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ENVIRONMENTAL RESEARCH AT THE MINING RESEARCH LABORATORY, CANMET, ELLIOT LAKE, ONTARIO, CANADA

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ELLIOT LAKE LABORATORY

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ENVIRONMENTAL RESEARCH AT THE MINING RESEARCH LABORATORY CANMET, ELLIOT LAKE, ONTARIO, CANADA

N.K. Dave* and T.P. Lim**

ABSTRACT

Mine/Mill Waste Management research at the Elliot Lake Laboratory started in the early seventies. The initial research activities were aimed towards reclamation of inactive tailings areas by revegetation to control erosion and to improve the general aesthetics. A major problem of all base metal and uranium mine tailings has been identified as oxidation and subsequent acid generation and leaching of tailings in the presence of secondary sulphide minerals of iron such as pyrite, marcasite and pyrrhotite which are not recovered in the milling process and are left with the tailings. Extensive biohydrogeochemical and contaminant migration pathway research has been undertaken to understand processes leading to generation, migration and release of contaminants from tailings via various environmental pathways. Two major tailings research programs: 1) National Uranium Tailings Program (NUPT), and Reactive Acid Tailings Stabilization Programme (RATS) have been undertaken to develop techniques that will enable the metal mine industry to ultimately abandon acid generating tailings in a predictive, cost effective and environmentally acceptable manner.

Key words: Reclamation; Revegetation; Tailings; Biohydrogeochemistry; Contaminant migration; Environmental pathways.

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RECHERCHE ENVIRONNEMENTALE AU LABORATOIRE DE RECHERCHE MINIÈRE CANMET, ELLIOT LAKE (ONTARIO), CANADA

N.K. Dave* et T.P. Lim**

RÉSUMÉ

La recherche sur la gestion des déchets de mine/concentrateur au Laboratoire de recherche minière d'Elliot Lake a débuté dans les premières années de 1970. Les premiers travaux de recherche portaient sur la remise en état des zones de résidus inactifs par la pose de végétation visant à limiter l'érosion et à améliorer l'esthétique générale. On a trouvé que tous les résidus de mines de métaux communs et d'uranium posaient un grave problème, celui de l'oxydation suivie de la production d'acide et de la lixiviation des résidus en présence de minéraux sulfurés secondaires du fer tels que la pyrite, la marcasite et la pyrrhotite qui ne sont pas récupérées lors de la concentration et qui sont rejetées avec les résidus. Des recherches poussées de biohydrogéochimie et des voies de migration des contaminants ont été entreprises pour comprendre les processus menant à la production, à la migration et à la libération de contaminants provenant des résidus par diverses voies environnementales. Deux grands programmes de recherche sur les résidus, (1) le Programme national de gestion des résidus d'uranium (PNGRU) et le Programme de stabilisation des résidus acides réactifs (SRAR) ont été lancés pour mettre au point des techniques permettant à l'industrie des mines de métaux d'abandonner ultimement leurs résidus acidogènes d'une manière prévisible, rentable et acceptable pour l'environnement.

MOTS CLÉS: remise en état, pose de végétation, résidus, biohydrogéochimie, migration de contaminants, voies environnementales.

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INTRODUCTION

Tailings research at the Elliot Lake Laboratory started in the early seventies. It was then recognized that the environmental problems associated with the mining and milling wastes were mainly caused by weathering and erosion. Reclamation of tailings areas to provide a stable natural cover such as vegetation was a very attractive option to rehabilitate the disturbed land and to reduce the environmental impact. The former location of the Elliot Lake Laboratory, adjacent to a large inactive tailings pile where during dry periods severe dusting problems were encountered, was an additional reason to start a tailings rehabilitation program. Since then the research has been pursued in various interesting fields of reclamation, hydrogeochemistry, contaminants migration, and cover technology. The overall objective of the research program is to develop a waste management technology such that, upon inactivity, mining wastes can be abandoned in an environmentally safe, cost effective and predictive manner.

BACKGROUND

Until 1985, most of the tailings research at the laboratory was done at local sites containing pyritic uranium tailings. Establishment of a Reactive Acid Tailings Stabilization (RATS) program in 1985 led to the work being carried out at other acid generating base metal mine tailings sites (containing high sulphides) in Ontario and Quebec.

There are about 180 million tonnes of uranium tailings in Canada. A majority of them, 150 million tonnes, are located in Elliot Lake (Figure 1), and the rest elsewhere in Ontario and Saskatchewan. Four of the sites: Quirke, Panel, Longlake and Crotch Lake are still operational waste management areas and the rest have been inactive since the early to late sixties. The

