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DEVELOPMENT OF URANIUM EXPLORATION METHODS
USING RADON

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ABSTRACT

This report gives the results of tests carried out during the 1968 field season to determine the applicability of the radon method for detailed prospecting for uranium. Radon tests in surface waters and in soils were carried out in three different geological environments; the Gatineau Hills, Quebec, and Sudbury and Elliot Lake, Ontario.

In the Gatineau Hills, seasonal variations, variations with depth of lake, with distance from shore, and with distance from uranium occurrence along shore, were studied. The results suggest that surface and underground water drainage is responsible for the radon and radium in the lake systems.

Where the overburden is one or two feet thick on-site radon and thoron determinations in soil emanations in the Gatineau Hills outlined radioactive pegmatites somewhat more clearly than did gamma-ray tests. Although radon levels varied by a factor of two, anomalies related to source were detected throughout the field season.

A radon anomaly, detected in a reconnaissance survey of the surface waters of the eastern quarter of the Sudbury irruptive, appears to be similar in origin to the anomalies investigated in the Gatineau Hills.

Radon and gamma-ray levels across the copper-nickel ore borders were comparatively low and meaningless.

In the Elliot Lake area the distribution of radon in four lakes was studied; two in the contaminated westward drainage channel of the southern limb of the Quirke syncline, and two in uncontaminated terrain overlying the uranium-ore-bearing Matinenda Formation. The results from the contaminated lakes demonstrate some of the principles of the radon prospecting method very well except for the fact that man, rather than nature, introduced the radium which gives rise to the high radon levels in the water system. The radon levels in the uncontaminated lakes are at least a factor of ten lower than in the contaminated lakes, and straddle the sensitivity limit of the instrument. Some shallow creek deltas are reflected in the radon profiles 50 feet from the mouth of the creek and hence could serve as starting points for regional investigations. Relative to the lakes in the Gatineau Hills, the radon levels in the two uncontaminated lakes in the Elliot Lake region are low. Regional backgrounds, rather than absolute radon levels, must therefore be employed to determine anomalies.

On-site radon determinations in soil emanations across the uranium ore zone at the Rio Algom Quirke Mine outline the ore zone more distinctly than do gamma-ray determinations. Soil tests across the projected contact of the Matinenda Formation in the southern limb of the Quirke syncline gave a negative anomaly at the contact.

In general the investigations have shown that depending on the medium and sampling density employed, the radon method can outline radioactive sources on a reconnaissance scale as well as on a more detailed scale.

DEVELOPMENT OF URANIUM EXPLORATION METHODS
USING RADON

INTRODUCTION

The positive correlation between natural uranium occurrences and radon concentrations in surface waters and soil emanations observed in the Bancroft and Ottawa - Hull regions during the 1967 field season (Dyck and Smith, 1968; Dyck, 1968) were encouraging enough to warrant more detailed studies of the behaviour of radon in natural environments. Factors such as concentration level changes — in particular with respect to background levels, optimum sampling density, time, and position, are important to the success of an exploration technique. The isotopes of radon of mass 222, 220, and 219, commonly known as radon, thoron and actinon, are radioactive members of the naturally radioactive series uranium-238, thorium-232, and uranium-235, respectively. All three are gases at conditions prevailing in natural environments, and hence much more mobile than the other members of the series thus making it easy to separate them from the other members of the series for purposes of detection and identification. More important, the radon transfers easily from the surface of solids to the air or natural waters where its mobility is greatly increased. Thus, in the case of surface waters, radon may be carried appreciable distances by turbulence at the surface of lakes or by the natural flow of rivers. Loss of radon by decay and by degassing limits the range of radon to several hundred feet. Only the 3.8-day radon-222 can reach such distances; thoron and actinon, with half-lives of 55 seconds and 4 seconds, will disappear within about five minutes and 20 seconds respectively after leaving the sources. The elements of the radioactive series, like many elements of economic importance, enter the natural water systems in ionic form or as finely suspended solids. Eventually these ions are adsorbed and deposited with the suspended matter on stream and lake bottoms. The concentration of radon in the water is thus a measure of the radium concentration in the sediments nearby, and therefore an indicator of uranium in the surrounding area.

One of the most important factors in radon prospecting studies is the proportion of groundwater in the water bodies under investigation. It has been known for a very long time that many groundwater regimes contain high radon concentrations. In fact, the concentration is often much higher than the theoretical value calculated from the observed radium concentrations in the water and the host rock (Smith et al., 1961; Kuroda, 1955; Kerry et al., 1966; Kulakova, 1966). Kuroda suggests that radon and thoron enter the water from the tufa deposits accumulated near the orifices of hot springs in Japan shortly prior to issue. Radium adsorption on the walls of

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fractures through which the water moves is thought to be responsible for the radon enrichment according to Kulakova. Results of radon and radium analyses of half a dozen well and spring waters by the writer are in line with the findings of the above workers. A prospector employing the radon method in search for uranium, will have to bear this fact in mind constantly, particularly in the case of streams and creeks, because they are so closely connected with groundwater. Surface lake waters are further removed, both in time and space from groundwaters and hence can be expected to have lower radon concentrations. As a rough guide average relative radon levels of 1 for lakes, 10 for streams, and 1,000 for wells or springs are equivalent in terms of uranium concentrations in a juvenile landscape, like the Gatineau Hills. However, landscape, the nature of the underground and surface water regimes, and solution properties of the radioactive minerals can considerably modify this.

The presence of radium in rocks and soils gives rise to radon in the soil-air. Radon concentrations in the soil will thus reflect the radium concentration in the soil and/or the rock below it, depending on the thickness of the soil. Much work has been carried out on the emanation of radon from soil. Thus, for example, the diffusion process can transport radon 12 feet in unconsolidated glacial debris and 26 feet in alluvium (Schroeder et al., 1965) in 40 days (the practical life expectancy of radon). The fact that a radon anomaly was observed at a distance of over 30 feet from the source (Wennervirta et al., 1960), suggests more rapid movement in certain cases, possibly through fissures in the rock. Capillary action could also be responsible for concentrating radium in surface layers of soils, and thus give rise to radon anomalies. Such enrichment of radon and thoron parents has been suggested by Israel and Bjornsson (1967) as a result of their investigations above faults.

Large variations in the radon concentration in the upper layers of the soil as a result of atmospheric variables, primarily moisture and barometric pressure fluctuations (Baranov, 1956; Kraner et al., 1964; Novikov and Kapkov, 1965; Pearson and Jones, 1966), make quantitative determinations of radon in soil difficult to interpret. A rapid survey method, giving relative radon levels, is probably more useful to the prospector than a quantitative but slower method.

This report summarizes investigations carried out during the 1968 field season. The behaviour of radon in natural waters and soils was studied in three different geological settings, the Gatineau Hills, Quebec, and Sudbury and Elliot Lake areas, Ontario. In lakes, radon concentrations as a function of distance along and from shore, of depth of lake, time of year, and geological environment, were determined. On-site determinations of radon and thoron in soil gas were carried out in order to test the applicability of the method for uranium prospecting, to determine optimum sampling frequency, and observe variation with season and environment.

ANALYTICAL AND SAMPLING METHODS

A detailed description of the apparatus and procedures for the analyses of radon in water and of radon-thoron emanations from soils is given elsewhere (Dyck, 1969).

The determination of radon in water involves degassing an aliquot of the sample with air, transferring this air to an evacuated zinc sulphide cell and counting the alpha activity of the air with a photomultiplier and scaler assembly. On-site radon-thoron emanations were determined with the same instrument using a cell modified in such a way as to permit the flow of soil gas through it. These gases were obtained from 1- or 2-foot deep holes punched into the soil with a needle bar. The gas was pumped through the cell with a rubber-bulb pump.

The method permitted the quantitative determination of radon in 30 to 40 water samples per man per day, with a practical lower detection limit of 1 or 2 pc/1 (picocuries/litre). A similar number of on-site determinations of alpha activity in soil emanations can be made with the modified cell.

Surface gamma-ray activity was measured with a scintillometer with a sensitivity of 20 counts per second/microroentgen per hour.

The sampling density used is evident in the plots discussed in the text. In general the sampling density for water samples varied from 100 feet to about 800 feet along lake shores and between 20 and 100 feet perpendicular to shorelines. For soil survey work the sampling density was varied from 25 to 100 feet along the surface and from 1 foot to 2 feet with depth. Distances between sites were stepped off. Although this method was found to result in an error of up to 10 per cent in very irregular terrain, it was much quicker than chaining. Directions were established with a Brunton compass.

Tests showed that the greatest single error in the analytical method was due to the randomness of the radioactive decay. However, even this error was small in all but a few cases compared to the sampling error resulting from the inhomogeneity of the sample at a site. Radon concentrations in water at a site varied by as much as a factor of 5 (Dyck, 1969). Reproducibility tests with soil gases showed that the average deviation from the mean was about ± 30 per cent. Adding to these variables the atmospheric variables, the reader can readily see why many measurements are required to discover trends, or why only large anomalies are interpretable. An indication of the reproducibility obtainable in soil test is evident from the raw data shown in Table 1.

Table 1. Results of reproducibility and sampling method tests from traverse A located 250 feet east of No. 1 Rio Algom Quirke Mine shaft in the Elliot Lake region. Numbers in columns are alpha counts/min. obtained in the first successive 3 one-minute counting intervals after filling of cell.

Sample site	1-foot fresh holes August 29, 1968			2-foot fresh holes August 29, 1968			2-foot August 29 holes covered over night August 30, 1968		
00 S	311	246	275	423	400	333	900	944	991
25 S	151	88	78	213	171	137	262	204	235
50 S	78	56	25	76	46	19	121	67	66
75 S	91	45	27	151	81	81	179	127	115
100 S	158	113	79	200	136	123	285	260	228
125 S	30	44	9	135	79	57	151	101	50
150 S	70	52	35	136	98	70	157	96	86

Analysis of the data in Table 1 shows that on the average, fresh 2-foot-deep holes give a radon concentration 70 per cent lower than the same holes covered for a day. The 1-foot fresh holes give average radon concentrations of only 40 per cent of the concentrations observed in the 2-foot, old holes. A similar correspondence is evident in the results plotted in Figure 8.

