Migration of Thorium, Uranium, Radium and Cs–137 in till Soils and their Uptake in Organic Matter and Peat

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Studsvik Energiteknik AB

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ABSTRACT

The distribution of U-238, Th-232, Th-228, Ra-226, Ra-228, Cs-137 and K-40 have been studied in soil and peat samples. Maximum Th and U values in peat were 215 and 248 ppm ash weight, respectively, with Th/U ratios clost to 1. An increase of Th and U and decrease of Th/U with depth was observed in the studied peat bog. Disequilibrium of Ra-228/Th-232 are interpreted as current or recent migration of these radionuclides i.e. indirectly of groundwater flow. The main part of Cs-137 in two vertical profiles of the peat bog was found in the lowest zones.

Enrichment of Ra isotopes (by the plant nutrient cycle) and differentration between Ra-228 and Ra-226 in the upper organic zone of soil profiles were observed.

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1 INTRODUCTION

As part of a SKB project on investigating the suitability of different bedrocks for radioactive waste storage, the natural radiation environment was studied in the Klipperås area, situated in south-east Sweden, Figure 1 (SUN 85). The study comprised the radionuclides U-238, Th-232, Th-228, Ra-226, Ra-228, Cs-137 and K-40 which were analyzed in samples of rock, soil, peat and plant material. A gamma survey and some preliminary radon measurements were also undertaken.

In certain organic soils and peat samples fairly high concentrations of radionuclides were observed. As the origin of these radionuclides could not be clearly explained, new samples have been taken and analyzed. The results of this extended investigation are given in the present paper. In addition to providing a general description of the background radioactivity level the main goal was to outline possible origins and migration pathways for radionuclides in the different organic soil and peat layers.

2 GEOLOGY

The topography of the area is mainly flat, slightly declining to the east with about a 35 m level difference over a 10 km distance. The bedrock has few and small outcrops and consists of granite (85 %), greenstones (about 7 %), dyke porphyries (about 6 %), the rest containing mafic and aplitic dykes.

The granites are grey-red to red and medium-grained to coarse medium-grained. The mineral composition is quartz, plagioclase, K-feldspar and a minor amount of dark minerals. The dyke porphyries are usually similar to the granite in composition but seem to be slightly more radioactive. The greenstone and mafic rocks have, as expected, low Th and U concentrations as seen from Table 1.

The bedrock is strongly fractured which is interesting from the migration point of view as groundwater from the bedrock may be able to reach the organic soil and peat layers, via fracture zones.

The overburden is mostly composed of glacial till with an average depth of 4 m. Bogs and fens are frequent and are often formed by terrestrialization (e.g. former lakes being transformed into peatland). The till soil in the western and north-western part of the area is rich in large granite boulders, which probably have a local origin. Towards the central part, the boulders decrease in size and in the eastern part, a more gravel-like till is found. The direction of the glacial ice movement was mainly from NNW to SSE (KNU 71).

3 HYDROLOGY

The general hydrological system is described by Sundblad et al (SUN 85). The western part (10 % of the total area) is drained by Hermantorpbäcken, a tributary to Hagebyån. The topography is flat with low hydraulic gradients. The total height difference within the western catchment area is about 15 meters.

The study concentrated on the western part of the area (Figure 1) with the main interest focused on a bog, called "Långesjön", see Figure 2. The main inlet to the bog is situated in its north-western part and covers about 2/3 of the total catchment area, which is 3 km^2. Two small inlets are also found in the northern part of the bog.

The bog is drained by two small brooks with the main outlet ("Confluence"), in the south-eastern part of the bog. In the south-western part the other brook ("Brook west") drains a small part of the bog and a slope area to the west of the bog.

The bog had earlier been ditched, resulting in a network of shallow dikes. This drainage lowered the ground water level about 0.5 - 1.0 meter. Generally, drainage of peatland results in lower groundwater level, lower evapotranspiration and higher discharge, but, only 10 - 30 % of the water in the peat is free and can be drained (GRI 77).

Two fracture zones occur in the bedrock underneath the bog. One has a north to south direction in the middle of the bog area (zone 12, Figure 1), and the other one goes from west to east just in the southern border of the bog area (zone 4, Figure 1) (SEH 86). Observations of the groundwater table in boreholes through the fracture zone 12, indicate artesian groundwater (SGA 85).

Alternative inflows of water to the bog are precipitation on the bog surface, surface water from inlet brooks, groundwater from the surroundings close to the bog and finally groundwater from fracture zones.

4 SAMPLES AND METHODS

The investigation concentrated on the terrestrialized lake "Långesjö". Depth profiles through the peat layers were sampled near the "shore" (B in Figure 1) where high thorium and uranium concentrations had been observed (SUN 85) and in the central part of the bog (F in Figure 1). A horizontal profile traversing the bog (and the fracture zone in the underlying rock) was also sampled (the P-serie, Figure 2). For comparison an organic soil profile in a small outflow area was sampled (H in Figure 1). In both areas profiles of till soil from higher levels were also investigated (e.g C and I in Figure 1).

The peat samples were taken with a bog drill (sample size being Ø 22 x 500 mm), assayed for pH in the field and immediately transferred into plastic bags. In the laboratory the samples were (wet) weighed, dried at 105°C and ashed at 450°C. The analyses of minerogenic soil samples were carried out on fractions < 2 mm. The samples are characterized in Table 2.

Uranium was analyzed by Delayed Neutron Analysis (DNA) when large volume samples were available and by Instrumental Neutron Activation Analysis (INAA) on small samples. Thorium was determined by INAA. The Th-232 and U-238 activities were calculated using the relations 3.93×10^3 Bq/g Th and 1.24×10^4 Bq/g U, respectively. Ra-226, Ra-228, Th-228, Cs-137 and K-40 were determined by gamma ray spectrometry measurements.

5 STUDIED RADIONUCLIDES OF THE U-238 AND TH-232 DECAY CHAINS

This study comprised U (U-238), Th (Th-232), Th-228, Ra-226 and Ra-228 which are all members of the U-238 or Th-232 decay chains. The involved parts of the decay chains are shown in Table 3.

The half-life of Ra-226 is of the same order of magnitude as many Quarternary deposits and has been utilized for geological dating (FER 82). The observed concentrations of Ra-226 in secondary quarternery formations like peat bogs are determined by the amounts of primarily deposited Ra-226 and Th-230, the decay period and possible later re-distribution of Ra-226 (e.g. due to groundwater flow, diffusion processes or plant uptake). Radioactive equilibrium between Ra-226 and Th-230 is established within 6 000 - 7 000 years. Unfortunately, Th-230 could not be determined in the present study and Ra-226 is instead related to U-238 in the following.

Ra-228 and Th-228 are both members of the Th-232 family (Table 3). Radioactive equilibrium between Ra-228 and Th-232 is established within 25 years and between Th-228 and Ra-228 within only a couple of years. Observed radioactive disequilibrium is thus a valuable indication of recent migration processes of radium and/or thorium and indirectly of e.g. groundwater flow.

6 RESULTS AND DISCUSSION

6.1 Thorium, uranium and radium in peat

Th and U concentrations and Th/U ratios for peat samples are given in Tables 4a and 4b. Depth profiles are shown in Figure 3 and the horizontal profile in Figure 4.

Fredriksson et al (FRE 85) analyzed thorium and uranium in peat samples representing 146 Swedish bogs (selected as extractable for heat production) and carried out more detailed investigations of the Th and U distribution in four representative peat bogs. In Table 9 their results are compared to the Långesjö peat values.

The Långesjö peat is characterized by higher Th content than is usually found in peat from Swedish bogs. Its U content is similar to the average for Swedish bogs but is considerably lower than those in the Storflyten and Skettmyren bogs which are characterized as "uranium-anomaleous" (FRE 85). The ranges of the Th and U concentrations in the analyzed peat samples from Klipperåsen are 7.4 - 215 and 3.6 - 248 ppm ashed weight, respectively.

Th and U, when given in ppm dry weight, usually increase with depth, while the Th/U ratio decrease with depth (Figure 3). The lowest Th/U ratio was obtained in the bottom peat layers which rest on clayey limnic sediments (0.40 in profile "F" and 0.45 in profile "B"). Decreasing Th/U ratio with depth is also a general trend for most depth profiles in e.g. the Storflyten, Skettmyren and Ralbo bogs (FRE 85).

