Figure 12 is not a cross-section but rather a diagram hypothetically placing the observed drillhole results into position relative to expected gamma log characteristics for any given uranium roll front. The gamma log characteristics represent the most useful information for the determination of the position of the drillhole in relation to the roll front. Care must be taken to make sure that the comparisons as to position of the drillholes in relation to any particular roll front are restricted to an individual sandstone aquifer. To establish the continuity of sandstone bodies a detailed stratigraphic and sedimentologic correlation is essential.

The fine disseminated pyrite oxidizes very quickly when exposed at surface and mineralized outcrops, such as the Green Street occurrence, do not contain any visible pyrite, although nearby drillholes of the same unit contain intact disseminated pyrite.

Connection between Saprolites and Uranium Mineralization

There appears to be a direct correlation between uranium enrichment in the basement rocks and the abundance of uranium occurrences in the overlying and adjacent basin fill strata in the Maritimes Basin area (Fig. 1). It is not surprising, therefore, that the majority of the uranium showings in the Horton Group occur in the Windsor area of the Maritimes Basin. Paleocurrent data from Horton Group rocks in the Windsor area indicate a predominantly northeasterly paleoflow into the basin. This is consistent with contributions to the basin fill material from the mineralized area near Millet Brook in the South Mountain Batholith. O'Beirne-Ryan and Zentilli (2003) have demonstrated that there are pre-Carboniferous paleoweathered horizons on the granitoid rocks of the South Mountain Batholith in the area adjacent to Three Mile Plains (Fig. 2). The pre-Carboniferous weathered profiles found in the area differ in appearance from the younger saprolites (pre-Triassic and pre-Pliestocene) and represent the oldest weathering event. The pre-Carboniferous paleoweathered surfaces have been relithified as a result of subsequent burial by as much as 5 km of Carboniferous sedimentary strata (Ryan and Zentilli, 1993). The relithification results in an indurated rock of granitoid composition and granite-like texture. On closer examination, however, it is clear that the individual grains are more rounded than the parent granite and that biotite is absent in all but the least weathered material. O'Beirne-Ryan and Zentilli (2003) point out that these horizons no longer exhibit isovolumetric weathering and, therefore, are no longer "saprolites" *senso stricto*. Lidmar-