OVERBURDEN   PEGMATITE   SCALE OF FEET

MARBLE   PYROXENITE   0   600

GNEISS   BIOTITE SCHIST   SOIL TRAVERSE
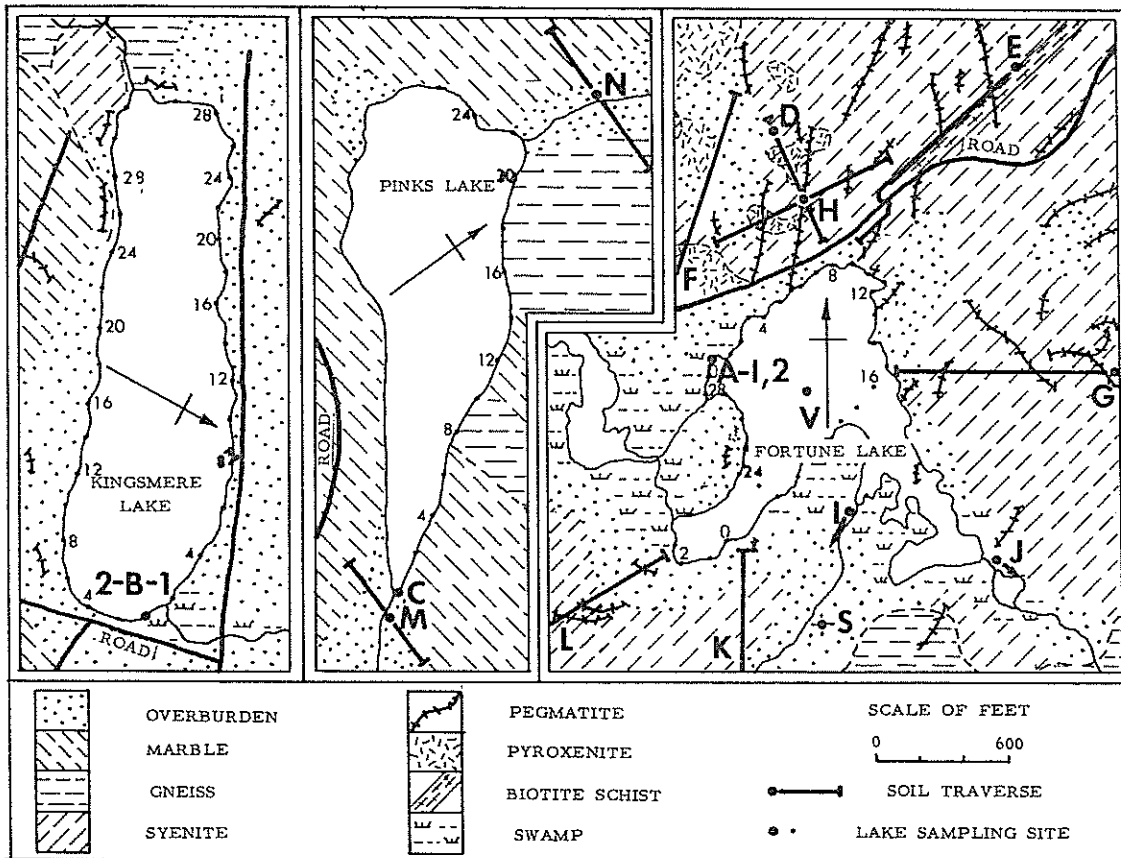
SYENITE   SWAMP   LAKE SAMPLING SITE

Figure 1.   Geology and radon sampling sites in the Gatineau Hills. Water sampling sites are shown by solid dots on the shores. Large dots indicate starting or zero position. Numbers along lake shores indicate distance from zero position in hundreds of feet. The location and direction of soil traverses are shown by heavy straight lines, except for the traverses around the shores of Kingsmere and Fortune lakes. These two coincide with the water sampling sites. Solid circles denote zero or starting position of a soil traverse. Capital letters near the zero position refer to the graphs in Figures 2, 3 and 4.

RESULTS AND DISCUSSION

A. Gatineau Hills, Quebec

The radon anomaly observed during the 1967 feasibility study (Dyck and Smith, 1968) in the surface waters in the Fortune and Kingsmere lakes area in the Gatineau Hills, was investigated in some detail during the 1968 season. The main purpose was to determine the source of the radon in the water and determine such factors as optimum sampling density, sampling site, and sampling time. The variation of radon with distance along shore, with lake depth, and with season was studied. Relative radon-thoron concentrations in the soils surrounding the lakes were measured at the same time.

The rocks in the Gatineau Hills consist of Aphebian metasediments ('Grenville series' of earlier workers) including marble, quartzite, and amphibolite gneiss which are intruded by syenite and granite and cut by late diabase dykes. The uranium-bearing minerals uraninite, uranothorite, and betafite have been noted in

the Fortune and Meach lakes areas but not in economic amounts; the richest occurr-
ences are in breccias where the apatite-phlogopite matrix contains up to 5 per cent
betafite, uranothorite is found in pegmatites throughout the district (D. D. Hogarth,
University of Ottawa, pers. comm., 1968).

The sampling sites of the three lakes and surrounding terrain investigated
during the 1968 field season are shown in Figure 1. The geology was taken from
Hogarth (1962).

1. Radon profiles in lakes

In the Fortune Lake area syenite intruded by pegmatite predominates.
Outcrops are numerous. The thickness of the soil cover seldom exceeds 2 feet. On
about one quarter of the selected soil test sites more than one attempt was necessary
to obtain a 1-foot-deep hole. According to Hogarth (pers. comm., 1968) the lake was
circular before beaver and man built dams to raise the water level 4 to 6 feet creating
the southern bays. It is surrounded by hills and hence receives runoff from all
directions. However, one is tempted to infer from the southeasterly direction of the
creek drainage pattern in the region that the movement of groundwater is also south-
westerly.

The radon determinations of water samples from Fortune Lake are plotted
in Figure 2, plots A-1 and A-2. Plots A-1 show the fluctuation of the radon content
with season, with September averages lowest and July averages highest. In spite of
fluctuations caused by boat movements and atmospheric factors such as wind, rain, and
barometric pressure fluctuations, two radon 'highs' persist, one near the 400-foot and
one near the 800-foot position. The same 'highs' show up even clearer in the complete
July profile shown in A-2. However, these peaks become less distinct with distance
from shore. This, plus the facts that the radon levels decrease generally with distance
from shore, particularly at the bottom of the lake, and the close proximity of pegmatite
dykes at these positions, leads one to the conclusion that the dykes to the north are
responsible for a large portion if not for all of the radon and radium in the lake. A
second source of radon is indicated by the weak anomaly at the 20 to 26 sample site
positions. The slope of the terrain around this bay, the high radon level in the soil gas
of traverse L, and the radioactive pegmatite outcrops along it, suggest that runoff has
carried radioactive matter into the shallow bay. The four sites marked in the bay
were sampled in September with the following average radon contents: shore samples
110 pc/l, 20 feet offshore surface samples 67 pc/l, 20 feet offshore bottom samples
61 pc/l. The shallow depth of 2 to 3 feet explains the small difference between bottom
and surface samples.

The relatively larger decrease in the radon content of bottom samples with
distance from shore is another indicator that the main radon source is near the shore.

The relatively high radon levels observed in July persisted throughout the
lake with only a slight decrease towards the centre. Five surface samples from the
geometric centre of the lake, one directly in the centre and four at the corners of a 400-
foot-square around the centre, had an average radon content of 45 pc/l. The average
of the bottom samples at the same sites was 9 pc/l. This test also supports the
contention that the radon source is near the shore. It also shows that surface turbulence
rather than diffusion is responsible for the distribution of radon in the top of the lake.
A vertical radon profile determined in September at site V shows clearly that diffusion
of radon is limited to about 20. The radon concentration and corresponding depth were
as follows:

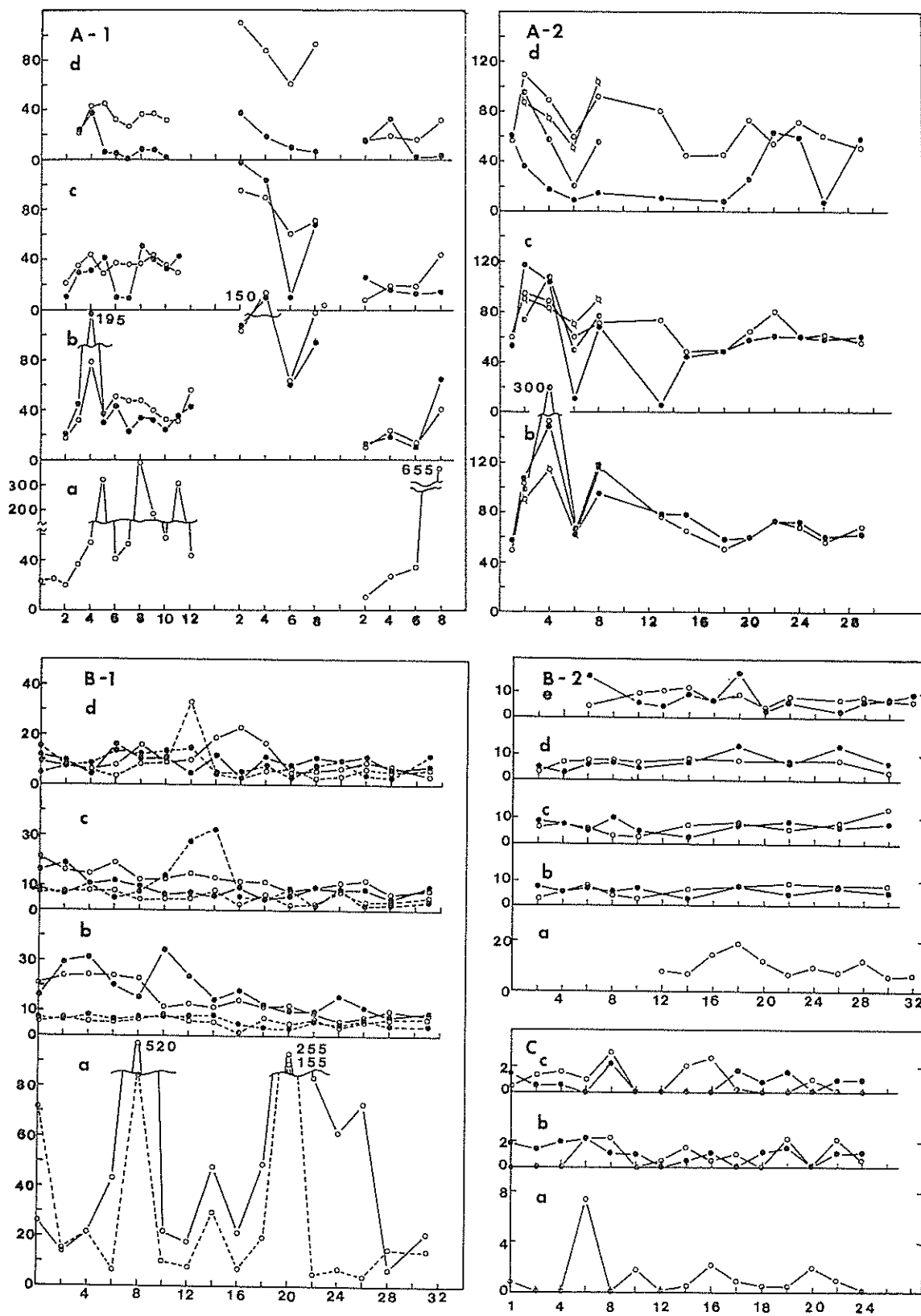| Feet	-0	9	18	28	37	46	55	64	74
pc/l	-14	15	2	0	0	2	0	4	16