The P profile across the bog was sampled in order to find possible radioactive anomalies due to migration via the underlying fracture zones. The varying vertical distribution of the elements and the varying bottom topography makes it, however, difficult to interpret values from only one depth level (100-150 cm was chosen in this case) and only general trends of Figure 4 are commented.

Both Th and U are highest in the margin zones of the bog; this is a general observation (FRE 85) but could in this case also be related to the fracture zones. The highest Th/U ratios (and the lowest Th and U values) are found in the slightly-decomposed peat layers in the central part of the bog (e.g. sites P 6, P 7 and P 8).

Measured activities of Ra-226, Ra-228 and Th-228 are shown in Table 4a where the activity ratios Ra-226/U-238, Ra-228/Th-232 and Th-228/Th-232 are also listed. Depth profiles of the ratios are shown in Figure 3.

In profile F, the activity ratios decrease with depth and both Ra-228 and Th-228 deviate from equilibrium with Th-232. The shapes of the activity ratio curves are difficult to interpret because of the complexity of the processes behind and lack of data (e.g. the Th-230 activity). However, the observed decrease of Ra-226/U-238 with depth could simply be the result of Ra-226 decay and thus roughly reflect the relative age of the peat layers. The disequilibrium Ra-228/Th-232 values indicate on the other hand either a fairly recent migration or that migration processes are now going on.

The Ra-226/U-238 ratio is low, almost constant (or slightly increasing with depth) in profile B (Figure 3). The Ra-228/Th-232 ratio increases with depth and is as high as 3.7 in the lowest zone. Also Th-228/Th-232 increases with depth but has a lower value, 2.1, in the lowest zone (which rests on limnic clayey layer). We interpret the disequilibrium values as due to a very recent (or current) supply of Ra-228. The alternative case, i.e. a removal of Th isotopes seems to be less plausible.

6.2 Thorium, uranium and radium in soils

Values of Th, U, Ra-226, Ra-228 and Th-228 for the soil profiles are shown in Table 4a, in which the ratios Th/U, Ra-226/U-238, Ra-228/Th-232 and Th-228/Th-232 are also given. Depth profiles of Th, U, Th/U, Ra-226/U-238 and Ra-228/Th-232 are shown in Figure 5.

From Figure 5 (with Th and U expressed in ppm ashed weight) it is clear that both Th and U are leached from the eluvial (A_2) zone of the podsol profiles D and I and also strongly enriched in the organic layer of profile H. Assuming 11.6 ppm Th and 4.2 ppm U (averages of the lowest zones of the four profiles) for uninfluenced till, the leached fractions of Th and U in the A_2 zones are of the order of 50 %.

No significant enrichment of Th and U are observed in the upper organic zone (A_{oo}) of the podsol profiles. This is expected as the uptake of these elements in plants is small. The striking enrichment of the peat-like organic zone of profile H (sample 50) is probably caused by ion-exchange or adsorption processes rather than via the plant nutrient cycle. If we assume 11.6 ppm Th and 4.3 ppm for the minerogenic fraction of sample 50, its organic fraction then contains 2.4 ppm Th and 2.5 ppm U (Expressed as ppm dry weight). The Th/U is 0.96, i.e. similar to the ratios of the Långesjö peat samples.

The activity ratios show strong disequilibrium between the radium isotopes and their parent isotopes Th-232 and U-238 in the upper organic layers of the soil profiles. The cause of this is probably the much higher plant uptake of radium isotopes as compared to thorium and uranium (SUN 85). When the plant debris are decomposed, the radium isotopes become enriched in the upper organic layers. Due to its shorter half-life, Ra-228 decays faster than Ra-226 resulting in the usually higher Ra-226/U-238 ratio as compared to Ra-228/Th-232.

Such a differentiation of Ra-228 and Ra-226 is also clear from a comparison of equivalent Th/U ratios of Ra-228 and Ra-226 (i.e. the theoretical weights of Th and U in equilibrium with measured amounts of Ra-228 and Ra-226). The Th/U equivalents of Ra-228 and Ra-226 in three different plants and the Th/U ratios of the soils at the growing sites are compared in Table 5a. The values are surprisingly similar, indicating that the plants take up Ra-228 and Ra-226 in roughly the same proportions as Th and U occur in the soil. Equivalent Th/U ratios for Ra-228 and Ra-226 in the upper organic zones are, however, much lower. The averages of Th/U and Ra-228/Ra-226 ratios for minerogenic soil zones, upper organic soil zones and plants, respectively are compared in Table 5b. Although the number of analyses are too few, the values support the idea of "fractionation" of Ra-228 and Ra-226, due to different decay rates, in those organic zones which mainly constitute decomposed plant debris.

If the above interpretation holds, it offers in principle a method of estimating the turnover time of radium in the plant nutrient cycle (in this case, of the order of 5 - 10 years). Further investigations of the distributions of the radium isotopes in plants, soil water and the underlying soil layers are, however, needed for confirmation.

6.3 Cs-137 and K-40 in peat and soil profiles

Cs-137 in the peat and soil layers is derived from nuclear explosions in the 50's and 60's (the sampling was made before the Chernobyl accident occurred) and was originally deposited on the ground surface. The present distribution is thus the result of migration during the last 20 - 30 years. The activity of K-40 is in fact a measure of the potassium concentration and the activity values can be converted to % K. Values obtained for Cs-137 and K-40 are given in Table 6 and are also plotted in depth profiles (Figure 6).

The two Cs-137 depth profiles in the Långesjö bog are quite different. In profile F, the Cs-137 activity of the peat samples decrease with depth and has its highest value in the underlying limnic clays. In profile B the activity values are higher when compared to profile F and increase with depth. The total activity of the samples has been estimated for the two profiles and are given in Table 6. Most Cs-137 of the F profile is concentrated in the limnic clay layer (about 53 %) and in the upper most 0 - 100 cm peat (about 29 %). Also in the B profile most Cs-137 (about 71 %) is found in the lowest peat layer (150 - 180 cm). This enrichment of Cs-137 in the bottom zones of the bog is striking and could possibly be the result of an upward migration, e.g. via the fracture zones in the bedrock below.

In Table 6 the Cs-137 concentration is also related to stable Cs whose present distribution in peat and organic soils is the result of natural Cs migration over long time. The stable Cs, when expressed as ppm of ash weight, does not vary notably between the different types of sample (range 0.79 - 7.7 ppm and with the averages 3.4 ppm for peat, 3.7 ppm for limnic clay and 3.1 ppm for till soil, respectively). The ratio Cs-137/Cs is high in the uppermost layer of profile F and decreases with depth whereas the opposite is the case for the profile B (Figure 6).

The activity of Cs-137 (as well as the Cs-137/Cs ratio) is highest in the upper organic zones of the soil profiles. A major part of Cs-137 in this zone was probably fixed to the soil particles already at the time of deposition rather than by the plant nutrient cycle. A considerable fraction of the fallout Cs-137 has, however, moved downwards which become more clear when expressing Cs-137 in Bq/m^3. Estimates are shown in Table 7.

6.4 Radionuclides in water

Only Ra-226 and U have been analyzed in water from Klipperås. Values from selected samples are given in Table 8. Most surface water samples have Ra-226/U-238 ratios around 2 - 4; two of the analyzed samples are, however, outstanding:

- Groundwater from borehole 8 (which was artesian at the sampling occasion) has high Ra-226 activity (and probably even higher Ra-228 activity) and a Ra-226/U-238 ratio > 60.
- Water from the creek in the western part of the bog (sample VA-5) has the highest measured U value, 1.4 ppb, and low Ra-226 activity which gives a Ra-226/U-238 ratio as low as 0.2.

6.5 Chemistry

The pH of surface water from the Klipperåsen area varies between 4 to 5 whereas the pH of artesian groundwater from borehole was 7.3 (SUN 85). Chemical analyses of water samples are presented elsewhere (SUN 85).

The measured pH for peat and soil samples from the profiles A, B, C, D, E and F is plotted versus depth in Figure 7a, b. C and D represent higher levels of a glacial till area, A (a peat profile) is situated on the western border of the Långesjö bog, B within the bog (but close to A) and F in the middle of the bog. Site E is located in a small bog about 1 km east of the bog Långesjö (Figure 1).