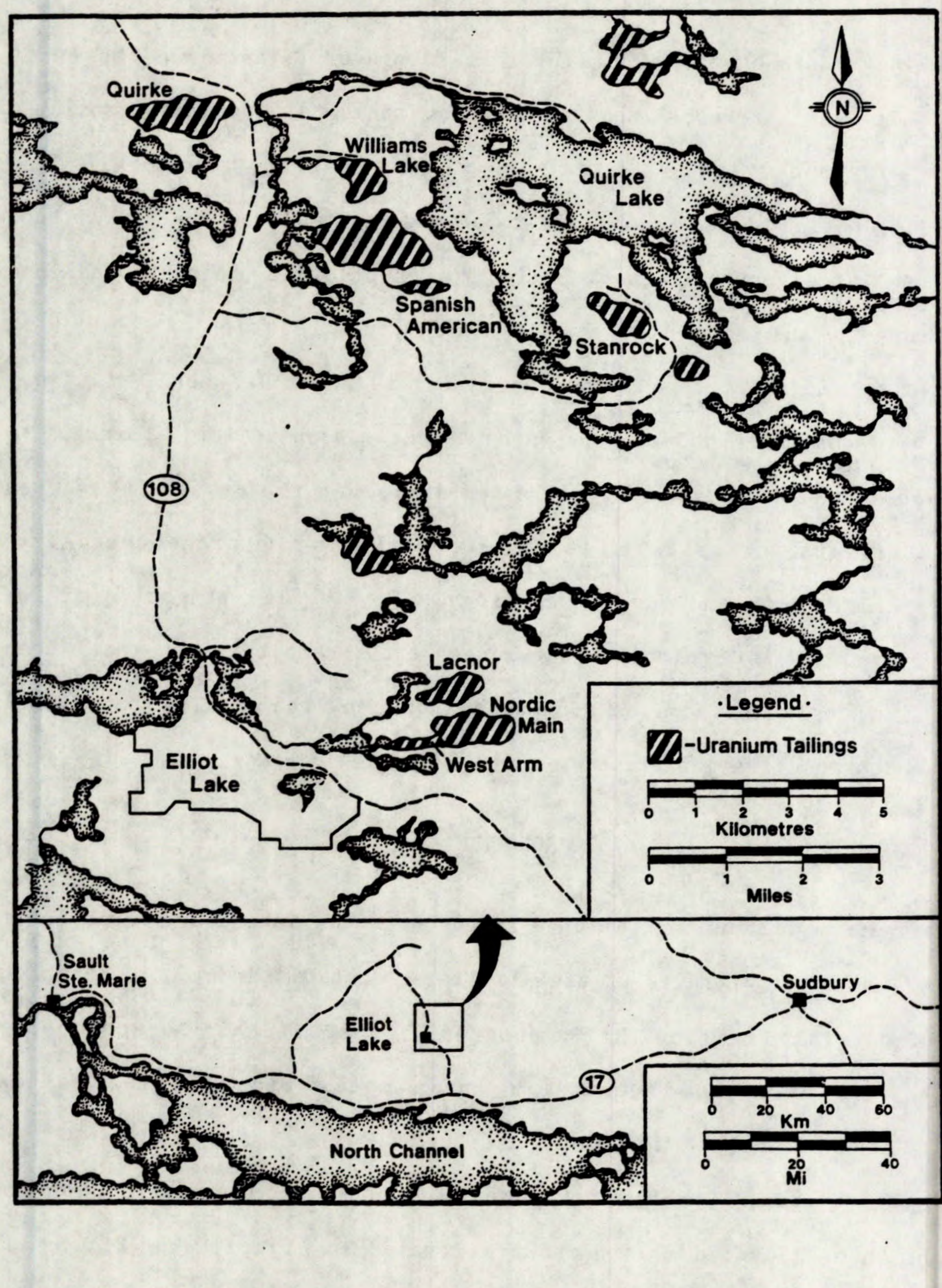

Fig. 1 - Location of uranium mine tailings, Elliot Lake, Ontario.

ore mined in Elliot Lake is a metamorphosed quartz pebble conglomerate containing 5-10% pyrite, 0.1% U_3O_8, 0.02% ThO_2, and approximately 0.056% rare earths, yttrium, cerium and neodymium oxides. The milling process involves grinding the ore to 55% smaller than 74 μm followed by acid digestion with hot dilute sulphuric acid. The resultant pregnant solution after clarification is passed through ion exchange columns where uranium is loaded on the ion exchange resin. The loaded resin is eluted with dilute nitric acid and uranium is precipitated from the eluate with ammonia or magnesia as diuranate. The concentrate is dried to make uranium concentrate product (yellow cake). The process effluent water containing SO_4^{-2}, NO_3^-, NH_4^+, Fe, Th, Mg and Ra-226 in solution is collected at the end of the mill circuit with the leached ore pulp where it is neutralized to pH 8-9 with limestone and lime, and then discharged to the tailings pond as a slurry containing 20% solids by weight. The solids are allowed to settle in extensive tailings impoundments, and the effluent is collected, treated with lime and barium chloride to meet the environmental discharge quality guidelines and discharged to the receiving water system.

Upon inactivity and weathering, the unstabilized tailings surface is subjected to wind and water erosion. The presence of other secondary minerals in the orebody, such as the metal sulphides of iron, like pyrite, marcasite and pyrrhotite, which are not recovered in the milling process and discharged to the tailings, causes oxidation of tailings. The process starts as an inorganic oxidation when water and oxygen are available and speeds up many times with the bacterial activities of the iron-oxidizing Thiobacillus-ferroxidans. This produces highly acidic conditions within the tailings which further leach residual minerals from the tailings, and thus produces highly acidic tailings porewater containing high total dissolved solids. With precipitation and recharge events, the oxidation reaction products are transported with surface run-off and sub-surface seepage to the surrounding natural water system leading to serious deterioration of its water quality, if left untreated. However, the mines treat the tailings effluent to meet environmental regulations.

This report provides an overview of the laboratory's research program. For details the reader is referred to appropriate publications listed in the bibliographic section.

RECLAMATION RESEARCH

The reclamation studies started with extensive growth chamber experiments and large scale field test plots to determine the proper amendments required for the tailings to support various agronomical species of perennial grasses and legumes. The tailings represented a very hostile environment with pH as low as 1.8, particle size varying from coarse sand and silt to slime fractions of silicious gangue material having very little nutrients or cation exchange capacity. Tables 1 and 2 describe the physical and chemical properties of the tailings in detail. Because of the oxidation of pyrite, the resultant leach liquor was very acidic (pH 1.8 to 2.5) with dissolved metals and sulphate contents in excess of 30,000 mg/L.

The first step was to neutralize the tailings surface to a depth of about 0.2 m with the application of agricultural lime and lime stone. Depending on the tailings size fraction, the lime requirements varied from 25-80 tonnes/hectare, the coarse fraction in general required less lime. Tables 3 and 4 respectively give the plant species used and their herbage yield. The most suitable agronomical vegetation species were perennial grasses: Creeping red fescue (Festuce rubra L.), and Red top (Agrostic alba L.), and a legume, Birdsfoot trefoil (Lotus corniculatus L.) in the ratio of 20:40:40. respectively at the rate of approximately 70 kg/ha.

Table 1 - Physical properties of uranium tailings

Size distribution (%)	
Fine sand (50 μm to 2 mm)	64
Silt/clay (2 μm to 50 μm)*	36
Field capacity (%)	1.2-7.3
Wilting coefficient (%)	0.3-0.7
Plant-available water (%)	0.5-7.0
Air entry value (cm H_2O)	50-100

* Clay-size particles have been identified, although there are no true platelike clay particles present.

Table 2 - Chemical properties of uranium tailings

pH	1.9
Cation exchange capacity (meq/100 g)	0.17
Extractable toxic metals (ppm)	
Al	22.2
Fe	250.0
Available nutrients (ppm)	
$N-NO_3$	3.04
P	0
Exchangeable bases (meq/100 g)	
K	0.041
Ca	7.61
Mg	0.003
Mineral content (% w/w oven dried)	
Si	41.3
Al	2.0
S	1.18
Fe	1.15
K	1.12
Ca	0.28
Mg	0.04
Pb, Mo, CO_2	0.05
Ni, Cu, Zn, Mn, P, Cl	0.01

Table 3 - Plant species used in field experiments*

Grasses	Legumes	Annuals
Colonial bentgrass	Vernal alfalfa	Vansoy soybeans
Creeping red fescue	Empire birdsfoot trefoil	Flax
Kentucky bluegrass	Black medic	Herta barley
Redtop	Penngift crownvetch	Broadleaf rape
Reed canarygrass	Ottawa red clover	Garry oats
Tall fescue	Yellow blossom sweet clover	Sunflower
Tetra petkus rye		United 107 corn
Climax timothy		Hybrid sudangrass sorghum
		Common lupen
		Yorkstar winter wheat

* Species underlined persisted through four growing seasons.

Table 4 - Mean herbage yield and percent ground cover for species growing on uranium tailings

Species	Yield (kg/m^2)	Ground Cover (%)
Reed canary grass	0.107	100
Ottawa red clover	0.016	10
Creeping red fescue	0.038	95
Birdsfoot trefoil	0.018	-
Redtop	0.066	100
Alfalfa	0.128	45
Tall fescue	0.046	88
Kentucky bluegrass	0.059	92
Climax timothy	0.056	81

Initial preparation of the seed bed included limestone and a balanced fertilizer 15:15:15 at the rate of 230 kg/ha worked well into the top 0.15 to 0.20 m of the tailings. About one week after the initial treatment the plant species were band seeded with 115 kg/ha of triple superphosphate (0-46-0). Subsequent maintenance fertilization was carried out monthly with 230 kg/ha of 5-20-20 for a total of 680 kg/ha in the first growing season. Table 5 describes the CANMET scheme developed for growing vegetation on pyritic uranium tailings. It entails a 5-year program of regular maintenance.