Figure 2.   Radon profiles in lakes in the Gatineau Hills.

These results also show that surface mixing in this lake did not extend beyond about 20 feet in depth.

Kingsmere Lake, situated about 2 miles south of Fortune Lake, was also studied in some detail. Much of the lake is surrounded by overburden. Gneiss predominates to the northwest and east and marble to the south. A few pegmatites around the lake, and syenite and gneiss in the southwestern corner are visible. The surface drainage pattern of the lake region is south and west.

The lake was sampled at 200-foot intervals on the north shore and at 400-foot intervals at the south shore in July. The north shore was resampled in September. The radon concentration profiles along the north shore are plotted in Figure 2, plots B-1 and B-2. As is evident, the radon fluctuations are similar to those observed in Fortune Lake, i.e. July levels are higher than September levels; radon levels decrease from shore towards the middle; pronounced peaks along the north shore (in the neighbourhood of sample sites 8 and 20) correspond with pegmatite showings nearby. However, average radon levels are somewhat lower and more diffused than those in Fortune Lake. This is probably because the lake is much shallower and longer and hence mixed more thoroughly.

Pinks Lake, 4 miles southeast of Fortune Lake, is surrounded by marble except for gneiss on the northeastern shore. No uranium occurrences have been noted

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Figure 2 (opposite)

Radon-222 concentrations of lake water samples in pc/l (vertical scale) plotted as a function of distance along the lake shore in hundreds of feet. Capital letters in the upper left corner refer to location of sampling traverses shown in Figure 1. Plots marked by small letters a, b, c, d, and e give the results of analyses of samples located 0-, 20-, 50-, and 100 feet offshore, and the middle of the lake, respectively. Solid circles denote samples from the bottom and open circles samples from the surface of the lake.

Plot A-1. Fortune Lake profiles. The results plotted on the left were obtained from samples collected June 11, 12, and 13, those in the middle on July 6, 8, 9, and 12, and those on the right on September 11. Average depth in feet and range of depth of the lake at traverses b, c, and d are: June; 4, 1-5; 8, 2-15; 18, 4-41. July; 2, 2-3; 8, 5-14; 18, 10-35. September; 2, 1-4; 6, 2-9; 11, 4-21. All dates in this and subsequent legends are for the year 1968.

Plot A-2. Complete Fortune Lake profiles obtained in July. Circles with tails represent results of surface samples taken with the water sampler rather than in the usual way, i.e. with the sample bottle. Half-filled circles represent results obtained half-way between surface and bottom of lake. Average depth in feet and range of depth of lake at traverses b, c, and e, are: 2, 1-3; 8, 1-33; and 17, 2-60.

Plot B-1. Kingsmere Lake profiles, north shore. Solid lines give results of samples collected July 15-26; dashed lines — September 24-26. Average depth in feet and range of depth of lake at traverses b, c, and d are: July; 4, 1-7; 10, 2-15; 15, 3-20. September; 4, 1-8; 9, 2-15; 15, 1-22.

Plot B-2. Kingsmere Lake profiles, south shore, obtained July 15-26. Average depth in feet and range of depth of lake at traverses b, c, d, and e are: 4, 1-8; .8, 3-15; 13, 8-20; 25, 17-32.

Plot C. Pinks Lake profiles, northeast shore, obtained October 16. Average depth in feet and range of depth of lake at traverses b and c are: 23, 3-14; 33, 2-1; 55.

near this lake. As can be seen in Figure 2, plots C, the radon levels in this lake, obtained in fall, barely exceed the detection limit of the instrument. The results illustrate that in the apparent absence of uranium radon concentrations are very low.

The pronounced increase in the radon levels in Fortune and Kingsmere lakes in July cannot be explained fully with the observations on hand. Rainfall, ground-water movement, and seasonal groundwater table changes seem to interact and produce the observed seasonal variation; rainfall alone does not explain this variation. Approximately the same amount of rain was recorded in the Ottawa (Uplands Airport) area during the same period preceding the July and the September sampling. That not all pegmatites near the lake affect the radon content of the lake is probably due to the size of the pegmatite body, its uranium content, and the groundwater drainage pattern.

A distinct possibility exists that Fortune Lake is spring-fed. Hogarth (pers. comm.) believes that before beaver- and man-made dams raised the water level of the lake, one or two springs were visible along the north shore. Letter S south of the lake (see Fig. 1) denotes the location of a spring which contained 10,500 pc/l radon and 440 pc/l radium on July 15, 1968. It, as well as the creek beside it, had stopped flowing in September. Several springs like this could explain the high radon level as well as the seasonal fluctuations of radon content observed in the lake.

2. Radon in soil emanations

In order to determine such factors as radon content, relative soil and rock type, optimum sampling frequency, reproducibility, and variation of radon in soil emanations with season, a number of tests were carried out at the same time as the water investigations. The instrument developed for this purpose permitted on-site determinations of relative radon concentrations and qualitatively gave a measure of the relative amounts of radon and thoron. Thin soil cover in the test area did not permit useful investigations of radon content with depth. Hence all tests were carried out with 1-foot-deep freshly made holes.

The results of the soil tests are summarized in Figures 3 and 4. The reader can match location and results of a traverse by matching the capital letters on the plots of Figures 3 and 4 with the same letters in Figure 1. Sampling density of 200, 100, and 50 feet were employed. However, most traverses were sampled at

100-foot intervals. The more or less radial pattern of the traverses in the Fortune Lake area was chosen in order to search out radioactive slopes around the lake. Results shown in plots D and E, Figure 3, and B-1, K, and L, Figure 4, give a measure of seasonal variations and reproducibility of the technique. Plots A and B-1, Figure 4, show that the radon peaks observed in the lakes also show up in the soil determinations. The high degree of correspondence between radioactive pegmatite and the radon content in the soil is best illustrated in plots D, E, and H, Figure 3.

By studying the results the reader may verify the following conclusions:

There is direct correspondence between the alpha activity of radon in the soil emanations and the gamma-ray activity at the surface of the test sites, with more pronounced fluctuations of the alpha activity.

Radon anomalies are reproducible, but the concentration levels can change by a factor of 2, with higher levels in fall than in early summer.