According to Wiklander (WIK 76) Eutric histosols are characterized by pH values around 5.5 or higher while Dystric histosols have a pH lower than 5.5. This classifies the peat in profile D (range 3.6 - 4.2) and F (range 3.5 - 4.7) as Dystric whereas the peat in profile B, with a pH around 5.5, represents the Eutric type. The pH values measured at Klipperåsen agree well with those in the carefully studied Komosse bog: around 4.5 within the bog, 5.7 in glacial till and 7.0 for groundwater below the bog (JOH 74).

The shape of the pH curve along the P profile is interesting with increasing pH values west of the fracture zone (Figure 8). The interpretation of the pH curve (measured at one level) is, similarly to the radionuclide curves, difficult because of the varying bottom topography and irregular variation of pH with depth.

The cation exchange capacity (CEC) was measured for some peat samples. The values varied between 1.2 - 1.5 mekv/g which are rather high values compared to reported values between 0.07 - 1.9 mekv/g (AND 84). However, the base-saturation is around 5 %.

Tritium and oxygen-18 were also measured for some samples in surface water and water in the top layers of the bog. The tritium content varied very little, between 3.6 - 4.2 Bq/l. These values can be compared with the tritium content, about 3.5 Bq/l, of recent precipitation. The corresponding oxygen-18 values were -8.7 to -10.9 (% SMOW).

6.6 Tracing migration pathways and groundwater flows in peat with Cs-137 and Ra-228/Th-232 ratios

Ra-228/Th-232 disequilibrium and the presence of significant Cs-137 activity in a peat sample both indicate a present mobilization (or one which occurred within the last 20 years) of these radionuclides, i.e. indirectly revealing young groundwater flows (or possibly diffusion processes) at the sample site.

Cs-137 values (given as ppm ash weight) versus Ra-228/Th-232 ratios for the analyzed peat samples are plotted in Figure 9. The above given criterion of young groundwater flow is especially fulfilled by sample 6 (the bottom peat layer of profile B) but also by 5 (the 100 - 150 cm level of the same profile) and 21/22. The last sample represents the uppermost 100 cm of the profile and thus may also include immobilized Cs-137, still at its original deposition site.

Alternative migration pathways of Cs-137 and Ra-228 to the bottom horizon of profile B are:

1 Downward migration of surface-deposited Cs-137. A source of Ra-228 is, however, difficult to find for this alternative.

2 Upward migration via the underlying fracture zone. Infiltrating groundwater must then have carried Cs-137 from the surface of the catchment area down to the groundwater in the bedrock. The excess Ra-228 in the peat can in this case more easily be explained by the high radium content of the artesian water from borehole 8 (Table 8, sample VA-2) which intersects the fracture zone. Although only Ra-226 was analyzed in VA-2, the Ra-228 activity is

probably also high as the activity ratio Ra-228/Ra-226 usually is 2 to 5 and even higher in groundwater (FER 82).

3 A groundwater flow in the till soil at site A was observed and estimated to about 1.0 E-5 m/s. However, no other data, like Ra-228 and Cs-137 activities in groundwater, which can support this alternative are available.

A comparison between the runoff for different catchments within the Klipperås area shows an increased runoff for "Brook west". The mean runoff for the other catchments is around 7 l/s km^2 whereas the corresponding value for "Brook west" is about 15 l/s km^2. Although one must be aware of the uncertainty because of few runoff measurements, these values indicate, however, an excess of runoff caused by additional groundwater flows, e.g. from the fracture zones.

Cs-137 migration and the establishment of Ra-228/Th-232 equilibrium covers a period of about 20 years which is very short compared to the age of a peat bog. With a sampling scheme covering the volume of a bog a migration pattern of Cs-137 and Ra-228 would be obtained and indirectly also main flow patterns of groundwater (if the migration is not exclusively based on diffusion). The knowledge of groundwater flows and the migration of elements in peat is often limited, especially as regards the deeper parts of bogs.

7 CONCLUSIONS

Although some of the findings and interpretations given in the present report are based on very few analyses and thus have to be checked and confirmed by furhter investigations, they are summarized as follows.

Considerable enrichment of thorium and uranium in organic matter was observed in peat bogs (large depressions) as well as in peat-like horizons of soil profiles (small swampy depressions). In the latter case the probable origins of Th and U are nearby till soils in which considerable leaching of these elements from the eluvial zone was demonstrated (e.g. sites H and I). Problem of origins and migration pathways of Th and U in peat bogs are, however, much more complicated.

The Ra isotopes are separated from the parent Th and U by the preferential Ra uptake in plants. A differentiation between Ra-228 and Ra-226 was observed in A_{oo} layers and is interpreted as due to different decay rates. Estimates of the Ra residence time in the plant nutrient cycle by comparing the Ra-228/Ra-226 ratio in e.g. soil water, plants and the A_{oo} layer (zone of decomposed plant debris) is suggested.

The main parts of Cs-137 in the two vertical peat sections are found in the bottom layers. It is not quite clear whether this Cs-137 originates from the surface above i.e. vertical migration directed downwards or enters the bog with groundwater flows from below. The distribution of Cs-137 in the soil profiles clearly shows that part of Cs-137 has migrated downwards and probably also reached the deeper groundwater.

Ra-228/Th-232 disequilibrium and the presence of Cs-137 in a peat sample are together strong indications of current or recent migration and indirectly of groundwater flows. The use of these parameters (alone or together) for tracing groundwater flow pattern in bogs is suggested.

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Table 1

Th and U concentrations in rocks

Rock type	n	Th ppm	U ppm	Th/U
Granite	7	20.7	6.8	3.0
Quartzporphyry	1	26.8	11.0	2.4
Greenstone	1	0.81	0.87	0.93
Dolerite	1	1.7	0.57	3.0

Table 2
Composition of soil samples

Site	Type of soil	Depth (cm)	Water content (%)	Organic content (% dry w.)
A	Organic	10-20	73	81
A	"	30-40	81	85
A	"	50-60	81	56
B	Peat	50-100	89	91
B	"	100-150	90	90
B	"	150-180	90	71
C 1)	Humus	0-10	42	22
C	Eluvial horizon	10-15	27	8
C	Illuvial "	15-25	30	8
C	" "	25-35	13	2
F	Peat	0-100	87	95
F	"	100-200	90	96
F	"	200-300	90	95
F	"	300-320	92	63
F	Clay	320-330	41	3
F	"	330-345	26	2
H 3)	Peat	10-15	81	88
H	"	25-30	64	31
H	Till	40-50	30	4
I 4)	Humus	5-10	71	86
I	Eluvial horizon	20-30	23	3
I	Illuvial "	40-60	13	2
D 2)	Humus	5-7	47	42
D	Eluvial horizon	7-15	16	3
D	Illuvial "	15-30	8	3

1) Till soil profile on the western "shore" of Långesjön bog. The area is now clear cut.

2) Podsol profile. Samples of fern from this area has been analyzed (SUN85).

3) Swampy area (outflow) with peat-like organic soil developed on till.

4) Podsol profile at about 1 m higher level site H.