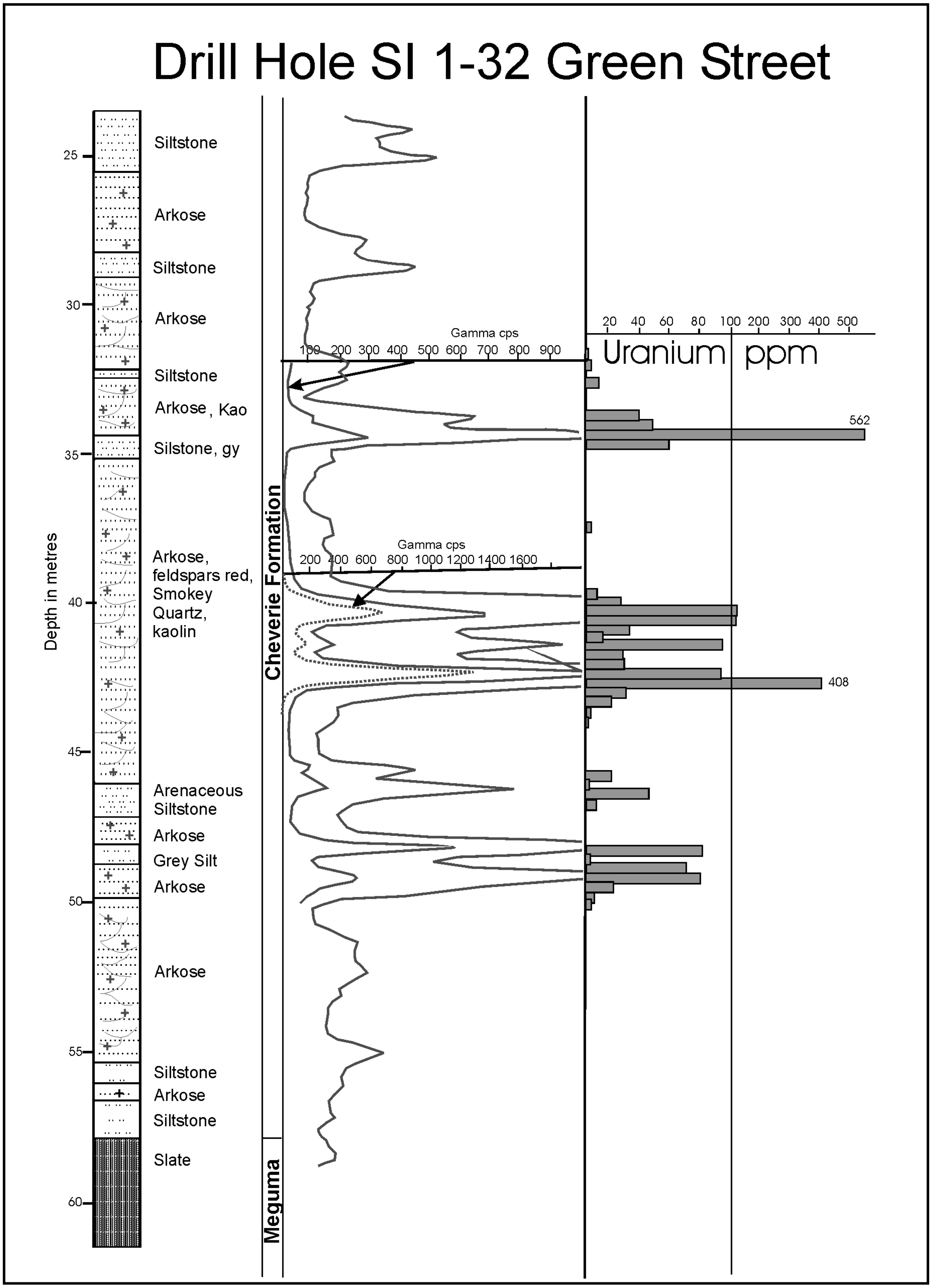

Figure 11. A partial log of drillhole SI 1-32 down-dip of the Green Street uranium occurrence. The mineralized interval in this hole has a double spike and a central sandstone anomaly as well, indicating that the intersection is immediately behind the roll front.