The radon-thoron ratio is about the same in the Fortune and Kingsmere lakes areas, with the radon component dominating. In the soils of Pinks Lake area this ratio is detectably smaller (see plots M and N, Fig. 4). This conclusion is derived from the relative decrease in the counting rate with time. One explanation for the change in the counting rate with time is that in the first two lake regions the main source of the radon is the bedrock below some thickness of soil, giving the short
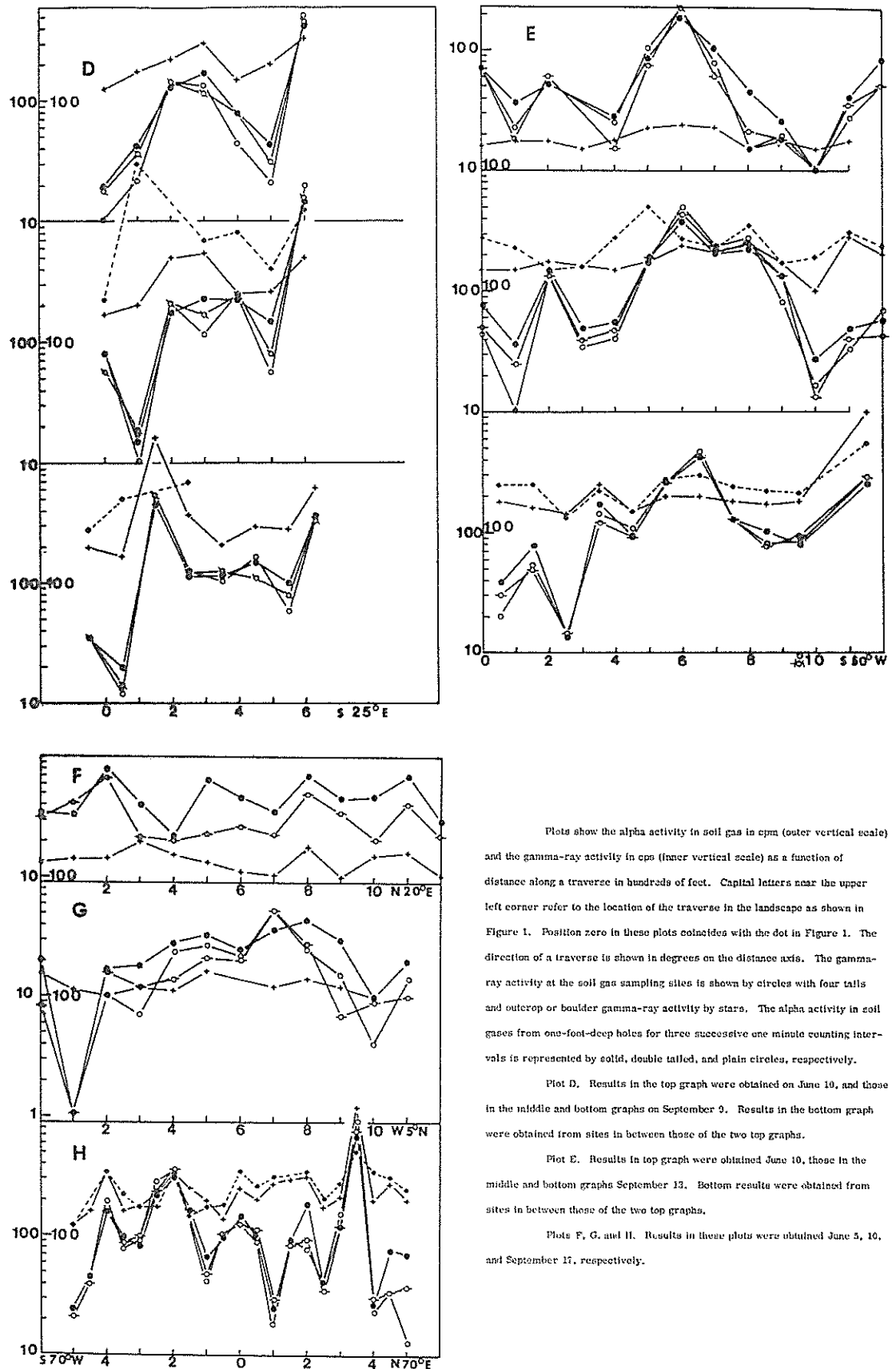
Figure 3. Radioactive emanations from soils in the Gatineau Hills.

Plots show the alpha activity in soil gas in cpm (outer vertical scale) and the gamma-ray activity in cps (inner vertical scale) as a function of distance along a traverse in hundreds of feet. Capital letters near the upper left corner refer to the location of the traverse in the landscape as shown in Figure 1. Position zero in these plots coincides with the dot in Figure 1. The direction of a traverse is shown in degrees on the distance axis. The gamma-ray activity at the soil gas sampling sites is shown by circles with four tails and outcrop or boulder gamma-ray activity by stars. The alpha activity in soil gases from one-foot-deep holes for three successive one minute counting intervals is represented by solid, double tailed, and plain circles, respectively.

Plot D. Results in the top graph were obtained on June 10, and those in the middle and bottom graphs on September 9. Results in the bottom graph were obtained from sites in between those of the two top graphs.

Plot E. Results in top graph were obtained June 10, those in the middle and bottom graphs September 13. Bottom results were obtained from sites in between those of the two top graphs.

Plots F, G, and H. Results in these plots were obtained June 5, 10, and September 17, respectively.
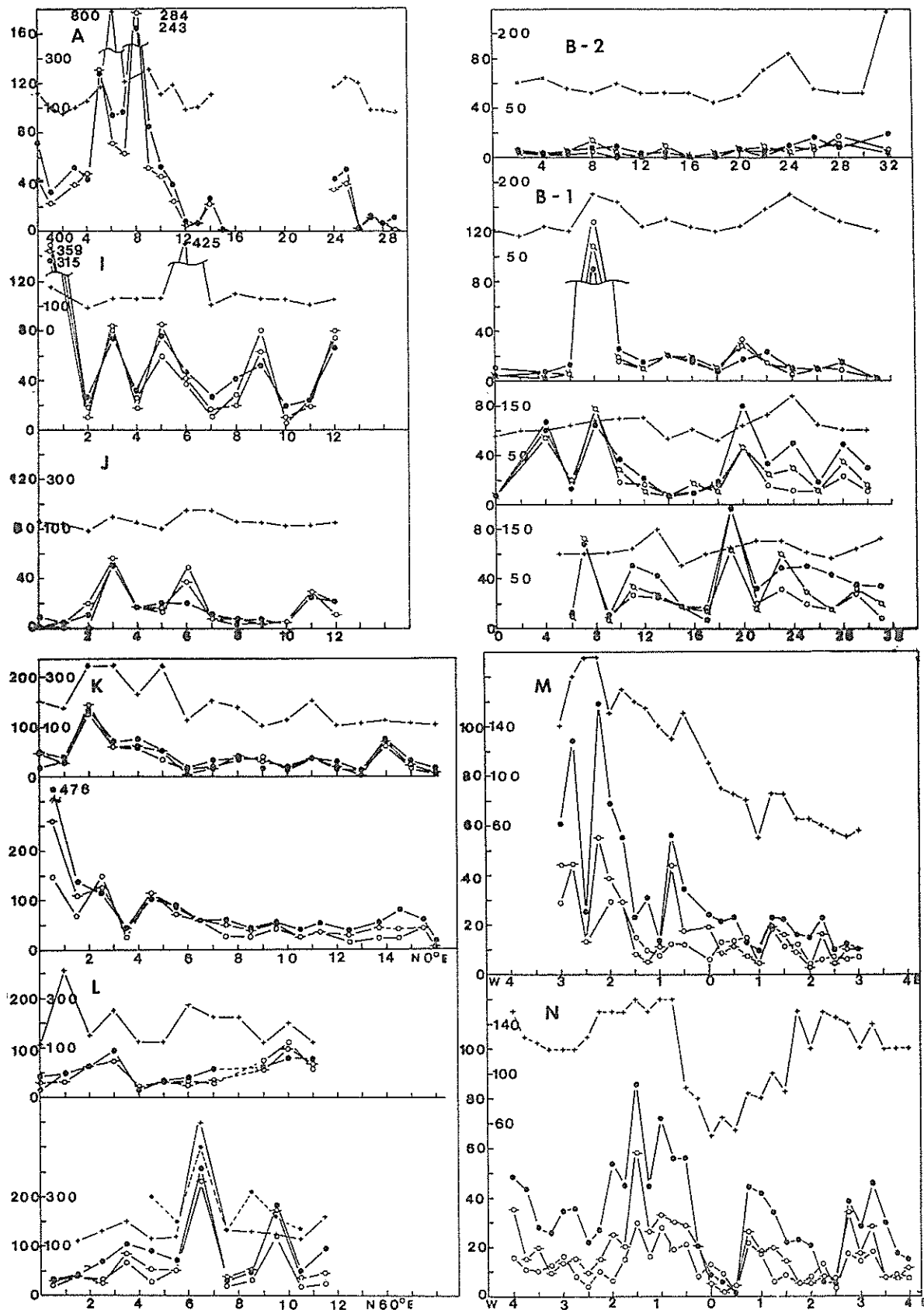
Figure 4.   Radioactive emanations from soil in the Gatineau Hills.   For explanation
of scales and symbols see Figure 3.

lived thoron component time to decay before reaching the test site. At Pinks Lake, on the other hand, the main source is the soil itself, giving the thoron a chance to enter the counting chamber before decaying. Because soil thickness is similar in the two regions the more likely explanation is that the uranium-thorium ratio is highest in the Fortune and Kingsmere lakes regions.

Sampling density of 50- to 100-foot intervals seems to give sufficient detail for most observations.

The higher radon levels in soils in September seem to coincide with lower levels in the lakes and vice versa. One is tempted to conclude from this that in the fall a larger proportion of the radon from the radioactive deposits was lost to the atmosphere directly, without entering the hydrosphere, because of the generally drier conditions that prevailed in the fall. Another indicator that moisture acted as a sealant is shown by the fact that the fall results fluctuated more violently from site to site than the early summer results when moister conditions prevailed. Water logging is believed to be responsible for some of the low values observed in traverses A, I, J, and B. Traverses I and J follow the creek beds with sample sites alternating from side to side. It is not evident that the radioactive spring at S, discussed in the section above, contributed to the alpha activity of traverse I. However, the radon level is appreciably higher in this traverse than that in traverse J. But, as was pointed out, water logging can easily mask 'true' radon levels. A simple example of the effect of water logging on the radon concentration in soil gas is evident in the results of traverse N, north of Pinks Lake. There is a low in both the alpha and gamma-ray activity as a result of overburden and moisture around the creek bed. Upslope, at the 225'E position a second radon low, not accompanied by a gamma-ray low, occurs at the contact between the overburden and the gneiss outcrop.

The general rise in the activity to the west, in plots M and N, Figure 4, is believed to be due to radioactive impurities in the marble. The increased activity coincided with gneissic impurities in the outcrops toward the western end of these traverses.

B. Sudbury, Ontario

The purpose of the investigation in the Sudbury Basin was to obtain a measure of the radon content of surface waters and soil gases in another geological setting, and to test the suggestion that nonuraniferous metallic deposits can be detected by the radon method provided uranium occurs in association with the major nonradioactive deposit.

Figure 4 (opposite)

Plot A. Emanations around Fortune Lake, obtained June 6.

Plots I and J. Emanations along the creeks to the south of Fortune Lake, obtained July 4 and 5.

Plot B-2. Emanations along the south shore of Kingsmere Lake, obtained July 24.

Plot B-1. Emanations along the north shore of Kingsmere Lake, obtained July 15 (upper plot) and September 19 (lower plots).

Plot K. Emanations south of Fortune Lake, obtained July 5 (upper plots) and September 5 (lower plots).

Plot L. Emanations west of Fortune Lake, obtained July 4 (upper plots) and September 9 (lower plots).