Table 3

Parts of the decay chains of U-238 and Th-232

Nuclide	Half-life	Decay type	
U-238	4.5 10^9 y	alpha	Analyzed
Tn-234	24 d	beta	
Pa-234	6.8 h	beta	
U-234	2.5 10^5 y	alpha	
Th-230	8.0 10^4 y	alpha	
Ra-226	1622 y	alpha	Analyzed
Th-232	1.4 10^9 y	alpha	Analyzed
Ra-228	6.7 y	beta	Analyzed
Ac-228	6.1 y	beta	
Th-228	1.9 y	alpha	Analyzed

Table 4a

Th, U, Ra and activity ratios in peat and soil samples

Site	Sample		Th	U	Th/U	Ra-226	Ra-228	Th-228	Ra-226/U-238	Ra-228/Th-232	Th-228/Th-232	Ash cont.
	No	Depth,cm	ppm D.W.	ppm D.W.		Bequerel/kg D.W.						% D.W.
F	21/22	0–100	5.0	4.0	1.3	61	42	42	1.2	2.1	2.1	4.78
F	23/24	100–200	5.4	6.3	0.87	78	42	40	1.0	2.0	1.9	3.65
F	25/26	200–300	7.6	9.8	0.78	71	44	46	0.59	1.5	1.5	5.09
F	27	300–320	13.8	34.5	0.40	168	36	62	0.39	0.65	1.1	37.3
F	28	320–330	11.3	7.8	1.5	68	42	37	0.70	0.95	0.83	97.3
F	29	330–345	8.9	4.4	2.0	62	30	24	1.1	0.86	0.68	97.6
B	4	50–100	11.1	15.4	0.72	85	39	48	0.45	0.89	1.1	8.8
B	5	100–150	6.6	9.9	0.66	64	43	47	0.52	1.7	1.8	
B	6	150–180	8.9	20.0	0.45	140	133	76	0.56	3.8	2.2	28.7
P 1	33	100–150	29.5	34.0	0.87	199	122	144	0.47	1.1	1.2	13.7
P 2	34	80–130	5.6	8.1	0.69	66	36	47	0.65	1.6	2.1	7.3
A	1	10– 20	11.8	13.3	0.89	88	38	60	0.54	0.82	1.3	19.2
A	2	30– 40	26.4	25.3	1.04	206	98	122	0.66	0.94	1.2	15.2
A	3	50– 60	43.9	35.1	1.3	295	192	238	0.68	1.1	1.4	44.5
C	8	0– 10	5.6	2.5	2.3	91	27	24	3.0	1.2	1.1	77.8
C	9	10– 15	7.5	2.9	2.6	84	24	29	2.3	0.81	0.98	92.2
C	10	15– 25	8.3	3.5	2.4	70	40	40	1.6	1.2	1.2	91.7
C	11	25– 35	10.0	4.0	2.5	65	46	50	1.3	1.2	1.3	97.9
H	50	10– 15	3.5	2.7	1.3	120	28	20	3.5	2.0	1.5	11.9
H	51	25– 30	9.8	5.6	1.8	96	36	38	1.4	0.93	1.0	69.0
H	52	40– 50	8.7	5.3	1.6	104	57	63	1.6	1.7	1.8	96.2
I	53	5– 10	1.3	0.49	2.6	75	11	15	12.2	2.2	3.0	14.1
I	54	20– 30	4.3	1.6	2.7	40	21	23	2.0	1.3	1.4	96.7
I	55	40– 60	13.2	3.6	3.6	155	59	73	3.4	1.0	1.3	97.5
D	13	5– 7	4.6	1.8	2.6							57.7
D	14	7– 15	4.6	2.0	2.3							97.0
D	15	15– 30	12.1	4.2	2.9							97.2

Table 4b

Th and U concentrations in peat samples of the horizontal "P" profile

Site	Sample No	Sample Depth, cm	Th ppm dry w.	U ppm dry w.	Th/U	Ash content % of dry w.
P 1	33	100-150	29.5	34.0	0.87	13.7
P 2	34	80-130	5.6	8.1	0.69	7.3
P 3	35	0- 50	0.77	0.70	1.1	2.1
	36	100-150	0.68	0.78	0.87	1.7
	37	150-200	3.6	4.4	0.82	3.6
P 4	38	70-120	1.6	1.0	1.6	2.3
P 5	39	100-150	0.14	0.12	1.2	1.3
P 6	40	0- 50	0.11	0.065	1.7	1.2
	41	100-150	0.071	0.045	1.6	0.83
	42	150-200	0.55	0.68	0.81	1.35
P 7	43	100-150	0.10	0.036	2.8	1.0
P 8	44	100-150	0.073	0.035	2.1	0.98
P 9	45	100-150	0.17	0.22	0.79	1.1
P 10	46	70-120	0.50	0.43	1.2	1.7
P 11	47	25- 75	2.8	2.7	1.0	2.42

Table 5a

Ra-228/Ra-226 ratios of plants (expressed as Th/U equivalents[x]) compared to Th/U weight ratios of underlying soil (values from SUN85)

Plant/soil types	Th/U equivalents of Ra-228/Ra-226 for plants	Th/U of underlying soil
Grass/peat	1.1	0.9
Grass/pasture ground	1.3	1.4
Fern/till soil	2.6	2.6

x) Theoretical weight ratio of Th-232 and U-238 in equilibrium with Ra-228 and Ra-226, respectively.

Table 5b

Averages of Th/U weight ratios and Ra-228/Ra-226 activity ratios for plants, upper organic soil zones and minerogenic soil zones

	Number of samples	Th/U	Ra-228/Ra-226 Activity ratio	Ra-228/Ra-226 Th/U equivalents
Plants	3	-	0.52	1.65
Soil: upper organic zones, ash cont. $<$ 15 % of dry w.	2	1.93	0.19	0.60
Soil: minerogenic zones, ash cont. $>$ 92 % of dry w.	11	2.29	0.47	1.51

Table 6

Cs-137, Cs-137/Cs ratio and K-40 in peat and soil samples

Site	Sample		Cs-137			Cs-137/Cs$^{x)}$	K-40	Ash content
	No	Depth, cm	Bq/kg dry w.	Total activity of sample Bq	%		Bq/kg dry w.	% of dry w.
F	21/22	0-100	16.3	0.65	29	240 10^{-10}	168	4.78
F	23/24	100-200	5.1	0.18	8	116	121	3.65
F	25/26	200-300	5.0	0.19	8.5	> 60	104	5.09
F	27	300-320	<15	< 0.04		< 45	330	37.3
F	28	320-330	23.5	0.52	52.7	23	1100	97.3
F	29	330-345	26.7	0.66		21	1030	97.6
B	4	50-100	< 15	0.32	9.9	< 200	100	8.8
B	5	100-150	42.2	0.76	23.6	491	91	9.6
B	6	150-180	212	2.14	66.5	754	430	28.7
P 1	33	100-150	-				200	13.7
P 2	34	80-130	5.5				94	7.3
A	1	10- 20	30.1			90	122	19.2
A	2	30- 40	21.3			-	178	15.2
A	3	50- 60	28.8			30	45	44.5
C	8	0- 10	89.2			303	576	77.8
C	9	10- 15	21.8			38	672	92.2
C	10	15- 25	15.9			23	741	91.7
C	11	25- 35	26.9			23	930	97.9
H	50	10- 15	29.7			> 200	104	11.9
H	51	25- 35	22.2			19	544	69.0
H	52	40- 50	11.8			10	752	96.2
I	53	5- 10	115			524	99	14.1
I	54	20- 30	11.8			48	688	96.7
I	55	40- 60	< 20			< 20	889	97.5

x) Weight ratio

Table 7

Estimates of volume concentrations of Cs-137 and Cs in profile C

Depth, cm	Cs-137 Bq/m^3	Cs g/m^3
0 - 10	3.6 10^4	0.37
10 - 15	1.6	1.3
15 - 25	1.1	1.1
25 - 35	3.5	4.6

Table 8

Concentrations of Ra-226 and uranium in water samples

Sample		Ra-226	U		Ra-226/U-238
		Bq/m^3	Bq/m^3	ppb	
VA-2	(Borehole 8)	150	< 5	< 0.2	> 60
Va-3	("Confluence")	15	7	0.28	4.3
VA-5	("Brook west")	4	34	1.35	0.2
VA-6	(Långegöl)	17	8	0.32	4.3
W-1	(Inlet west)	22	15	0.60	3.0

Table 9

Comparison between Th and U averages in peat of different bogs

	n	ppm ash weight			
		Th		U	
		mean	C_v(%)	mean	C_v(%)
Långesjö bog	28	57	0.93	66	0.97
Average of 146 bogs		40		70	
Björkeberg bog	37	20	2.15	11	1.73
Ralbo "	49	26	0.77	33	1.27
Storflyten "	76	40	0.53	537	1.71
Skettmyren "	78	27	0.44	212	3.03