Following CANMET's scheme and others developed by the area mining companies, most of the inactive tailings sites in the Elliot Lake area have been revegetated since 1978. Stabilization of the tailings surface with a vegetative cover has reduced wind and water erosion and has developed a top 10-20 cm soil-like layer composed of decaying organic matter. The cover has greatly improved the general aesthetics of the area and the lush green vegetation has been self-sustaining. To a certain extent the amount of water percolating through the tailings is also reduced because of the increased evapotranspiration, but the overall quality of the water draining from a tailings area has not been improved.

With the establishment of a successful agronomical grass and legume vegative cover, the tailings have also been colonized by native vegetation including many shrubs and deciduous trees representing the species of the neighbouring forest. The most successful establishment has been along the roadways and at sites where the competition from the established grass was low. Among trees, both White Birch (B. Papyrifera marsh), and Trembling Aspen (P. Tremuloides michx) have been the most suitable. Because of the monoculture the growth of coniferous trees has not been very successful although two species, Jack Pine (Pinus banksiana) and Red Pine (Pinus resinosa) have been found to be the most adaptive.

Table 5 - CANMET scheme for vegetating uranium tailings

Year 1	Year 2	Years 3 to 5
Clear area of debris	Fertilize with 33-0-0 at 120 kg/ha	Fertilize with 33-0-0 at 120 kg/ha
Apply limestone at 25 to 80 tonnes/ha*	Reseed bare patches	Fertilize with 5-20-20 at 240 kg/ha***
Fertilize initially with 5-20-20 at 240 kg/ha	Fertilize with 5-20-20 at 240 kg/ha	
Rototill top 0.15 to 0.2 m		
Seed** and fertilize with 0-46-0 at 120 kg/ha		
Fertilize with 5-20-20 at 240 kg/ha		

* Rate of limestone application is specific to each tailings area.

** Seed recommended is a 20:40:40 mixture of Creeping Red Fescue, Redtop, and Birdsfoot Trefoil at 70 kg/ha.

*** Apply at monthly intervals during the growing season.

Figures 2 and 3 show one of the tailings sites (Nordic Tailings) before and after reclamation which represents the best success of such a program. Because of its proximity to the former location of the Elliot Lake Laboratory, Nordic site was selected as the experimental site for most of the tailings research program that followed. In 1985, about 20% of the vegetation was destroyed because of spring flooding where approximately 30% of the area was water logged. Since then, the damaged area has re-established itself with vegetation encroaching from the perimeter. The site was assessed in 1987 which showed an increased potential of regrowth with about 30% biomass yield and ground cover compared to that of the undamaged site.

HYDROGEOCHEMICAL INVESTIGATIONS

The hydrogeochemical investigations of tailings basins were first initiated to measure the success of the reclamation program in controlling the release of contaminants to the environment. The earlier studies were done to determine the flow patterns of surface and sub-surface water in a tailings basin and its quality. The studies gradually evolved into a complete hydrological and geochemical investigation of tailings for both vadose (unsaturated) and phreatic (saturated) zones to determine the origin and migration of contaminants. The tailings area was completely instrumented, after an initial geophysical and hydrologic survey, with multi-level piezometer nests along the major groundwater flow lines. At a given location, piezometers were installed at an interval of approximately 1 m to various depths in the tailings, into the formation below the tailings, and into the bedrock. In the area where the groundwater flow pattern was lateral, multi-level bundle piezometers were installed. Measurements of piezometer pressure heads determined the complete hydrological setting of the basin. For both unsaturated and saturated zones, solid core and porewater samples were

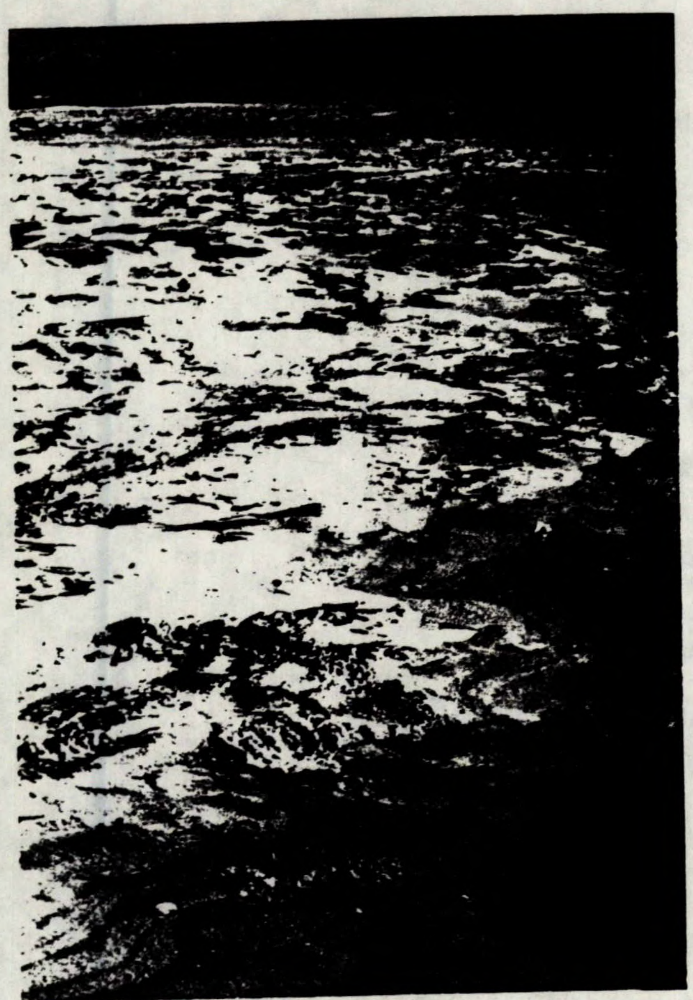

Fig. 2 - Nordic Mine uranium tailings: before revegetation (1971).

Fig. 3 - Nordic Mine uranium tailings: after revegetation (1984).

obtained for physical and mineralogical (for solids), and geochemical distribution profiles. In the unsaturated zone, tailings pore gas samples were also analyzed for oxygen, nitrogen and carbon dioxide component distribution profiles.

Figures 4 to 9 show the hydrogeochemistry of the Nordic tailings basin. In the unsaturated or vadose zone, the oxidation of pyrite starts in the top surface and the zone of activity gradually moves downward as the pyrite is consumed. The oxidation reaction products: hydrogen, sulphate, metal ions and radionuclides are released from solids to the tailings porewater as a result of subsequent leaching. With recharge events and infiltration, these products are gradually transported downward into the saturated zone below the water table known as the phreatic zone. In this zone, the residual neutralized porewater is thus gradually being replaced by the highly acidic containing high total dissolved solids recharge porewater. The acidic porewater joins the horizontal flow in the sandy aquifer near the tailings impoundment dams and appears as a contaminant plume in the surrounding formation (Figure 5).