Plots M and N. Emanations near the south and north ends of Pinks Lake, obtained on October 8 and 2, respectively.
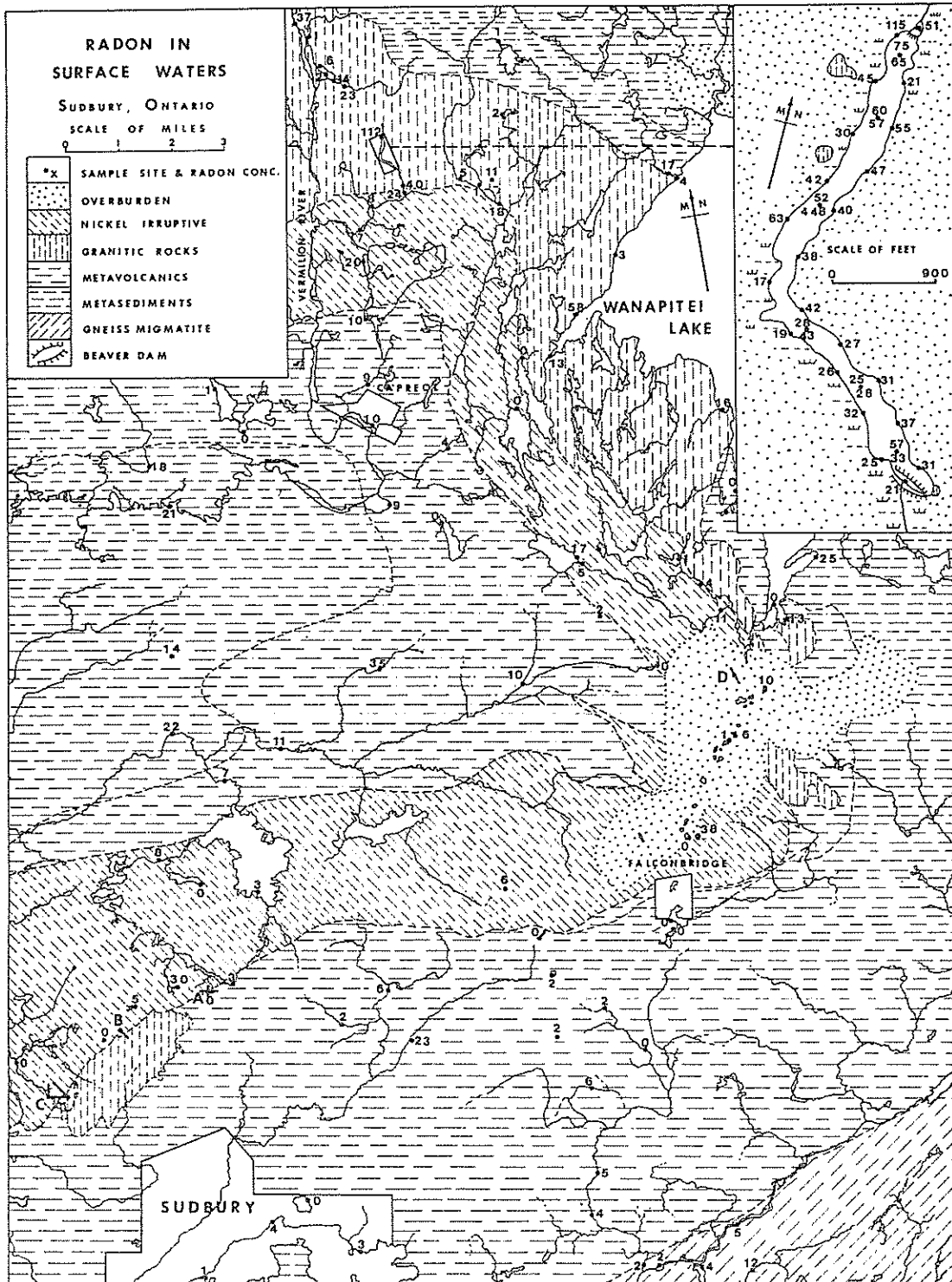
Figure 5. Radon concentrations in surface waters in the eastern part of the Sudbury Irruptive.

Sampling sites and radon concentration in pc/l are indicated by dots with numbers. Heavy straight lines with dots indicate direction and position zero of soil traverses. Capital letters refer to soil gas results plotted in Figure 6.

The simplified geology shown in Figure 5 was taken from the Ontario Department of Mines, Geological Map P. 405, Sudbury Mining area, 1968 reissue. Except for pockets of gravel, overburden is scarce near the copper-nickel ore-bearing zone. Towards the middle of the irruptive overburden is more extensive. Outside the irruptive a number of radioactive occurrences have been noted near the base of the Huronian system between the Agnew Lake area and Lake Temagami. The occurrences are similar lithologically to the uraniferous ores of the Elliot Lake area and lie at the same stratigraphic horizon (Thomson, 1960). No radioactive occurrences have been reported inside the irruptive or at the contact zone.

1. Radon in surface water

Eighty-eight stream and lake water samples in and around the eastern quarter of Sudbury irruptive were collected and tested for radon in a reconnaissance survey on a scale of about 1 sample per 3 square miles. All samples were collected from shore if accessible by road. The results are plotted at the sample sites in Figure 5. All samples were collected during the last two weeks of June. Average radon concentrations in 46 stream and creek samples were 10 pc/l and in 42 lake samples 9.4 pc/l. The division into streams and lakes is somewhat arbitrary. Many lakes, while having areas similar to those of lakes, were actually high-water-level swamps in a drainage channel. This aging feature of the landscape is probably also responsible for the small difference in the radon concentrations of streams and lakes. Similar averages from the Gatineau Hills differed by a factor of 10 (Dyck and Smith, 1968). The radon concentration in waters flowing from areas underlain by meta-volcanics and metasediments in the centre of the irruptive as well as those from granites north of the irruptive are somewhat higher and more persistent than those from the same formations to the southeast of the ore zone and from the nickel irruptive. Because the overburden in the centre of the irruptive is much thicker than near the fringes, the higher radon levels may reflect a higher uranium content in the overburden. The Vermilion River, although approaching lake size in certain portions, has a radon content sufficiently high to make one wonder whether it is receiving radioactive material from the Milnet fault region to the north where several uranium occurrences have been noted (Thomson, 1960).

The highest radon concentration was found in a small lake 5 miles north of Capreol. The results of the subsequent detailed investigation of the radon distribution in the lake is shown in detail at the top right corner of Figure 5. The numbers along the shore give the radon concentration of shore samples and the dots indicate sample sites. The numbers below the lake middle sample sites give radon values from the bottom of the lake and those above the site surface concentrations. The lake measures about 600 feet at its widest point and stretches for about 5,000 feet in a north-south direction. Its average depth is about 3 feet, with isolated holes reaching 6 to 8 feet. The range and average radon concentration of the 37 samples were 448 to 17 pc/l and 52 pc/l respectively. The average radon concentration in the inlet or northern half of the lake was 72 pc/l compared to 30 pc/l for the outlet end. Cache Lake, situated about 2 miles north of the small lake was sampled at four sites along its southwest shore. The radon values, although only 1/4 to 1/2 as large as those in the small lake, increase notably toward the southeast end, suggesting a common source for the radon in these two lakes. A scintillometer reading double that of normal, from the small granite outcrop shown on the map west of the lake, suggests another source. The larger outcrop shown on the map, as well as outcrops north of the lake along a trail did not give unusual scintillometer readings. The generally swampy conditions of the region between these lakes also suggest groundwater as a possible source of the radon anomaly.
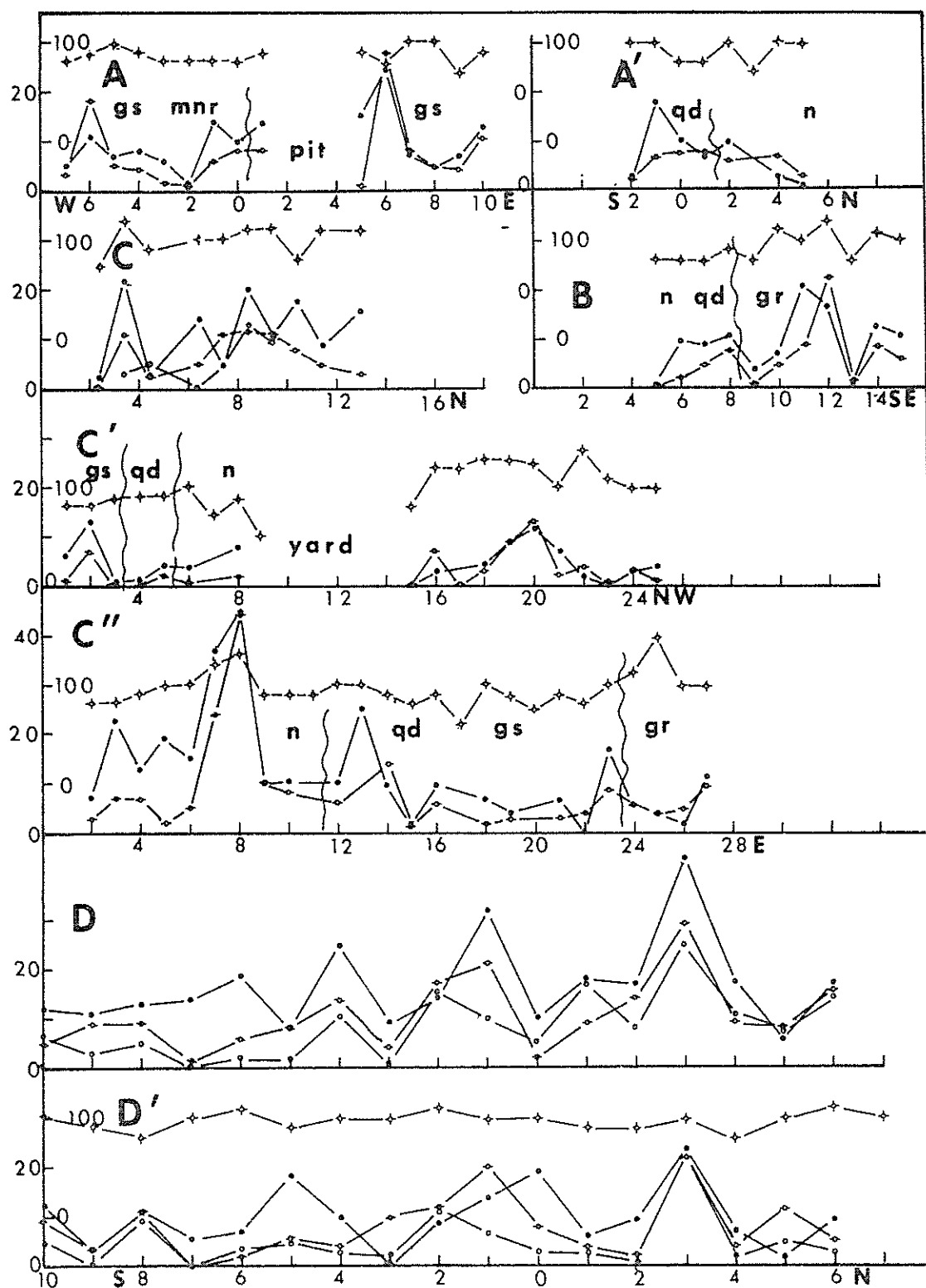
Figure 6. Radioactive emanations from soil in the Sudbury area.