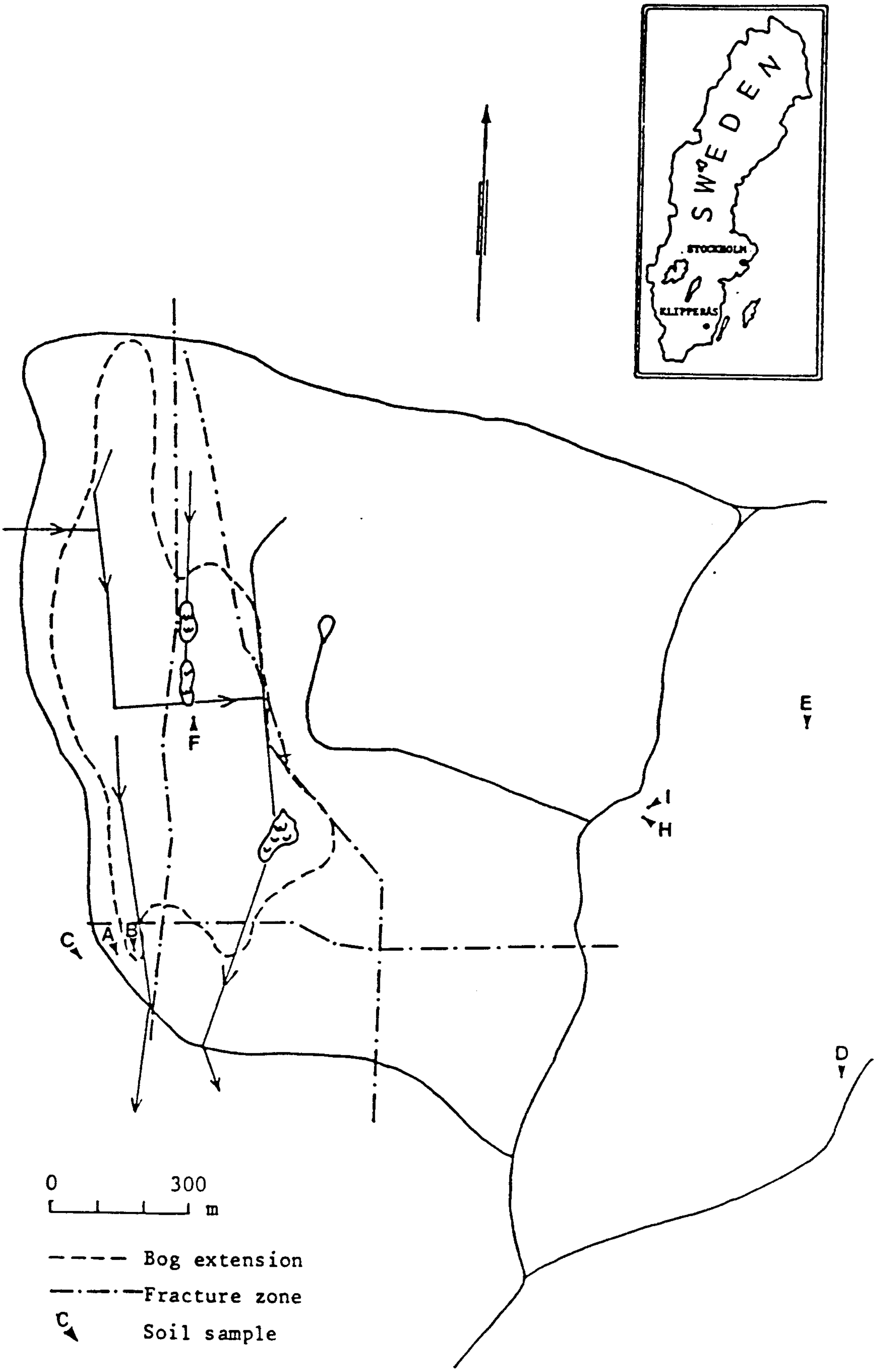


Figure 1 INVESTIGATION AREA AND SAMPLING SITES

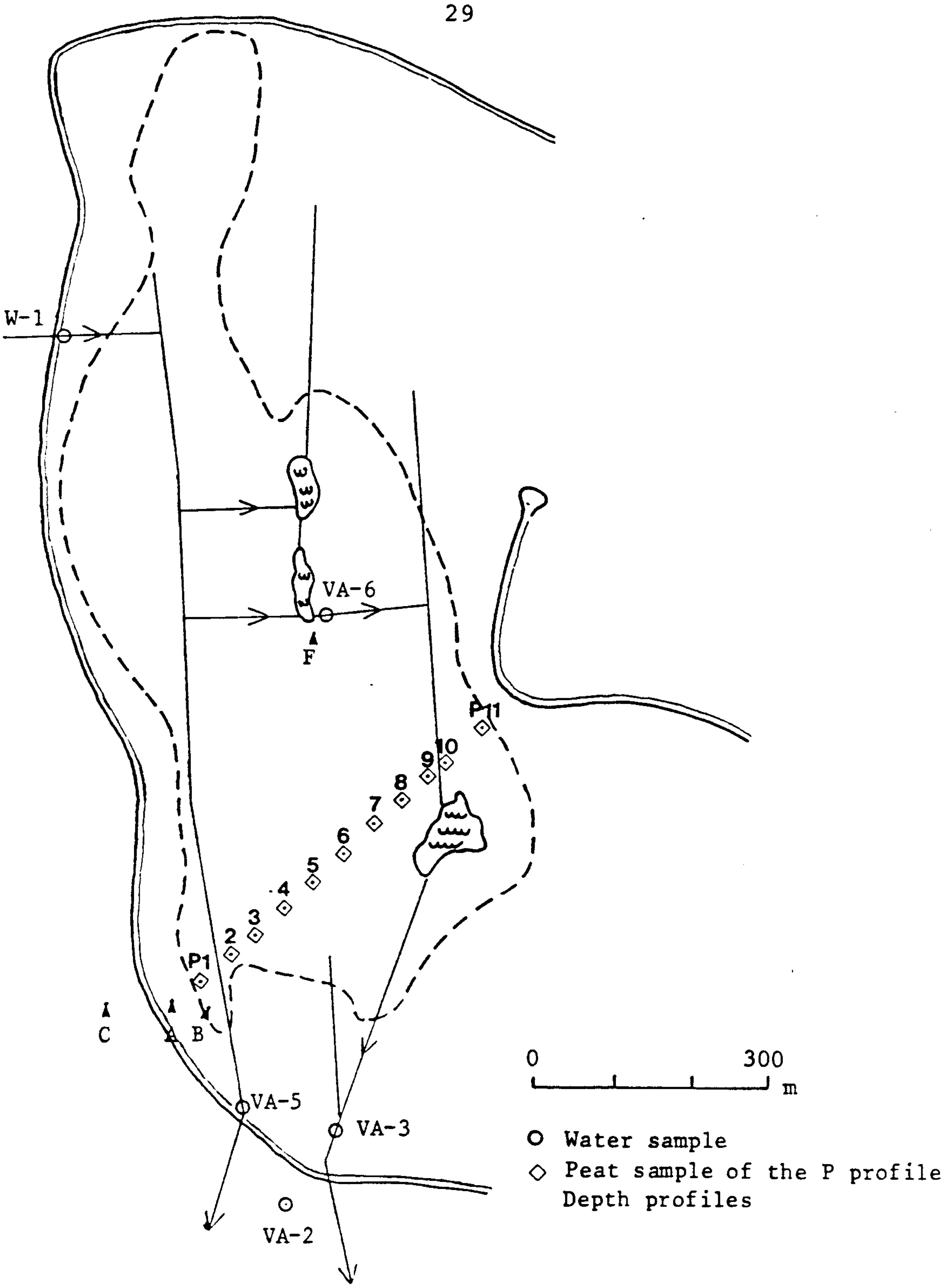