The water table profiles of the study site are shown in Figure 6. The water table varied in depth from 1 m in the fine-grained tailings to approximately 10 m in the coarse-grained tailings site T-8. Below the water table in the saturated zone, as the acidic recharge porewater slowly migrates downward, the acidity is consumed by the residual alkaline buffer present in the tailings. The neutralizing process results in precipitation, and or, co-precipitation of iron and metal hydroxides or carbonates along with gypsum, thereby decreasing the dissolved metal concentrations in the porewater below the neutralizing zone. Heavy metals and radionuclides are also co-precipitated or adsorbed in this zone. The boundary between the original process water and fresh recharge water is marked by the high chloride levels which resulted from the use of sodium hypochlorite as oxidant in the original

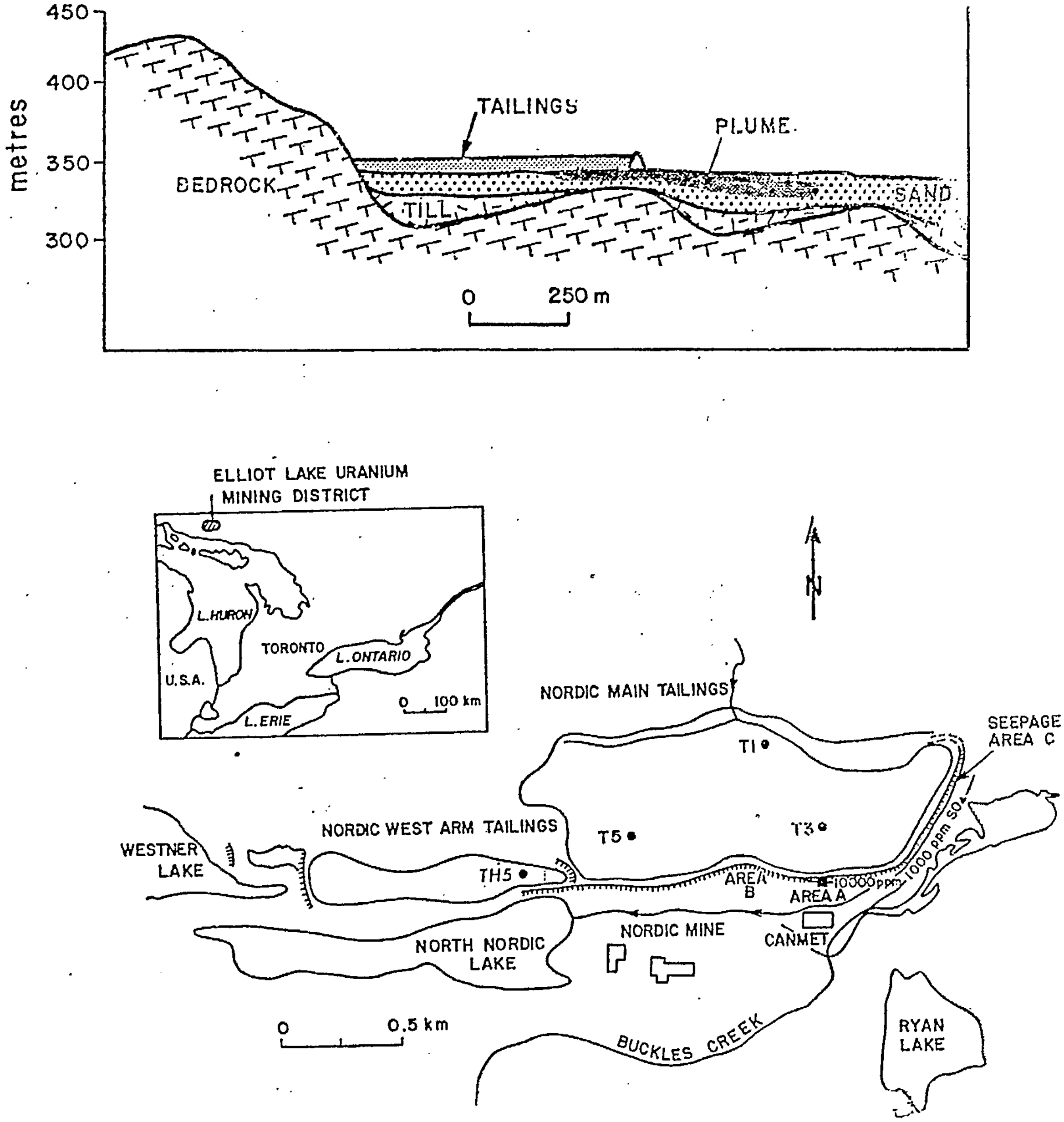

Fig. 4 - Generalized locations of the Nordic Mine tailings impoundments, monitoring sites and areas of acidic seepage, and geological cross-section through the Nordic Main tailings area.

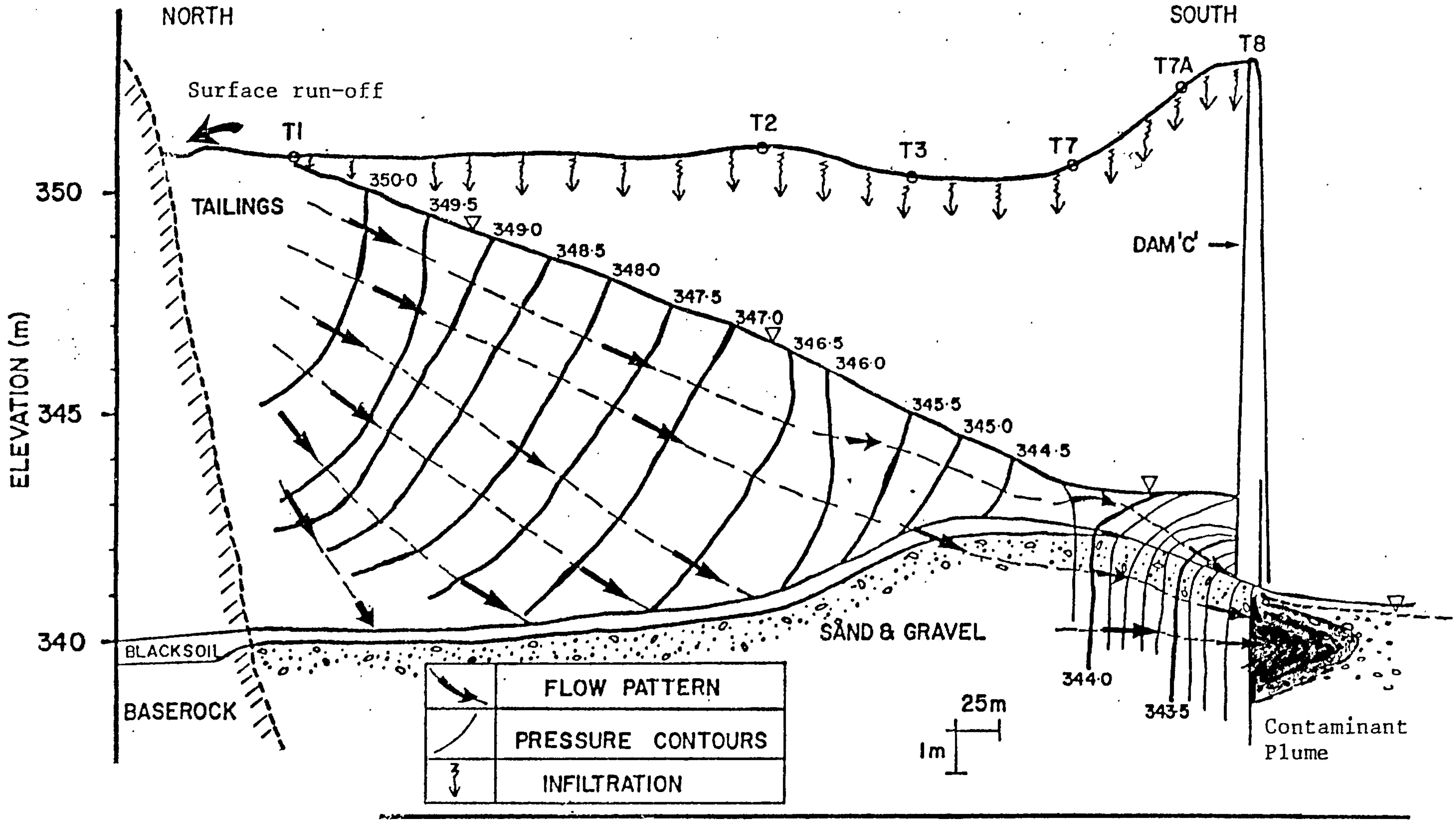

Fig. 5 - Overland based tailings management scenario - generation of contaminants and their migration as sub-surface seepage and surface runoff.