2. Radon in soil emanations

Radon measurements in soil gas were carried out across contact zones between norite and granite, norite and quartz diorite, and norite and greenstone, and across a stretch of gravel. The tests across contact zones were carried out along the McKim road north of Sudbury, and the gravel tests about 4 miles north of Falconbridge. Position zero and direction of traverse is indicated by dots and heavy straight lines on Figure 5. Capital letters near the traverse identify it with plots in Figure 6. Except for the gravel, soil thicknesses were such that it was difficult to find enough soil to make a hole 1 foot deep. Although radon and thoron were present in detectable quantities in all formations, with thoron predominating, no significant variation in levels could be detected between rock formations.

More than 3 inches of rain fell during the two weeks stay in the Sudbury area. This could be partially responsible for the low radon counts. The fact that gamma-ray activity was also lower than in other regions confirms the lack of uranium and thorium in these rocks. Several air samples taken underground at the 4,500-foot level in dead-end, unventilated drifts in norite and greenstone at the Falconbridge Mine contained no detectable quantities of thoron and barely detectable amounts of radon.

The slight trend in the radon level of the gravel traverse test of 2-foot-deep holes cannot be interpreted from the information on hand.

Perhaps a more precise sampling technique and more sensitive instruments will permit meaningful correlation between radon concentration and rock type at the low levels encountered at Sudbury.

Figure 6 (opposite)

The plots show the alpha activity in soil gas in cpm (outer vertical scale) and the gamma-ray activity at the surface of the soil in cps (inner vertical scale) as a function of distance along a traverse in hundreds of feet. Capital letters near the upper left corner refer to the location of the traverse in the area shown in Figure 5. The direction of the traverse is shown by the letters N, S, E, W on the distance axis. The small letters in the figure indicate rock type as follows: gs-greenstone, gr-granite, qd-quartz diorite, n-norite, and mnr-Mount Nickel Mine rock. The gamma-ray activity at the surface of the soil is shown by circles with 4 tails. The alpha activity of the soil gas for three successive one minute counting intervals is represented by solid, double tailed, and plain circles. Results shown in plots D were obtained from freshly made 2-foot-deep holes, all other results were obtained from freshly made 1-foot-deep holes. All determinations were carried out during the last two weeks of June.

Plots A and A'. Emanations at the Mount Nickel Mine. Position zero is about 100 feet west of the large water filled pit.

Plot B. Emanations south of McKim road. Position zero is located 1.5 miles east of the railway and McKim road intersection on the McKim road.

Plots C, C' and C". Emanations at the McKim Mine. Position zero of both C and C" is located at the intersection of the McKim road and the railway tracks. Position zero of C' is located at the 2,000 foot mark of C".

Plots D and D'. Activities in gravel 1.3 miles northeast of the Sudbury Airport. Position zero as located at the intersection of the power line and the road. Plot D gives the results of freshly made 2-foot-deep holes and plot D' of freshly made 1-foot-deep holes.
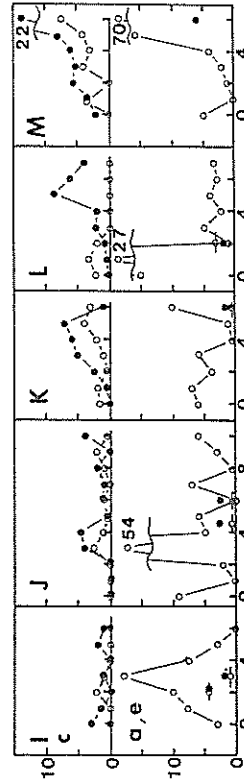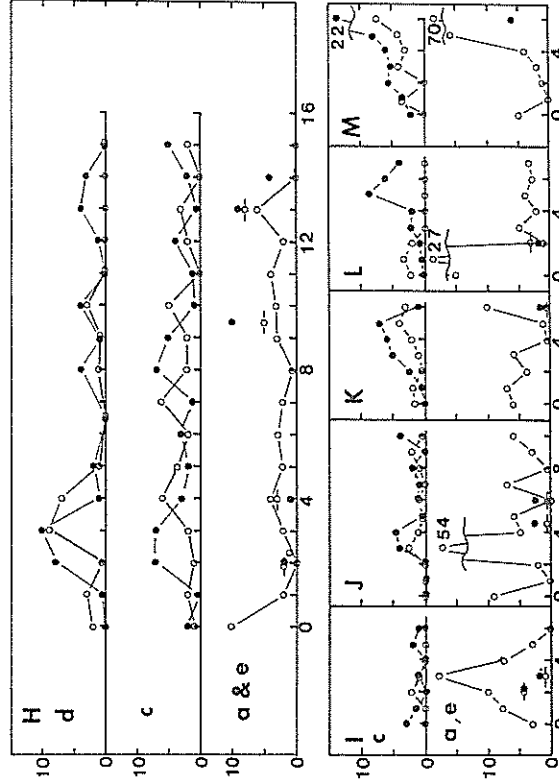
Figure content:

SERPENT

ESPANOLA & BRUCE

MISSISSAGI

ARCHEAN

SCALE OF MILES

0   1/2

KEWEENAWAN

GOWGANDA

TEN MILE LAKE

M   K   L   J

H
d
c
a & e

I
c
a,e

J

K

L

M
22
c
70
a,e

STINSON LAKE

NONAME LAKE

G

E

D

ROAD

TAILINGS

MISSISSAGI

PECORS, RAMSAY LAKE, MCKIM

MATINENDA

KEEWATIN

OVERBURDEN

SCALE OF MILES

0   1/4   1/2

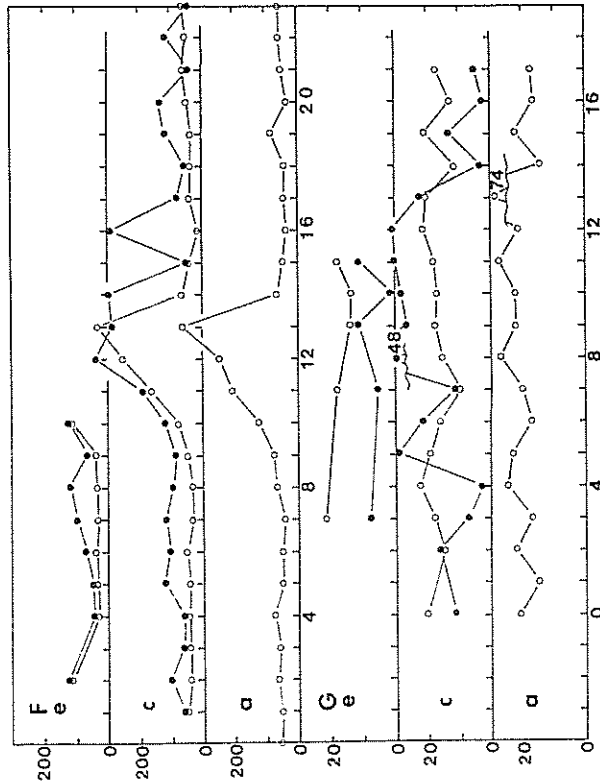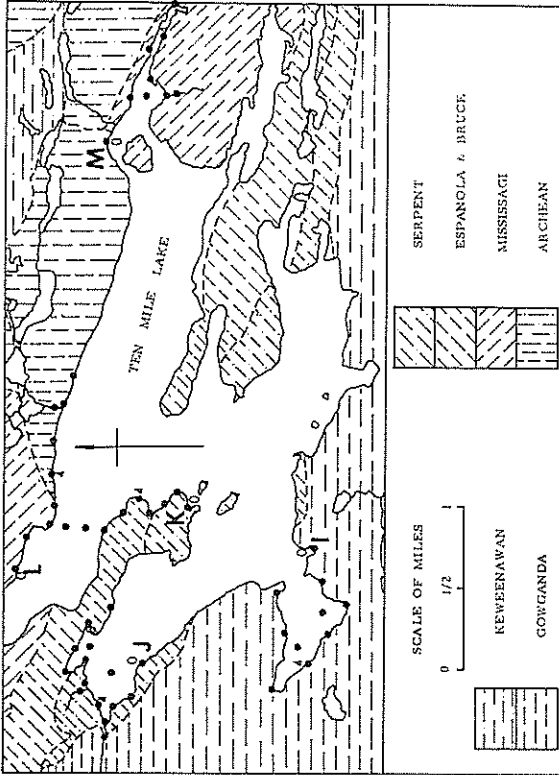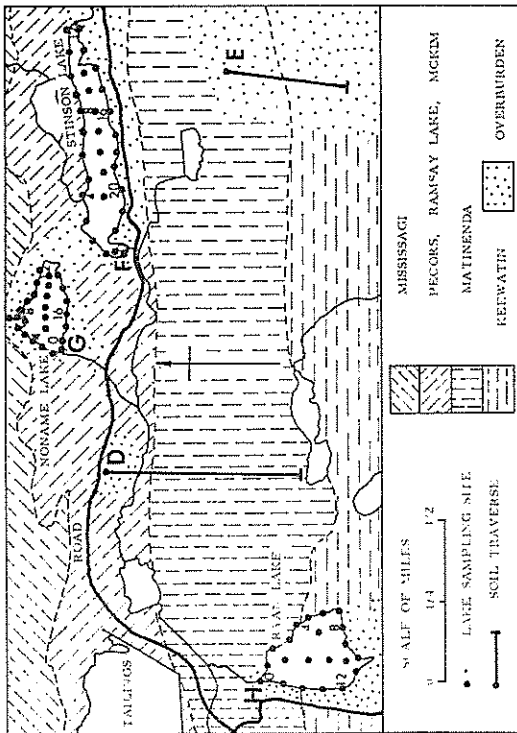LAKE SAMPLING SITE

SOIL TRAVERSE

F
e
c
a

G
e
c
a
48
74

Figure 7. Radon profiles in selected lakes in the Elliot Lake region.