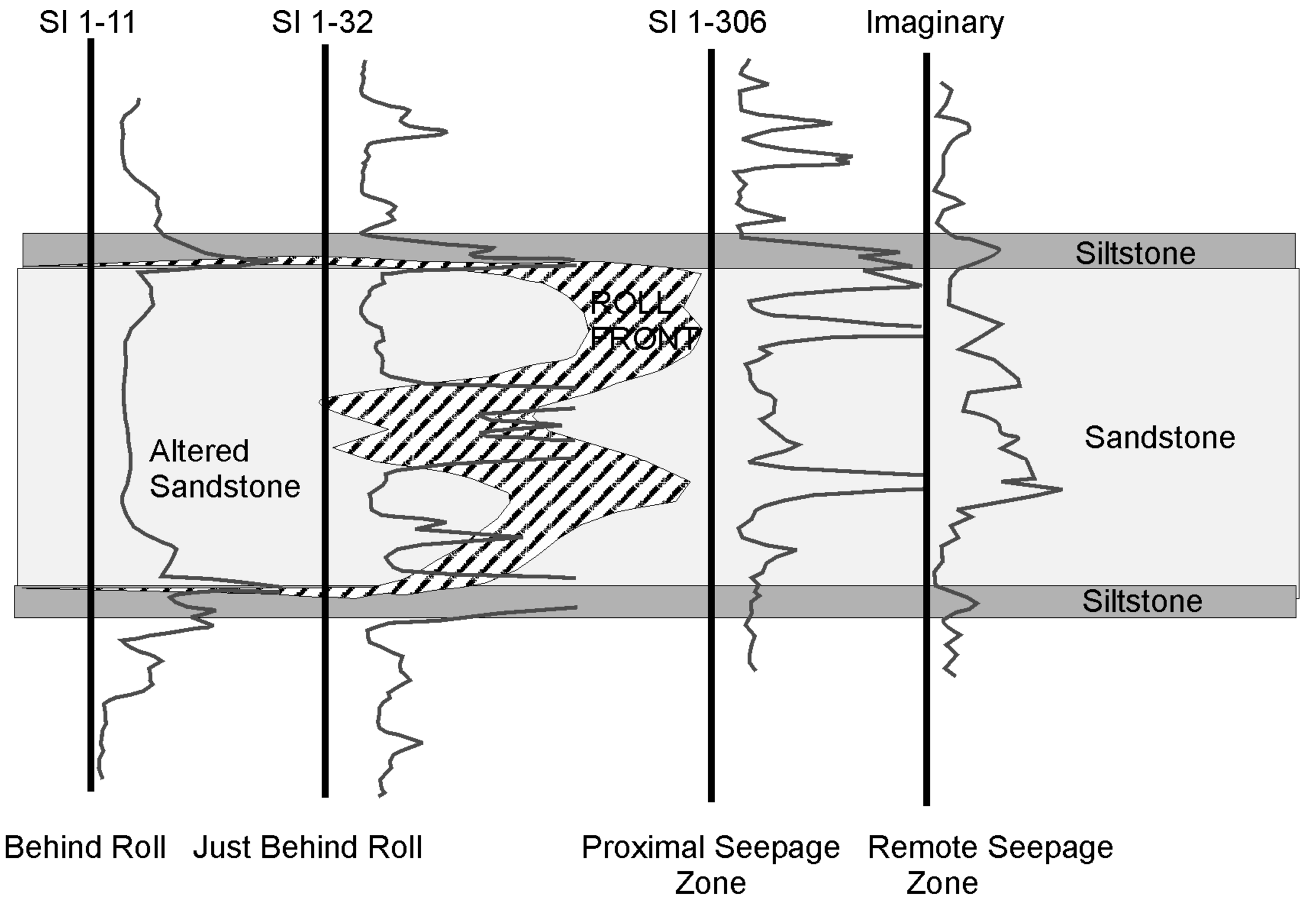

Figure 12. This figure is not a cross-section. The figure shows the relative position of the drillholes to a roll front. The gamma logs for drillholes 1-11, 1-32 and 1-306 are approximately correct although some minor adjustments of the depth scale were undertaken to accommodate the diagram. The gamma intensity scales are approximately equal. The fourth hole is imaginary as the Saarberg Interplan drilling was predominantly up-dip of the roll fronts.

Bergstrom *et al.* (1997) have described similar relithified saprolites from paleosurfaces in Sweden ranging in age from Cambrian to Cretaceous. There are some interesting implications of pre-Carboniferous weathering in regard to exhumation of the South Mountain Batholith. The circa 380 Ma batholith must have been exhumed from 8-12 km depth and exposed for a sufficient time for saprolite to develop, and all of this must have happened prior to deposition of the overlying strata which are as old as 355 Ma. Similar pre-Carboniferous saprolites also occur in south-central Cape Breton Island, Nova Scotia, and southeastern New Brunswick, suggesting a regional scale pre-Carboniferous weathering event (Ryan *et al.,* 2005).

It is noteworthy that biotite, which originally contained uranium (Fig. 9), has been completely weathered out in the upper portions of the paleoweathered horizon. It is logical to assume that the weathering process liberated significant quantities of uranium. In addition, where biotites have not been completely weathered significant changes have occurred within the biotite grains even at early stages of weathering, resulting in uranium being more susceptible to leaching (O'Beirne-Ryan and Zentilli, 2003).

Preliminary geochemistry of the pre-Carboniferous saprolite profiles (Fig. 13) indicates that uranium is mobilized by weathering. During moderate weathering the uranium increases, probably the result of remobilization within the weathering profile. In the case of more intense weathering there is more than a 40% depletion of uranium relative to the fresh granite, reflecting the destruction of biotite and other ferro-magnesium silicates in the saprolites. In addition to the chemical and mineralogical changes in the

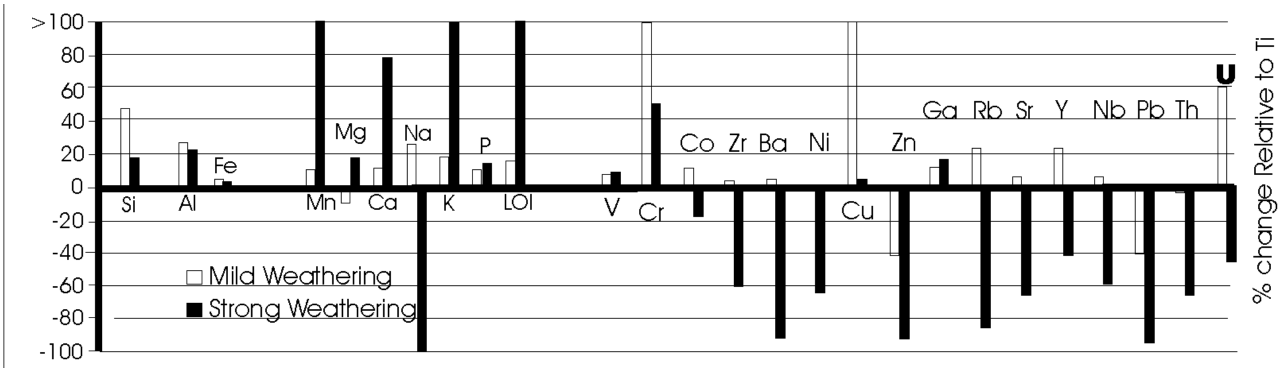

Figure 13. Relative depletion-enrichment geochemical diagram for Pre-Carboniferous saprolite from drillhole 4 km northwest of the Three Mile Plains area. The fresh granitoid represents the zero line with depletion in percent below the line and enrichments above the line, after O'Beirne-Ryan and Zentilli (2006).

weathered horizons there is also a coincident increase in the porosity and permeability of the these saprolites and, therefore, they become preferred conduits for fluid flow.