Figure 2 SAMPLING SITES IN THE "LÅNGESJÖ" BOG AREA

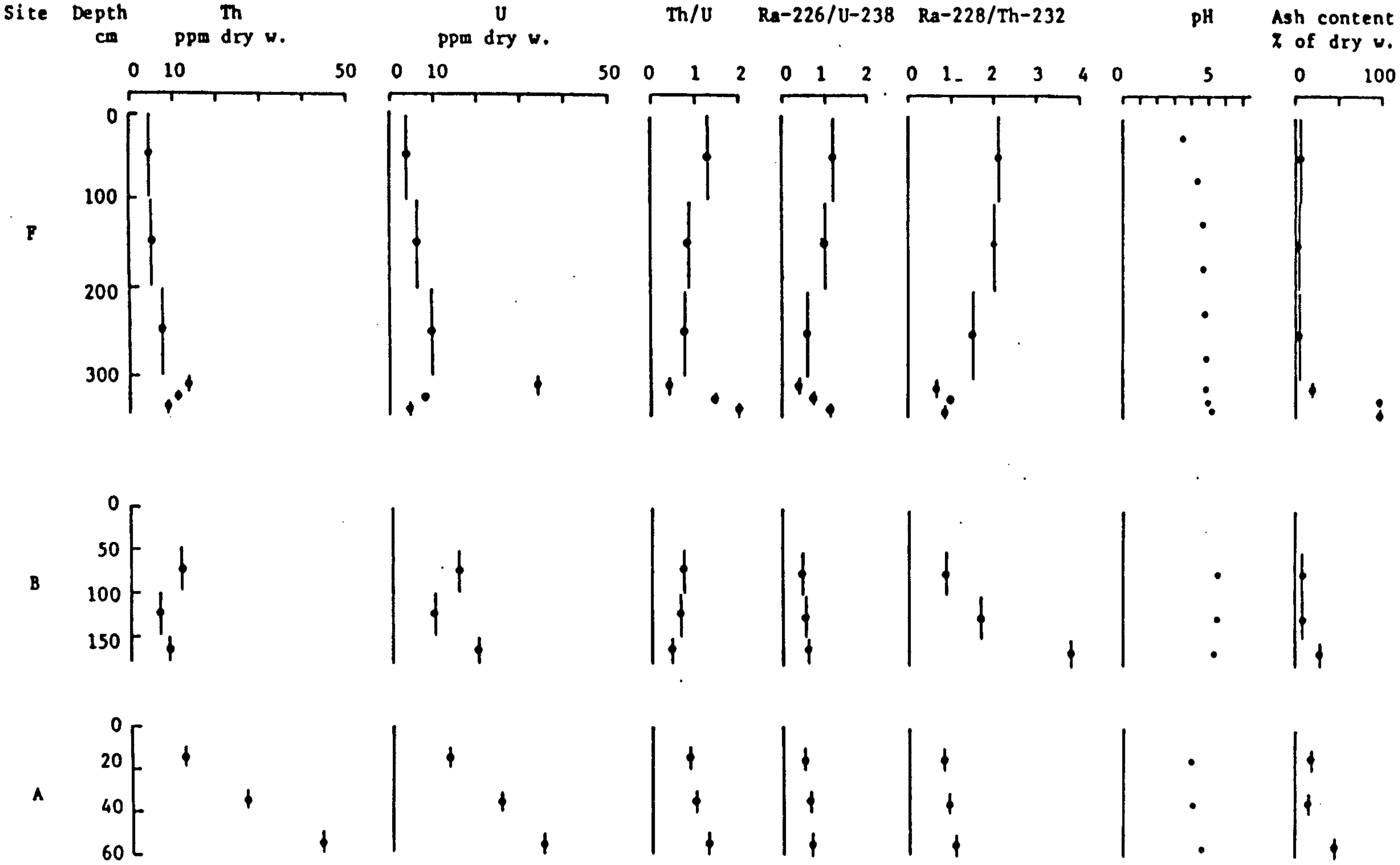


Figure 3 DEPTH PROFILES IN PEAT

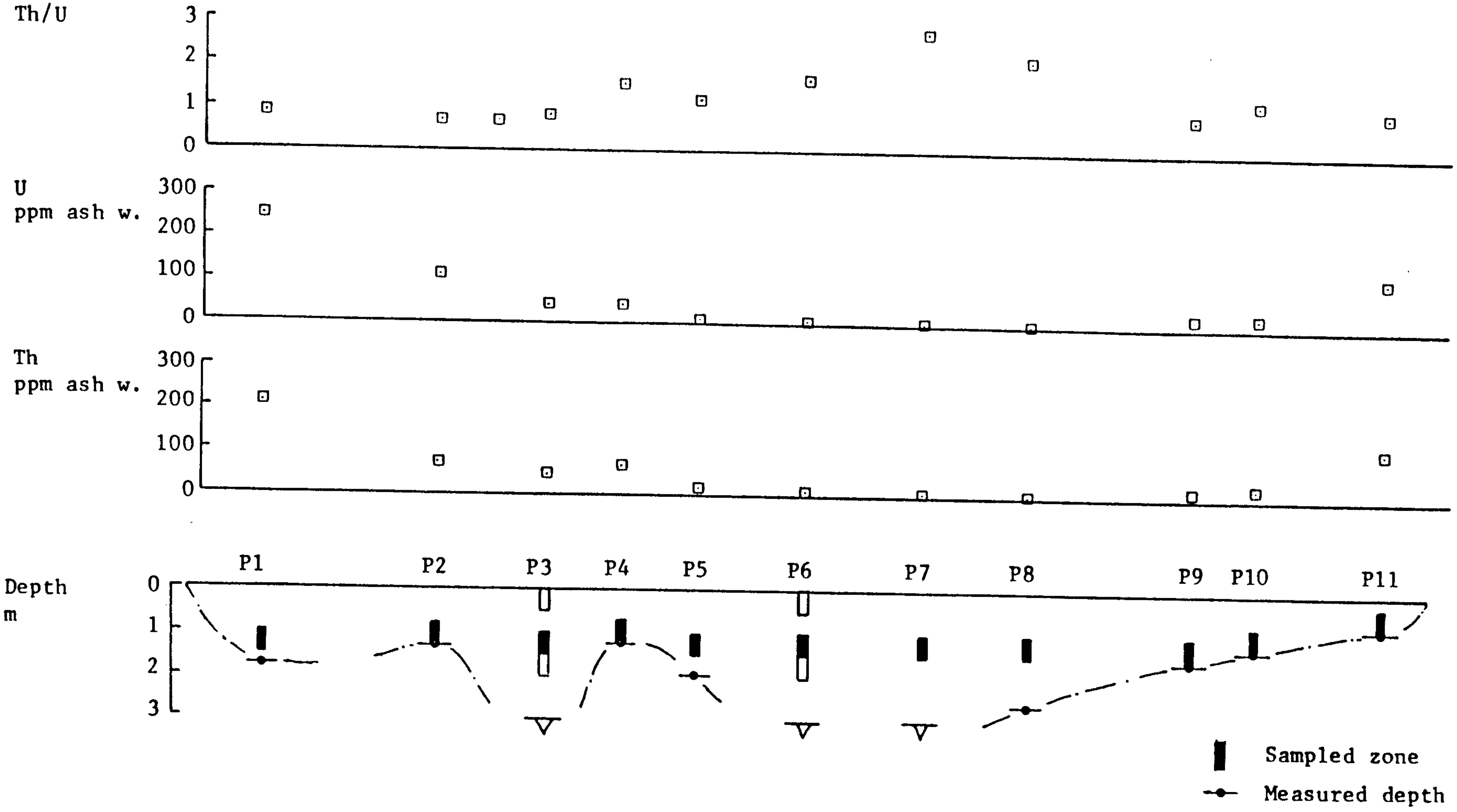