The maps in the figure show the location of the lakes and the geology (Robertson, 1961) surrounding the lakes. Dots along the shores and in the middle of the lakes indicate the approximate position from which water samples were taken. Capital letters and numbers along the shores permit correlation of sample sites with radon concentrations in the graphs. The graphs show the radon concentration of the lake water samples in pc/l (vertical scale) as a function of sample site shown in the maps. Capital letters in the left upper corner of the plots permit location of the sample site on the maps. Small letters a, c, d, and e refer to shore, 50 feet off-shore, 100 feet offshore, and lake middle, respectively. Circles denote results of surface water samples and dots lake bottom samples. Circles with tails in plots I to M denote offshore surface samples. All samples were collected and analyzed during August.

Average depth and range of depth of feet of sampled lake traverses are as follows: F-c, 12, 1-31; e, 20, 3-33. G-c, 16, 3-28; e, 22, 3-38. H-c, 8, 2-20; d, 14, 4-25; e, 26, 22-29. I-c, 16, 10-20; e, 32, 20-45. J-c, 12, 1-30; e, 96, 86-105. K-c, 20, 1-40; e, 150. L-c, 26, 10-42; e, 130. M-c, 22, 9-39; e, 57.

C. Elliot Lake, Ontario

Elliot Lake is one of the major uranium producing regions of the world and if feasible a uranium exploration method development study should include this area.

A report on the stratigraphy, structure, and economic geology of Elliot Lake uranium camp has been published by Robertson (1968). Uranium ore outcrops in two places: the Quirke zone on the north limb of the Quirke syncline, and the Nordic zone on the south limb. The uranium occurs in quartz-pebble conglomerate near the base of the Matinenda Formation. The main uranium-bearing minerals are uraninite, brannerite, and monazite, which occur as microscopic grains in the matrix of the conglomerate. Thorium occurs with uranium but generally in much smaller quantities. A regional survey of radon in surface waters in the Elliot Lake area was carried out by Smith (Smith and Dyck, in press).

This section of the report describes detailed investigations of the behaviour of radon in four selected lakes in or near the Serpent River drainage system, which drains the entire area. At the same time radon determinations from soils above uranium ore in the Quirke zone and from soils above the Nordic zone, where the ore is of subeconomic grade, were carried out.

All tests were carried out during August. Lakes were sampled during rainy days and soils on dry days.

1. Radon profiles in lakes

The three small lakes investigated in the Elliot Lake region are located south and east of the Rio Algom Nordic mine. Their relative positions are shown on Figure 7.

The overburden shown on the map was added by the writer to indicate where it was encountered in this work. It does not give a complete picture of the overburden of the region depicted by the map. The lakes drain westward along the valley developed over argillites of the Pecors Formation, with the present divide between this and the main Serpent River drainage channel just half a mile east of Stinson Lake. Lake shore and mid-lake sampling sites are marked with dots. Numbers and capital letters along the shores are meant to aid in the correlations of the sample sites on the map and radon concentrations plotted in the same figure.

A relatively high radon concentration with a pronounced peak at position 12 of Stinson Lake is at once evident. The explanation is that several years ago, water from Pecors Lake, east of Stinson Lake, was pumped into Pardee Lake which drains into Stinson Lake. This water was used to supplement the water supply of the Nordic mine. Pecors Lake belongs to the Serpent River drainage channel, which had received mine effluents from the uranium mines on the northern limb of the syncline. The radon concentration in 'Noname' Lake, although less than half that in Stinson Lake, is still about four times that found in Ryan Lake. An interesting picture emerges from a comparison of the radon concentrations in the bottom and surface samples of Stinson and 'Noname' lakes. Bottom samples from Stinson Lake almost without exception contain more radon than surface samples. In 'Noname' Lake the radon concentration in bottom samples is higher only at stations 5 to 13 in the 50-foot offshore traverse. The inverted radon concentration levels at positions 14 to 4 (clockwise) of the 50-foot offshore traverse and the lake middle positions can best be explained as follows: radon and radium enter 'Noname' Lake via the gravel bed separating it and Stinson Lake. This conclusion is based on the facts that 'Noname' Lake is downstream in the westward drainage channel, and its water level was about 10 feet below that of Stinson Lake. The difference in the water levels was caused by a pump which had been working

for several days, only one week before the lake was sampled. This drop in the water level caused a general movement of the top of the lake toward the pump which was stationed at position O, carrying with it radon from the northern shore where concentrations near the bottom are higher. The higher radon concentrations at the bottom of all positions between 5 and 13 indicate that the water enters the lake on a broad front along the northern shore, rather than the eastern bay as one would expect from the topography. The results of the two lakes studied, display the potential of the radon method for detailed prospecting for uranium, provided the radium or radon from an orebody is able to enter the water system. For examples of natural rather than man-made contamination of lakes, the reader is referred to the accounts of the Gatineau Hills and the Sudbury investigations.

Ryan Lake overlies the Matinenda Formation in which the uraniferous conglomerate occurs. The lake drains to the north and is not known to have received contaminated water from mining operations. It was hoped that the contact zone between the Matinenda Formation and the Archean would show up in the radon profile. However, except for a weak anomaly near stations 1 to 5 in the 100-foot traverse (see plots H in Fig. 7), there is no evidence of this contact in the radon profiles. Levels fluctuate randomly around 4 pc/l, with about twice as many bottom samples showing higher radon concentrations than surface samples. With a detection limit of 1 to 2 pc/l the randomness is not surprising. It must also be mentioned that the radon in the laboratory air, used for the determination of cell background sample scrubbing, was found to fluctuate between 0.5 and 4 pc/l.

While corrections for this effect were applied, it no doubt influenced the reproducibility of the results at the low radon levels encountered in Ryan Lake.

Several factors dictated the choice of Ten Mile Lake for a radon study. It lies in the most elevated region of the Serpent River drainage channel, and overlies several geological strata including the Matinenda Formation. Access to the lake is by plane and boat taxi and a quarter-mile portage. The geology (Robertson, 1963) surrounding the lake, surface shore sample sites, and off-shore sample sites are shown on Figure 7. Capital letters and numbers identify sample sites and radon plots shown in the same figure. Small, but persistent trends are evident in the radon profiles. Absolute radon concentrations are similar to those observed in Ryan Lake. It is impossible to explain these trends with the available information. A few probable explanations are offered nonetheless. A local source, on or somewhat upslope from the shore, is suggested by the results of plot I a. The highs in plots J and M correspond with creek deltas. Samples from several hundred feet upstream from the deltas had a radon content of 25 and 122 pc/l. In contrast, the creeks near J 5 and L 6 had radon contents of 8 and 0 pc/l. These creeks had no deltas associated with them. The results support the logical argument that creek deltas can serve as sensitive indicators of uranium occurrences of the area drained by the creek. The radon concentration at site M 5 is fairly high, considering the generally low concentrations in Ten Mile and Ryan lakes, and warrants further investigation.

The low radon levels encountered in the uncontaminated lakes in the Elliot Lake area compared to the radon levels in the Sudbury and Gatineau Hills areas, even though the lakes overlie uraniferous rocks, suggest that the rock containing the uranium is resistant to erosion. Regional backgrounds, rather than absolute radon concentrations must be employed to determine anomalies.