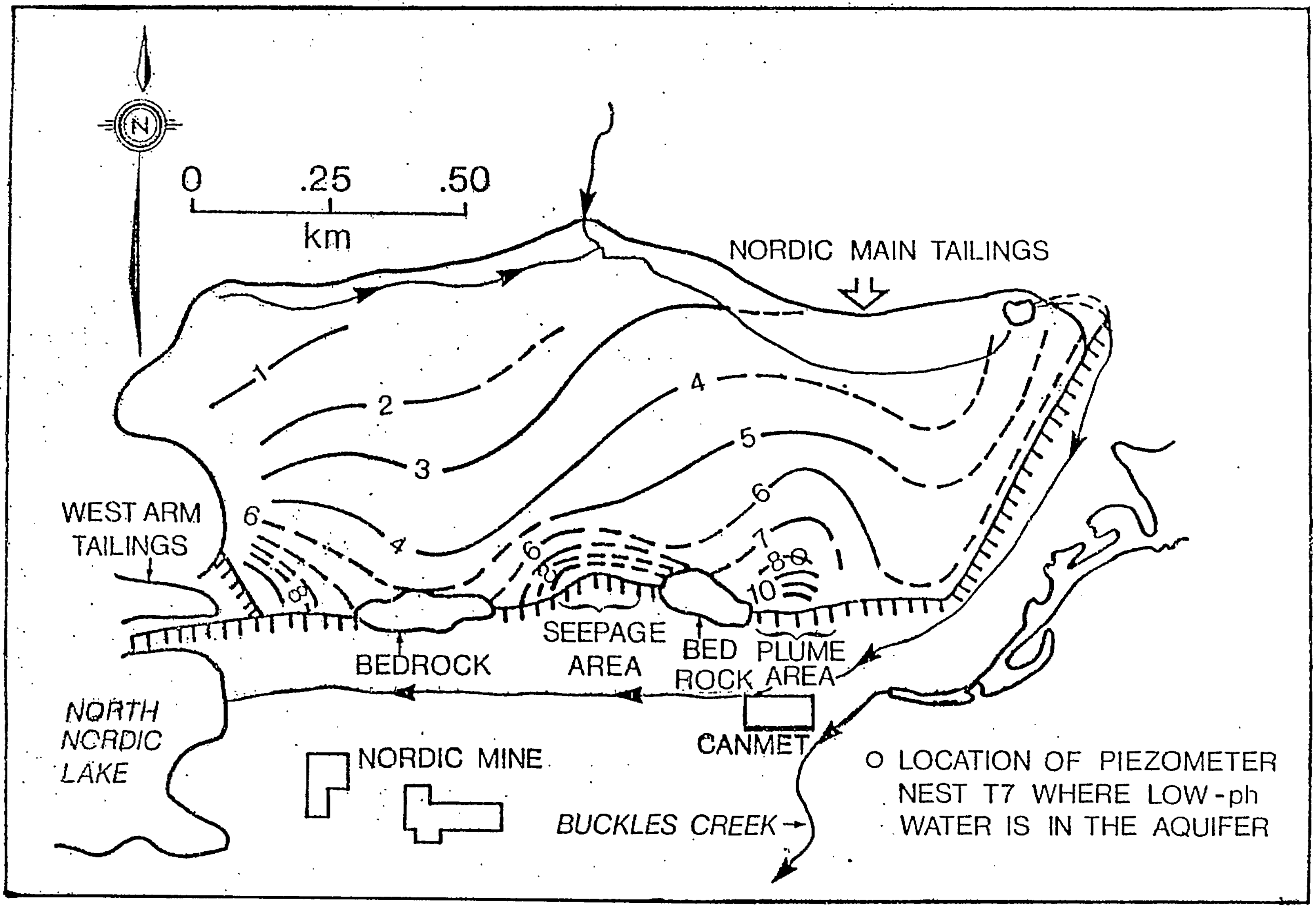

Fig. 6 - Map of hydrogeologic features in the study area (adapted from Cherry et al. 1980). Water-table contour interval is 1 m.