Environmental Implications

The initial exploration and subsequent drilling in the Three Mile Plains area was sparked by the discovery of radon anomalies in soil gas and well waters in the area. In addition, uranium and radium in well waters were weakly anomalous in the area. It is not difficult to infer that there are environmental implications of these uranium occurrences. There are two radon in soil gas anomaly areas at Three Mile Plains (Fig. 14), one of which occurs immediately north-northwest and downslope (downstream) of the Green Street uranium occurrences, the other north of the Maple Brook occurrence.

Kronfeld *et al.* (2004) studied uranium series isotopes in the Avon Valley area to the west and southwest of the Three Mile Plains area. Their study found that uranium concentration in ground and surface waters was generally low, except immediately adjacent to weathering uranium occurrences in the Millet Brook area. Radon, however, was generally slightly anomalous throughout the area, suggesting continual degassing from uranium-enriched bedrock. Kronfeld *et al.* (2004) suggested that this may be due to constant flushing. In this way the relatively high precipitation rates in the region and the high permeabilities of the sandstone aquifers in the Horton Group may account for the wide distribution of radon in well waters. Page (1999) found a strong positive correlation of dissolved uranium and radon in the Saarberg Interplan sample set, studied from water derived primarily from the Horton Group aquifers, in contrast to the lack of correlation in the Kronfeld *et al.* (2004) data from the Avon River study, which included water from the South Mountain Batholith as well as the Carboniferous basin fill units. The samples compiled by Page (1999) were collected by Saarberg Interplan Canada Ltd. with great care taken to minimize degassing effects within the individual wells, suggesting that problems with the Avon Valley data may have been due to inappropriate sampling techniques. Johannessen (2001) explained that at the time of sampling there was a water shortage in the area, which precluded running water from the wells for an appropriate time interval before taking samples. Therefore, degassing of the radon would have been a possible source of error. Drilled wells generally have higher radon levels than dug wells, primarily due to degassing over a larger surface area. Some of the highest radon levels (up to 1777 Bq/L) in the Saarberg Interplan regional study, however, were from dug wells in the Three Mile Plains area (Morse and Harder, 1979). Morse and Harder (1979) indicate that the levels from the Windsor area study are comparable to studies they had undertaken in uranium-producing areas in Texas. The anomalous levels are in excess of 100 times greater than background levels established by Dyck *et al.* (1976) for Carboniferous rocks elsewhere in the Maritimes Basin. The existence of any radium in well water above the detection limit of 8 piC/L