2. Radon in soil emanations

Radon determinations in soils were carried out on the northern limb of the Quirke syncline where ore grade uranium outcrops and on the southern limb where low
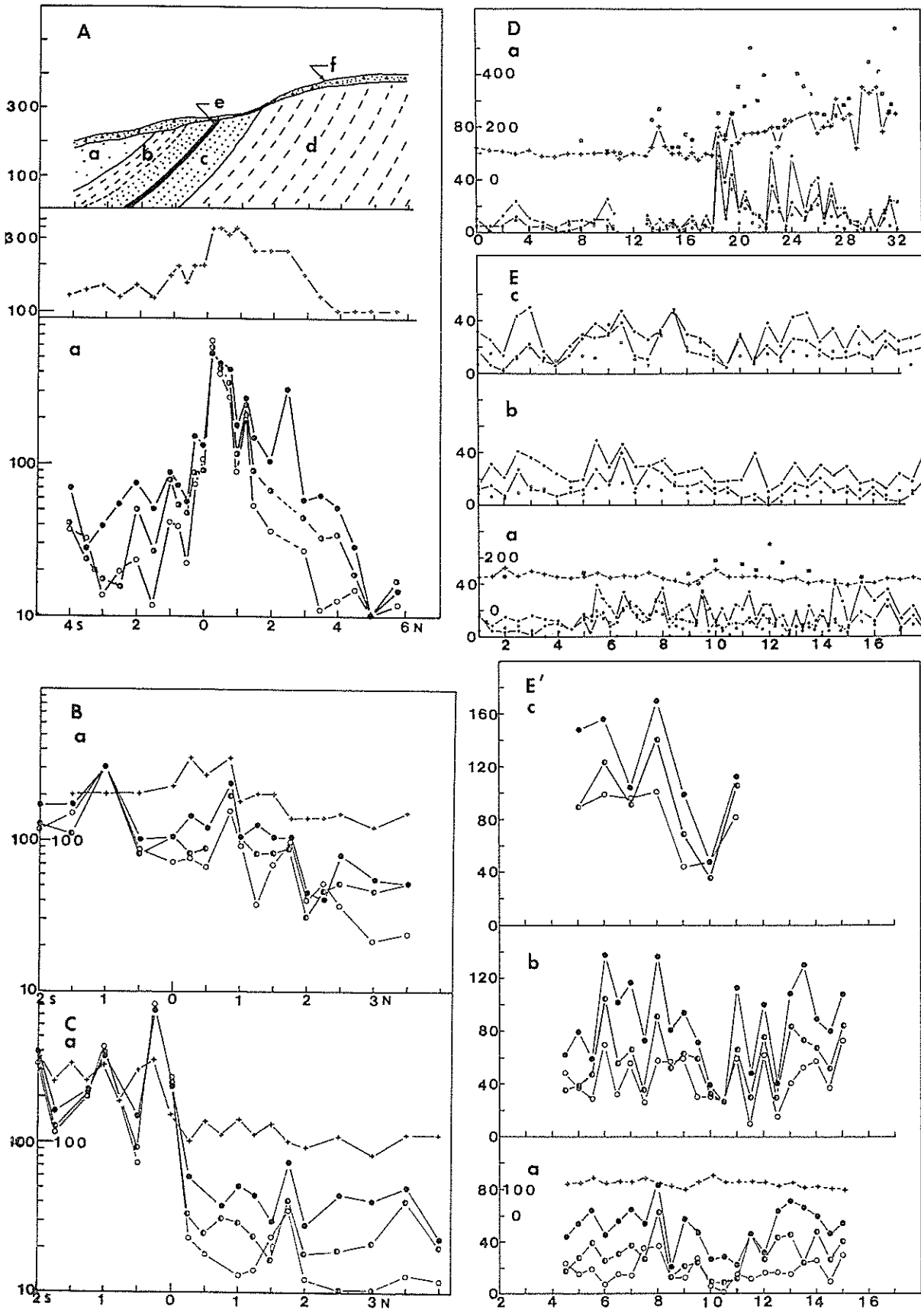
Figure 8.   Radioactive emanations from soil in the Elliot Lake region.

grade quartz conglomerate of the Matinenda Formation occurs. The results of tests along 3 traverses across the ore zone east of the No. 1 shaft of the Rio Algom Quirke mine are plotted in Figure 8, plots A, B, and C. The geological cross-section near traverse A, also shown in the figure, was taken from Robertson (1968). The over-burden consists mainly of gravel and glacial till. The thickness is not known exactly, but mine geologists estimate it to be between 5 and 15 feet where the ore occurs. Position O of the traverses was chosen along the trail which follows the strike of the ore zone. Little disturbance of the overburden was noticeable at traverse A. At traverses B and C considerable disturbance of the overburden over the ore zone and downslope from the ore zone was evident. However, the radon anomaly is clearly distinguishable, particularly in plots A and C and closely parallels the gamma-ray anomaly. The radon peak to background activity ratio in the two traverses is about 15, whereas the gamma-ray peak to background ratio at the surface is about 3 for the same traverses. Outcrop or boulder gamma-ray peak to background ratios were found to be about 10 along the same traverses. Similar improvements in the detection of uranium were obtained in a test over a uranium deposit in the Bancroft region, Ontario, in 1967 (Dyck, 1968).

The location and direction of the soil traverses D and E, tested in the southern limb, are shown on the map of Figure 7. The results are plotted in plots D, E, and E' of Figure 8. The low radon levels in plots D and E were obtained with a faulty soil gas pump. This had the effect of lowering the radon activity by a factor of 2 to 3 compared to those obtained with a good pump. However, relative variations were not affected drastically.

The alpha and gamma-ray activities of traverse D increase near the 1,800-foot mark. This coincides with a marked increase in the proportion of rock outcrop. In fact, at some sites it was difficult to find enough soil to make a 1-foot-deep hole.

Figure 8 (opposite)

Plots show the alpha activity in soil gas in cpm (outer vertical scale) and the gamma-ray activity at the surface of the soil in cps (inner vertical scale) as a function of distance along a traverse in hundreds of feet. Circles with four tails denote gamma-ray activity at the surface of the sample sites, and stars, gamma-ray activity of boulders or outcrop near the site. The alpha activity in soil gases for three successive one minute counting intervals are represented by dots, half filled circles, and plain circles, respectively. Small letters a, b, and c in the graphs indicate that the radon measurements were obtained from freshly made one-foot-deep holes, freshly made two-foot-deep holes, and one day old two-foot-deep holes, respectively.

Plot A. Emanations across a subcrop of conglomerate ore at the Rio Algom Quirke mine. Position zero is located 250 feet east of No. 1 shaft. The geological cross-section at the top of the figure was taken from Robertson (1968). Small letters a to f in the cross-section denote upper Mississagi quartzite, middle Mississagi greywacke – argillite, lower Mississagi quartzite – conglomerate, basement andesite – diorite etc., main conglomerate ore, and gravel, respectively. The vertical scale for the cross-section denotes relative elevation in feet.

Plots B and C. Emanations across the same ore zone as plots A 800 and 1,400 feet east of No. 1 shaft.

Plots D, E, and E'. Emanations from traverses D and E, the location of which are shown in Figure 7. The results of plots D and E were obtained with a faulty soil gas pump; plots E' with a good pump.

Traverse E is located 2 miles east of Nordic Townsite. Gently rising topography levels off near the 1,100-foot position and begins to drop slightly near the 1,500-foot position. Overburden, consisting of glacial boulder till, is estimated by the mining geologists of Rio Algom Mines, to be between 15 and 25-feet thick, with increasing thickness to the south. Development of a soil profile is evident. The alpha activities obtained from the soil gas along these traverses are shown in plots E and E' of Figure 8. The results of graph E, although obtained with a poor pump, are included to support the contention that even though radon concentrations in the soil may change for a variety of reasons, trends are reproducible. Note, for instance, the negative anomaly at the 1,050-foot position in plot E' obtained with a good pump. Although not recognizable in the results of the 1-foot-deep holes in plot E, it begins to show up in the tests from old 2-foot-deep holes. This anomaly coincides with the projected contact of the Matinenda Formation. The anomaly may be caused by water logging or a sharp change in the thickness of overburden, or both.

The predominance of radon over thoron at the peak of the plots across the ore zone at the Quirke Mine, indicates that, either the major portion of the radioactive emanation originated from a depth somewhat removed from the test site or that the ratio of radium 226 to radium 224, and under equilibrium conditions, the ratio of uranium to thorium, is larger at the peaks than at the shoulders where a distinct decrease in the alpha activity with time is evident. In view of impervious nature of the soil and the inferred thickness of overburden at traverse E, the pronounced decrease of the alpha activity of the soil gas with time suggests that the thorium and its radium daughter in the soil are the major source of the activity.

ACKNOWLEDGMENTS

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APPENDIX

Radium-226 Content of Lake Muds

In Table 2 below are listed the radium contents of lake muds from the various lakes investigated during the 1968 field season. This should be looked upon as indicative rather than representative, mainly because of the small number of samples involved. Also the muds were very fine, and hence could not be filtered very efficiently, giving too high a radon concentration, and hence radium concentration, in at least one filtrate. This is evident from the comparison of the radon concentration of the filtrate from Stinson Lake with that from the clear composite sample. The composite samples consisted of a mixture of ten or more clear samples from a lake. Their radon or radium-222 content was; Stinson Lake - 3.4; 'Noname Lake' - 5.4; Ryan Lake - 1.6; Ten Mile Lake - 1.5 pc/l. Radon concentrations of water samples stored for six weeks or longer are equivalent to the radium-222 concentration of the sample. Hence the results of the composite samples as well as those of column 4 compared to those in the last column of the table show that on a unit weight basis the radium concentration in the muds is very roughly 1,000 times that in the water. The muds are therefore a more sensitive indicator of uranium than the waters above them.

The last column gives the Ra concentration of dissolved samples. Except for the Gatineau Park samples, the average radon concentration of the dissolved samples is approximately double that of the undissolved samples, indicating a 50 per cent emanation efficiency for undissolved samples. It may also be of interest to note that the average loss of weight on ignition amounted to nearly 50 per cent indicating a relatively high organic content of the mud samples.

Table 2. Radium-226 in lake muds

Region, sample site, and number of samples (X)	Average radon conc. of 250 ml samples, pc/l			pc of radon from mud	weight of dry mud, gm	Ra-226 content of dry mud, pc/gm	
	mud and water		clear water, 6 weeks after filtering				
	at time of sampling	6 weeks after sampling				undis-solved[1]	dis-solved
Gatineau Hills region							
Fortune Lake (1)	18	22	2	5.0	0.8	6.3	4.4
Pinks Lake (1)	0.0	5.8	0.2	1.4	1.7	0.8	0.3
Sudbury region							
Smale Lake (3)	171	4.7	1.6	2.3	1.4	1.6	3.6
Elliot Lake region							
Stinson Lake (2)	208	1730	132	800	7.6	104	238
Noname Lake (1)	13	28	3.2	6.2	3.5	1.8	3.1
Ryan Lake (2)	13	16	3.0	6.5	4.0	1.6	2.4
Ten Mile Lake (5)	6.6	7.8	1.5	7.4	8.1	0.9	3.0

[1] The radium in the undissolved samples was determined by putting a weighed amount of dry sample into 8 ounces of distilled water, sealing the bottle for a known length of time, and determining the radon in the water in the usual manner. The radium in the dissolved samples was determined in a similar manner except that a weighed amount of sample was ignited at 450°C for several hours and then dissolved in hydro-fluoric acid and perchloric acid prior to the radon determination.