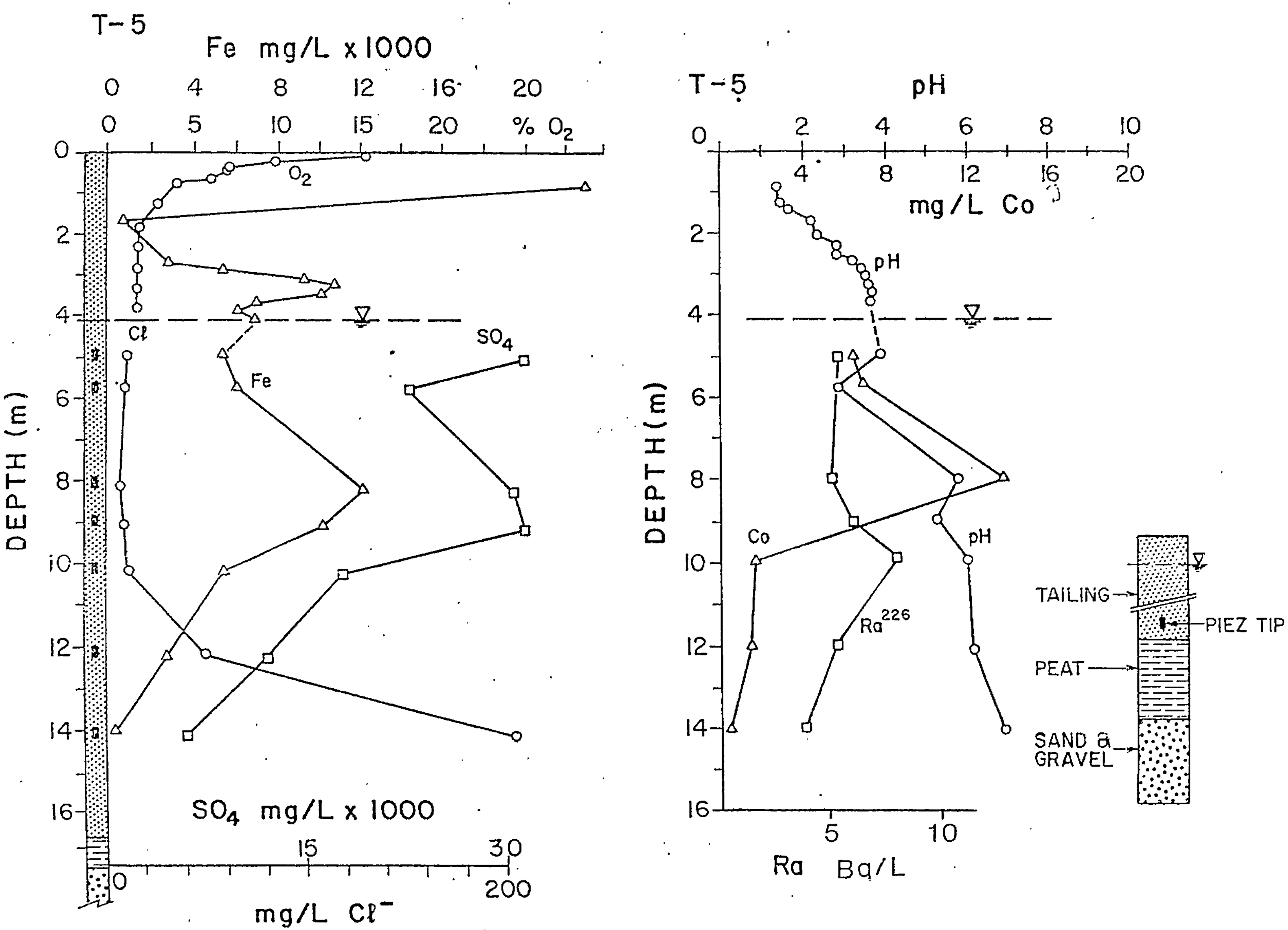

Fig. 7 - Hydrochemical profiles of pH, Cl, SO_4, Fe(total), Co, and Ra-226 of saturated and unsaturated and unsaturated zones and O_2 gas content of unsaturated zone at a coarse-grained site, T-5, on Nordic Main tailings.

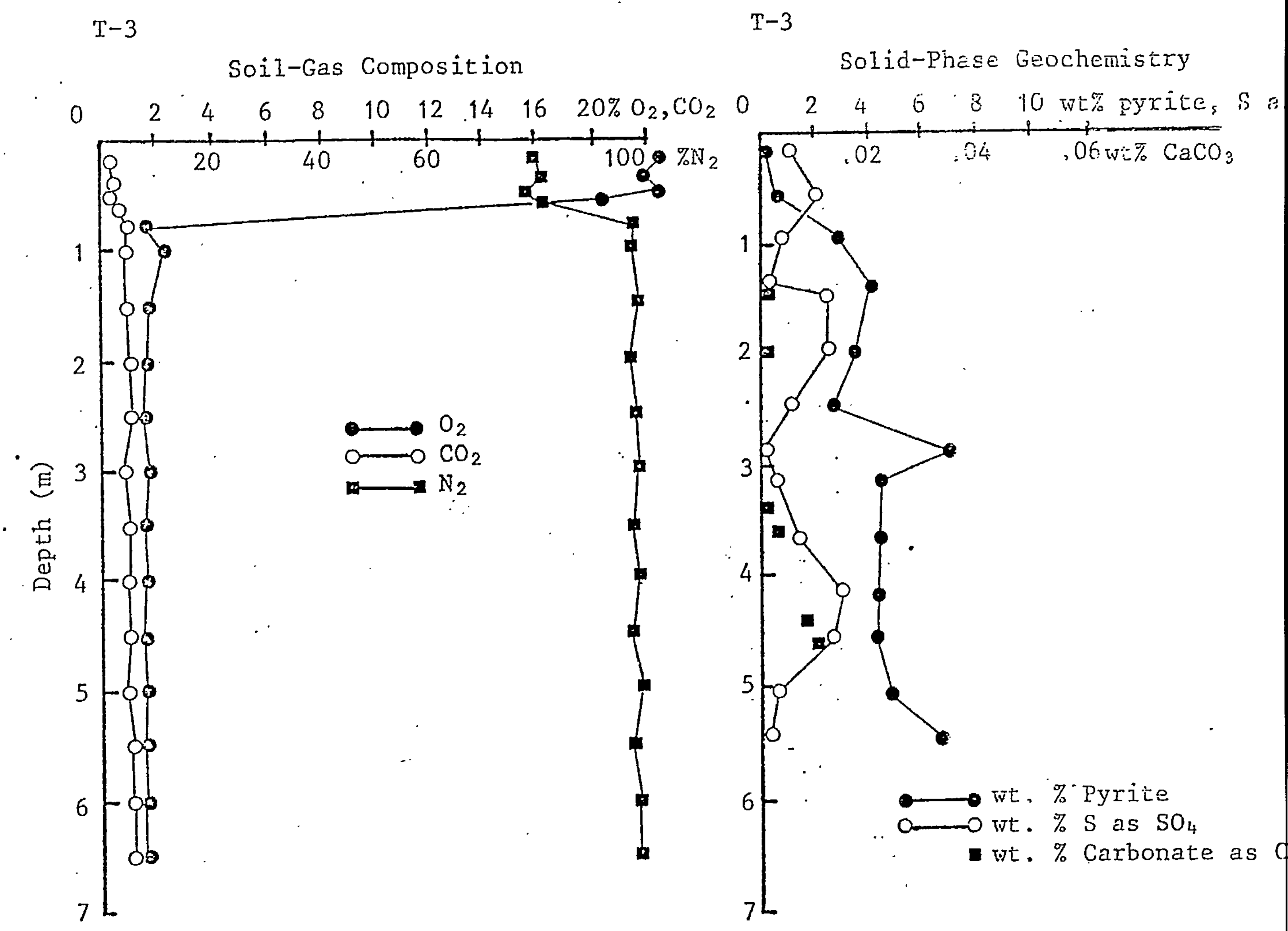

Fig. 8 - Soil-gas composition and solid-phase geochemistry profiles at a medium-grained site, T-3, on the Nordic Main tailings.