Figure 4 HORIZONTAL P-PROFILE IN PEAT

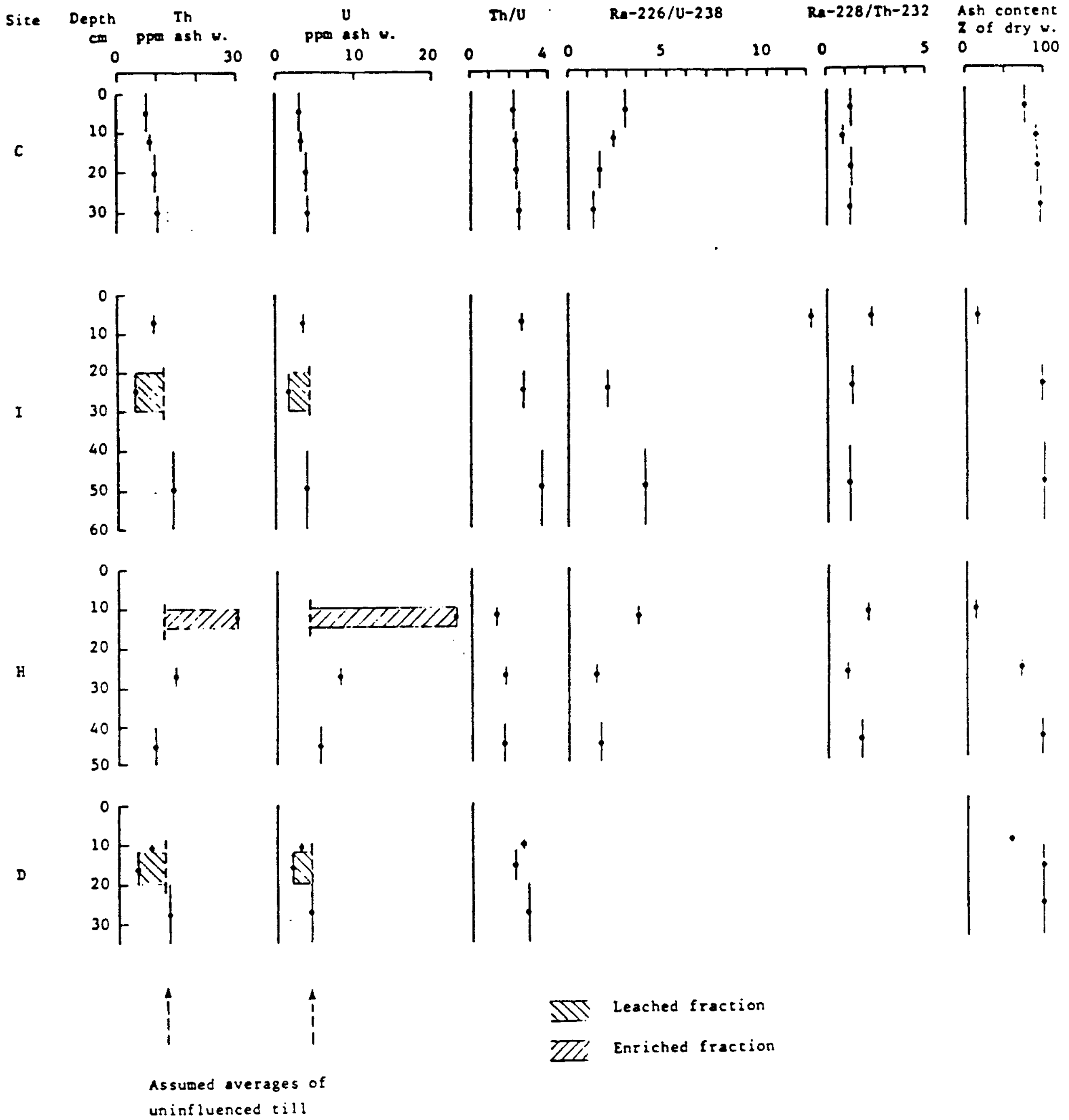
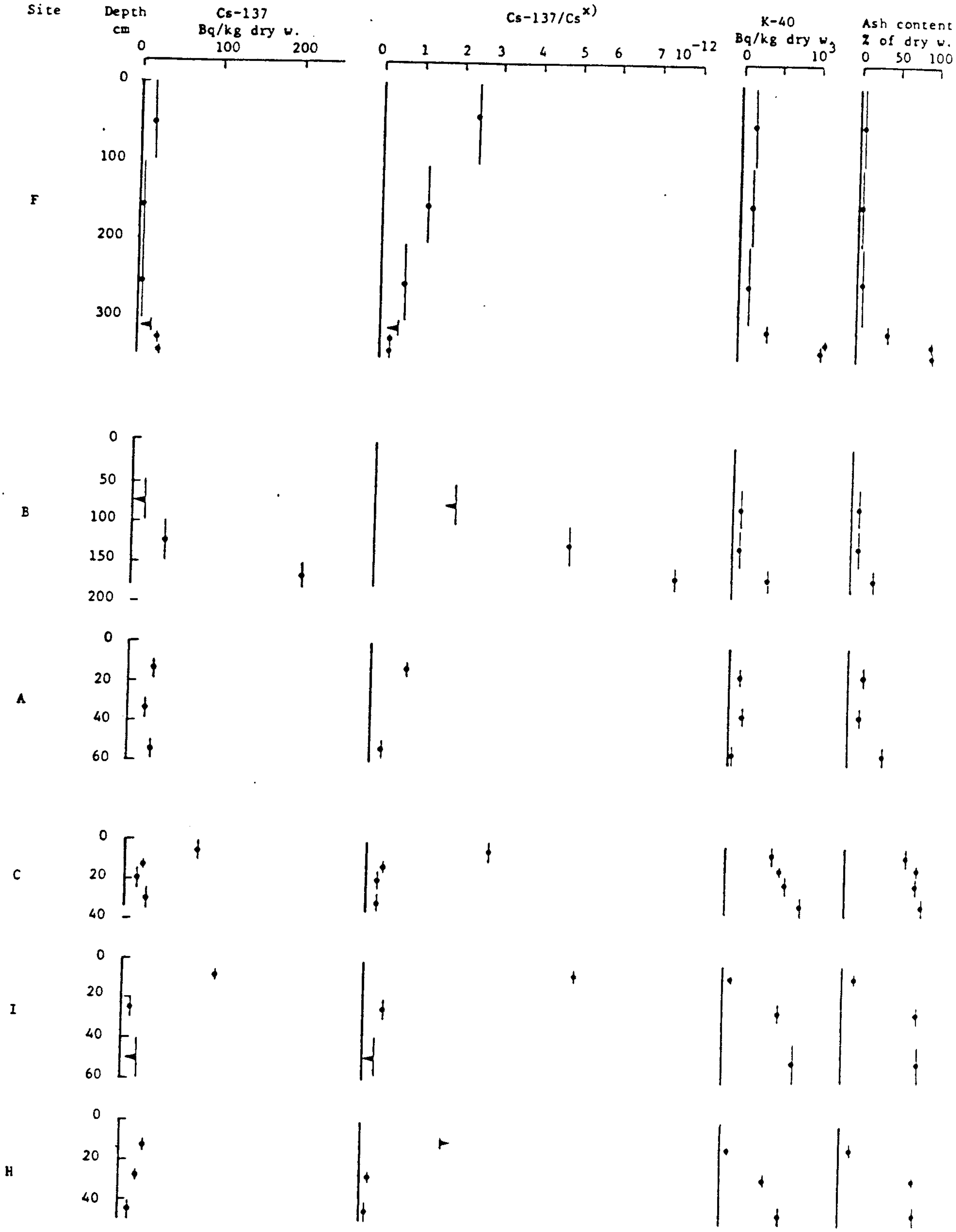