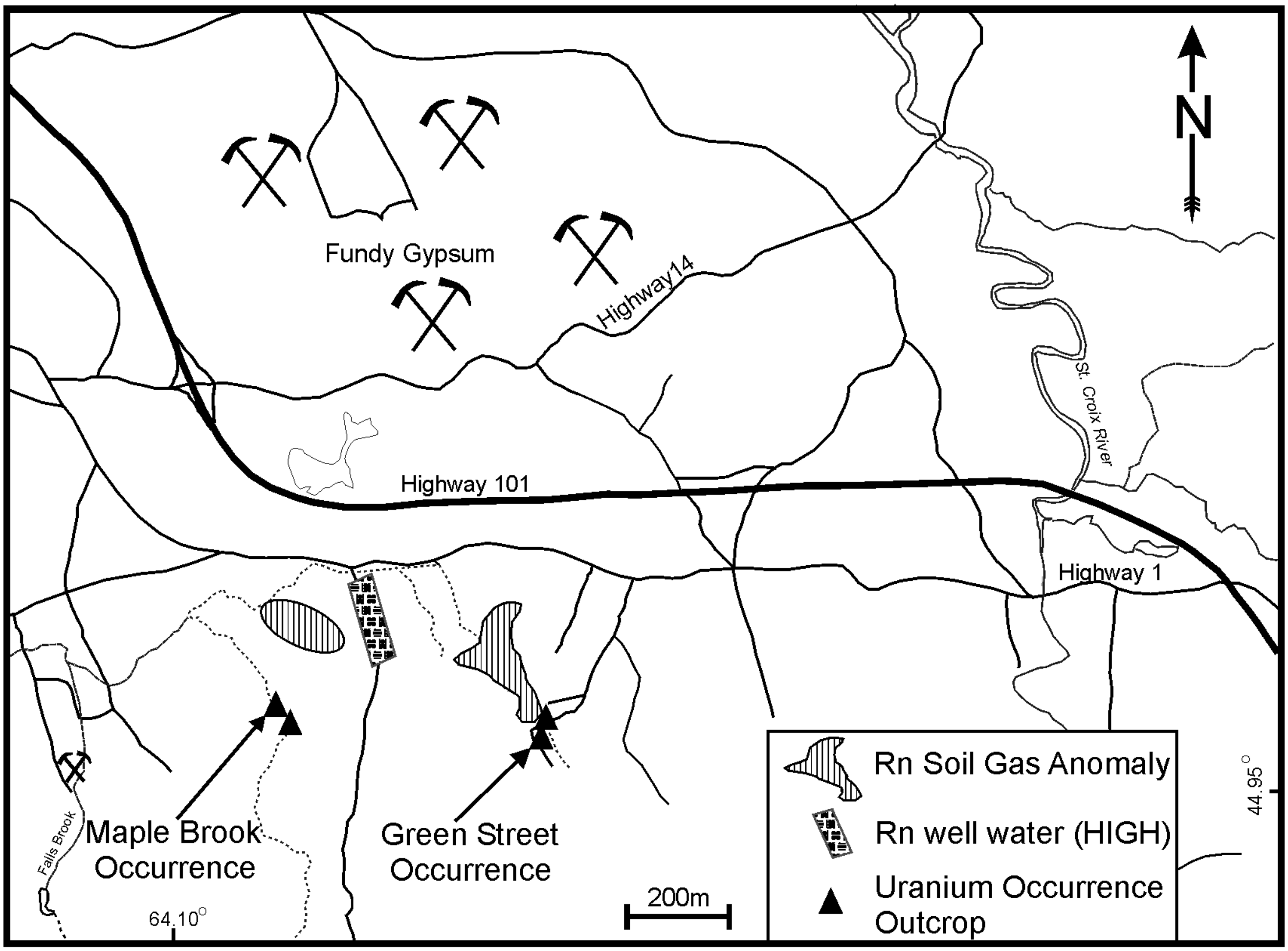

Figure 14. Location map of radon soil anomalies and radon in well water anomalies in the Three Mile Plains area, near Windsor, Nova Scotia.

was considered anomalous by Morse and Harder (1979). There are five radium readings above detection limits in the well waters in the area of the anomalous radon north of the Three Mile Plains occurrences (Page, 1999). Outside Three Mile Plains only three isolated radium readings above the detection limit were recorded in the remainder of the 2400 samples collected by Saarberg Interplan Canada Ltd. in the Carboniferous strata of Atlantic Canada. This, however, may be the result of sampling bias, as sampling focused on the areas held under uranium exploration license by the company at the time of the survey.

Interestingly, there were radon soil gas and well water anomalies documented by Morse and Harder (1979) north of the West Branch of the Avon River along Mines Road, where drilling revealed no uranium the Horton Group strata. The drilling did intersect paleosaprolites under the Horton Group in the drillholes up-dip from radon anomalies. Page (1999) also found a moderate GIS correlation with faults and unconformities versus radon levels in the water wells. At the time of exploration-related studies in the 1970s and 1980s, there was an incomplete understanding of the paleoweathering surfaces below the Carboniferous strata in the Maritimes Basin and, therefore, no direct correlation to these was attempted. The presence of radon and radium anomalies associated with pre-Carboniferous saprolites in the Mines Road area, in the absence of roll-front mineralization in the area, clearly demonstrates that areas near these saprolite horizons must also be examined for potential high levels of uranium, radon and radium.

One aspect of the uranium and radon impacts on the environment that is not clearly understood is the rate and quantity of uranium and radon contributed to surface- and groundwater from mineralized outcrops. A study (B.Sc. Honors supervised by the authors) is under way to determine how much uranium can be leached under various conditions from uranium-bearing samples collected at the Green Street occurrence. This leaching study should aid in assessing environmental implications of similar uranium occurrences

Conclusions

Although this paper deals primarily with uranium and associated elements from occurrences in the Windsor area of Nova Scotia, the regional nature of the pre-Carboniferous weathering episode and the areal extent of the Horton Group strata throughout eastern Canada would seem to imply that the environmental issues related to the uranium mineralization might exist throughout the Maritimes Basin. This may be of particular note in areas that have elevated uranium levels in granitoid basement rocks adjacent to the Carboniferous basin fill.

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