T - 3

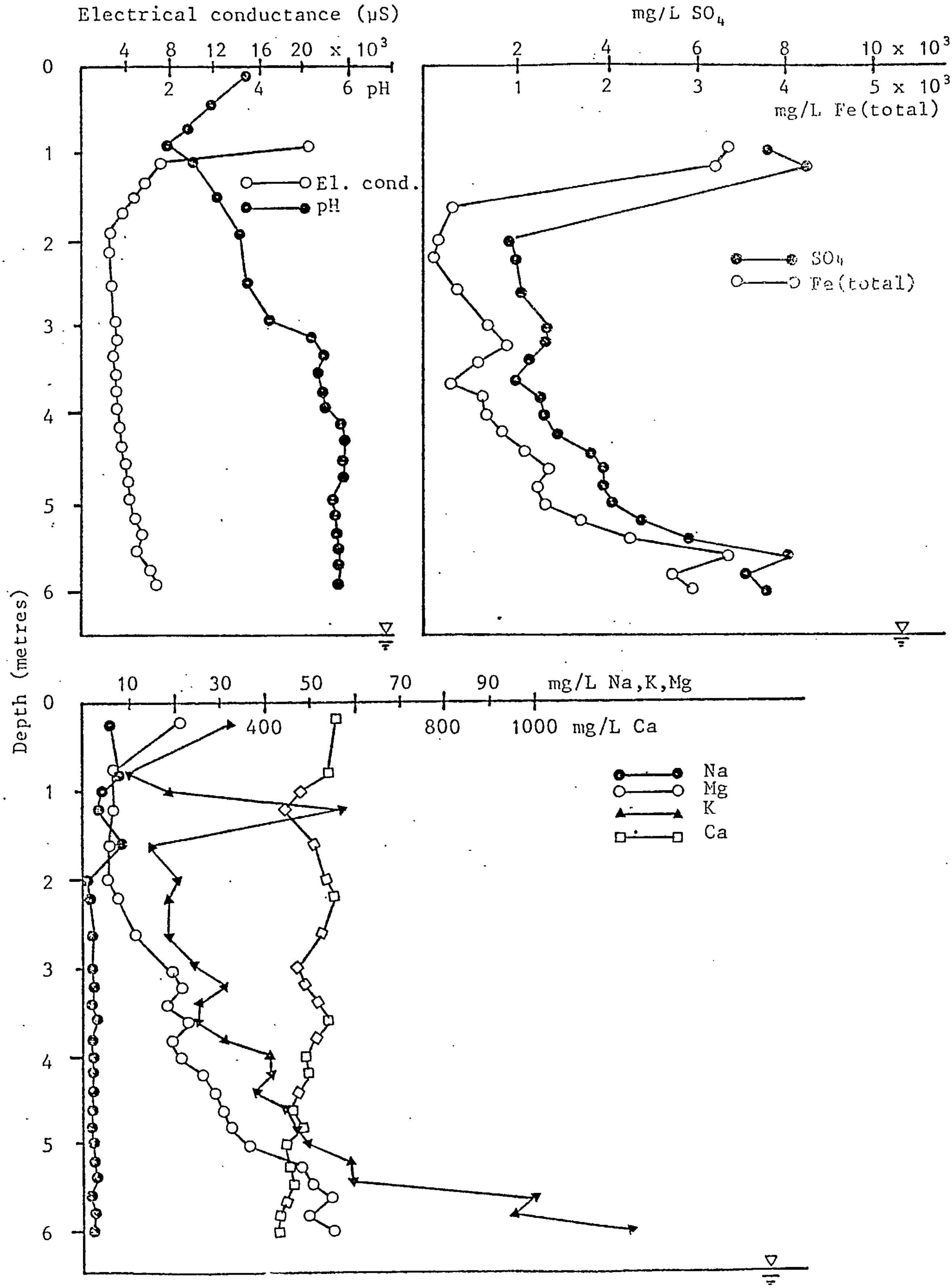

Fig. 9 - Hydrochemical profiles of pH, electrical conductance, SO_4, Fe(total), Na, K, Mg and Ca of unsaturated zone at T-3 site on the Nordic Main tailings in August 1980.

milling process (Figure 7). Similar results were observed for a medium-grained tailings site (T-3) where the active zone of oxidation was shallow because of decreased porosity and higher pyrite content associated with finer particle size (Figures 8 and 9). In the oxidized zone, pyrite has been completely altered and the acidified zone is indicated by the consumption of the alkaline buffer $CaCo_3$ below the active zone of oxidation. To a certain extent oxidation also takes place within the watertable fluctuation zone where some bacterial activity was also observed.

At the bottom of the tailings where a black peat layer exists, varying in thickness from 0.3 to 1 m, anoxic conditions were observed which supported sulphate reducing bacteria (as evident by the presence of H_2S). The action of these bacteria coupled with the reduced hydraulic permeability and increased ion exchange capacity of the peat layer retarded the migration of metals and radionuclides in the alluvial deposit below the tailings - peat interface layer.

Figure 10 shows the tailings solid phase chemical profiles. The results show that within the tailings two distinct zones of stratification exist; an upper zone of slightly increasing, or uniform, concentration of constituents with depth except in the top 1 to 2 m, where the concentrations were low, and a lower zone, approximately 1 m in thickness, near the tailings - peat interface, where the constituents were concentrated. In the peat layer underneath the tailings, the concentrations of various constituents decreased rapidly with depth. No significant levels of contaminant penetration below the peat layer were observed. The top 2 to 5 m tailings layer has been acidified with an average pH in the range of 3.8 compared to 5.8 to 6.5 underneath it. Ra-226 concentrations measured in the solution phase were in the range of 3700 to 5500 mBq/L in the tailings porewater, and 50 to 80 mBq/L in the groundwater beneath the peat layer near the bedrock contact.

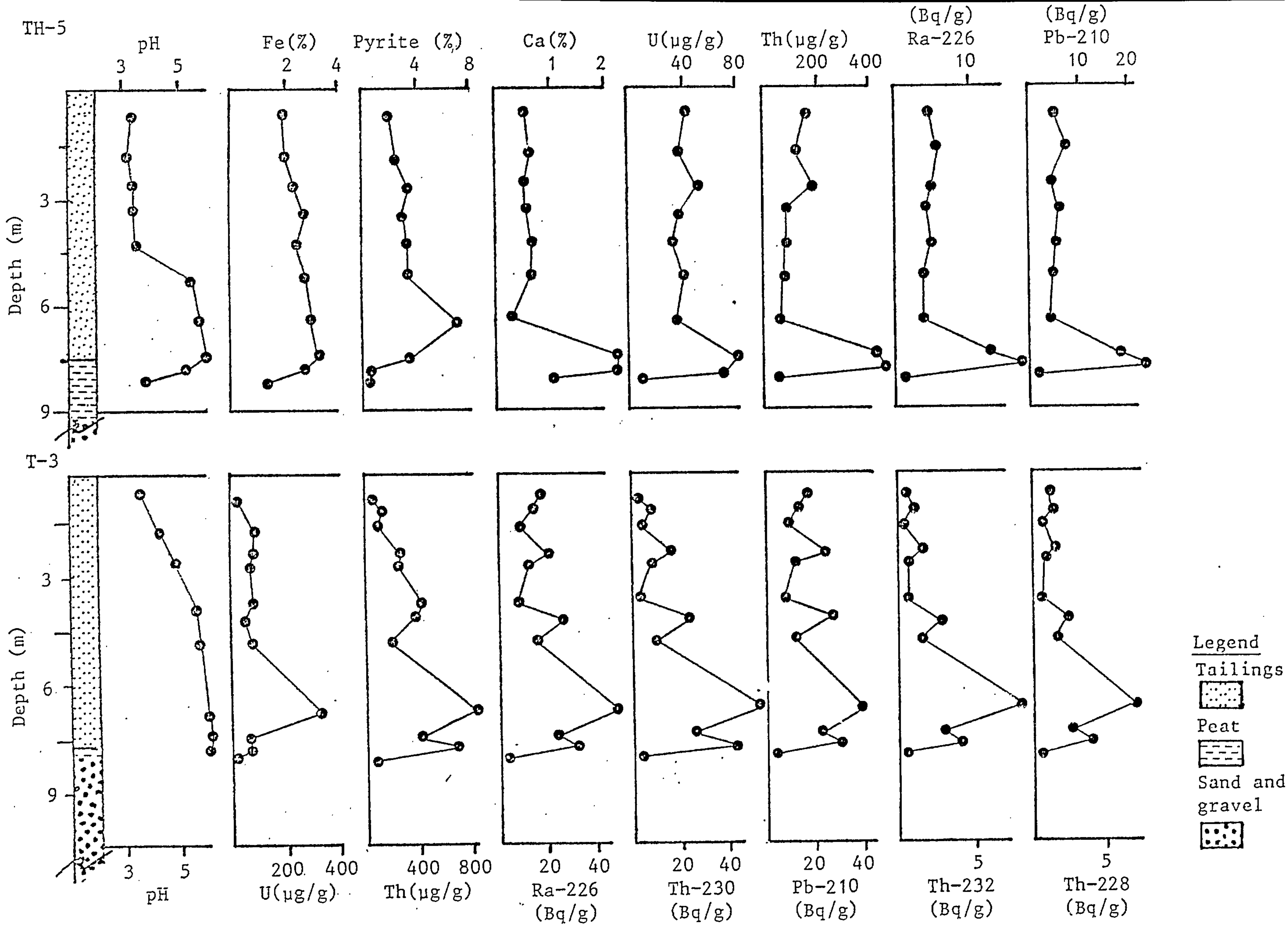

Fig. 10 - Chemical and radioisotope distribution profiles of the tailings solid phase at sites TH-5 on the Nordic West-Arm, and T-3 on the Nordic Main tailings.