Figure 5 DEPTH PROFILES IN SOIL



x) Weight ratio

Figure 6 DEPTH PROFILES OF Cs-137 AND K-40

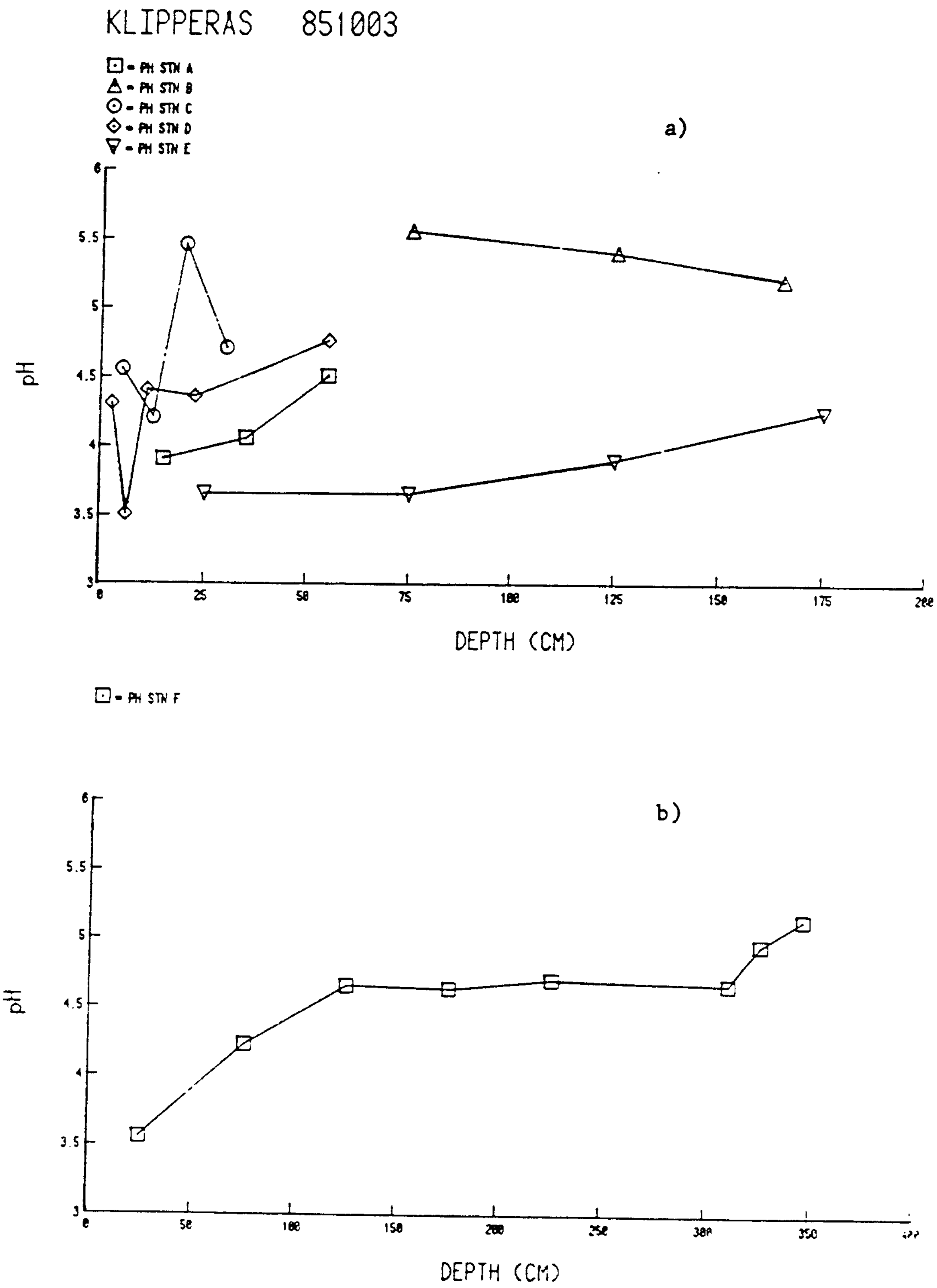


Figure 7 DEPTH PROFILES OF pH IN SOIL AND PEAT.
a) SITES A - E
b) SITE F

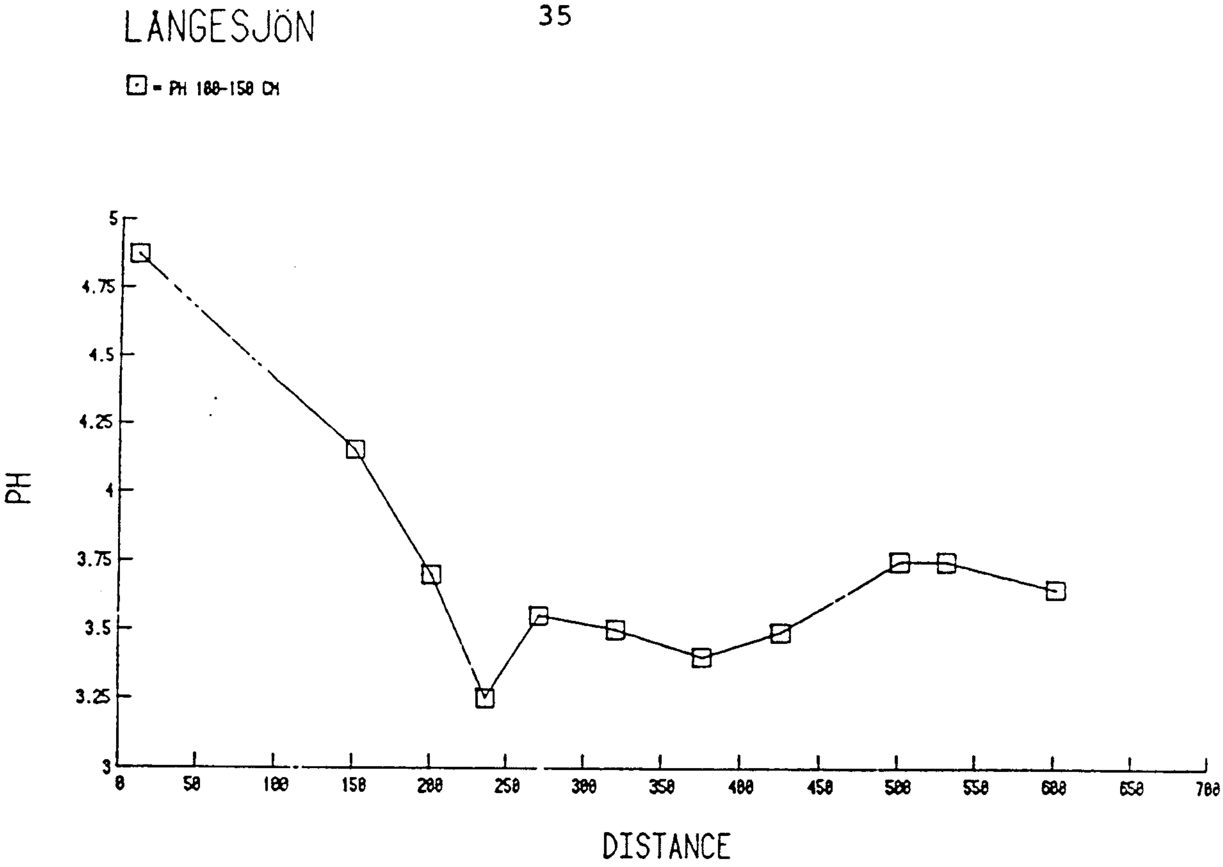


Figure 8 pH IN PEAT SAMPLES ALONG THE HORIZONTAL "P" PROFILE

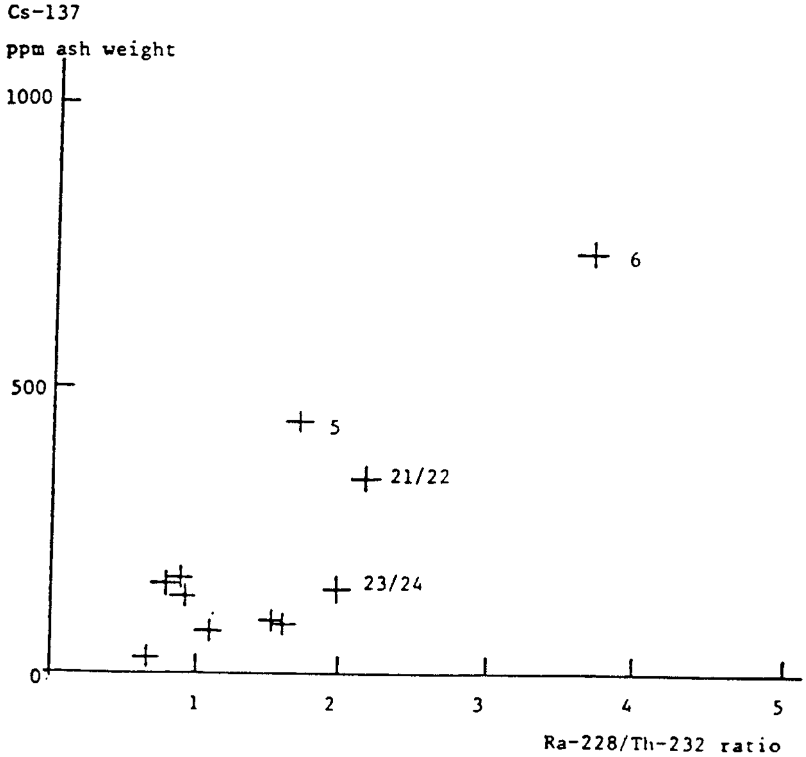


Figure 9 Cs-137 VERSUS THE Ra-228/Th-232 RATIO FOR PEAT SAMPLES

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B Allard
University of Linköping, Sweden
March 26, 1986

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Royal Institute of Technology, Stockholm, Sweden
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Risö National Laboratory, Roskilde, Denmark
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