Various possible mechanisms are believed to contribute to the observed trends of solid phase stratification. They are: a) accumulation of fines (particle size smaller than 74 μm) containing precipitates of gypsum and metal hydroxides, in the lower zone produced by the settling process during the initial deposition of the tailings; b) co-precipitation and adsorption of major heavy metals and radionuclides from the residual neutralized process water in contact with the lower zone; and c) co-precipitation and adsorption of major heavy metals and radionuclides from the neutralization of the highly acidic, high TDS water.

Similar results were obtained at other sites with slightly altered profiles near the tailings bottom layer depending on the hydrologic setting and the type of the formation material below the tailings which determined the movement of contaminants.

CONTAMINANTS MIGRATION STUDIES

With the oxidation of pyrite and subsequent leaching of residual minerals from tailings, contaminants that originate in the tailings porewater are transported via surface and groundwater regimes to the environment. There is also uptake and transfer of contaminants from tailings porewater to vegetation, to herbivores and insects, and to carnivores and eventually to man. Dusting of tailings and release and dispersal of radioactive gas, radon and its progeny (from uranium tailings) are other environmental pathways affecting man.

At the Nordic tailings site the acidic recharge water, containing high total dissolved solids, enters the horizontally flowing groundwater near the impoundment dam face and appears as a contaminants plume in the nearby aquifer. The plume consists of three sections (Figure 11). The inner core, which is at a pH less than 5, contains several thousand (6000 to 10000) mg/L

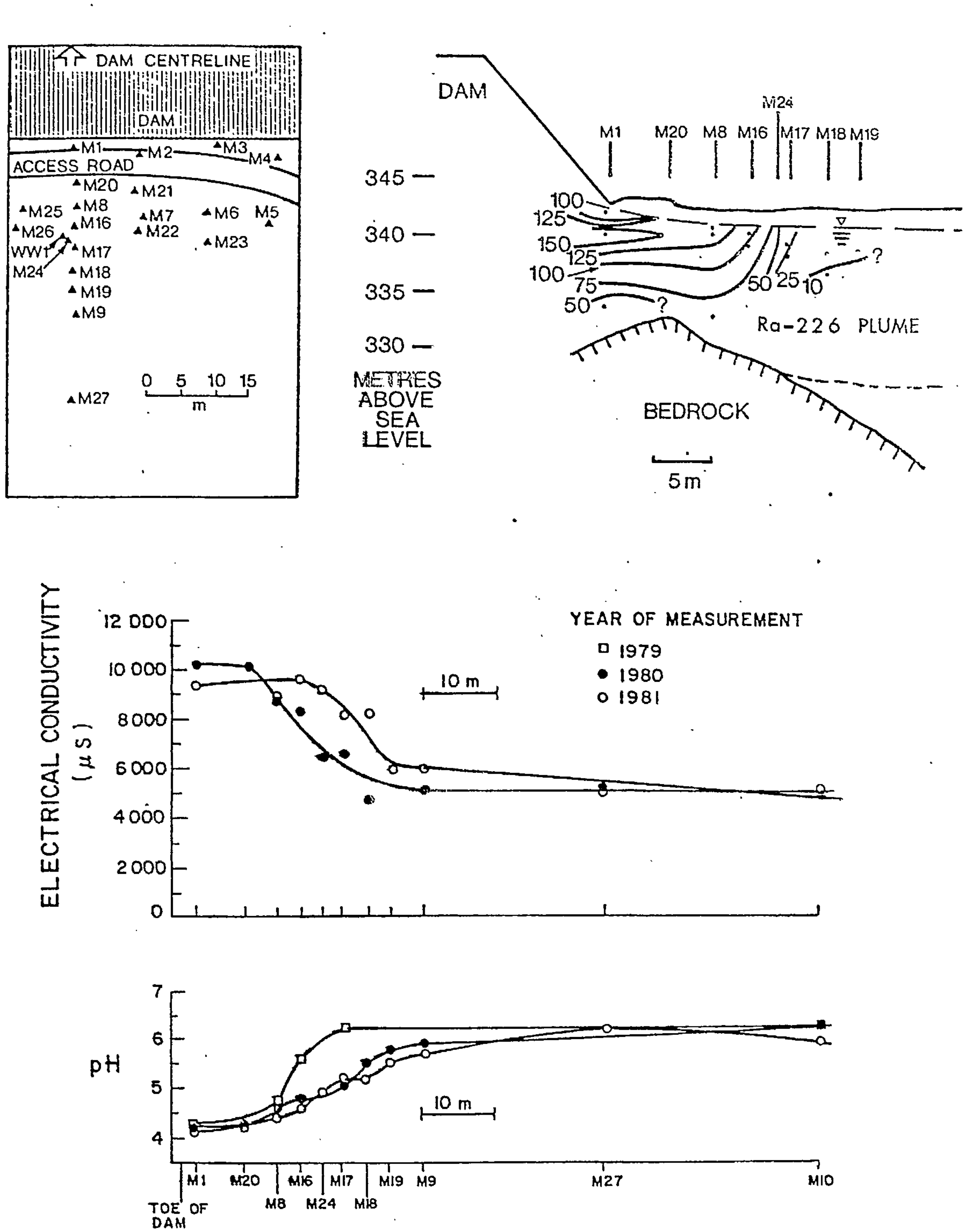

Fig. 11 - Cross-section of Ra-226 (pCI/L, 1 pCi = 37 mBq) in the plume area and variation of electrical conductance and pH with distance from the dam centre line at the Nordic Main site. Locations of monitoring bundle piezometers are shown in the inset.

of Fe and SO_4^{-2}, over 3700 mBq/L Ra-226, and a high concentration of other contaminants. The outer zone, which surrounds the inner core and extends several hundred meters down-gradient, is at a pH greater than 5.7 and contains a few thousand (2000) mg/L of Fe and SO_4^{-2}, approximately 370 mBq/L of Ra-226, and a relatively low concentration of other contaminants. The neutralization zone is the transition region between the other two zones.

Groundwater near the dam has a velocity of 700 m/a, however, the inner core is moving only a few metres per year. The zone of low pH is strongly retarded, its velocity being only 0.1 to 0.3 percent of the groundwater flow rate. This retardation of contaminants movement is caused by pH neutralization and chemical precipitation of siderite and gypsum as calcite present in the formation material (about 1%) dissolved in the neutralization zone.

Oxidation of pyrite and other metal sulphides proceeds only when both oxygen and water are available. The presence of Thiobacillus Ferroxidans greatly enhances the oxidation process. The Elliot Lake/Sudbury Basin is located in a climatic zone of net annual precipitation gain (total precipitation - total evaporation) of approximately 250 mm, thereby making moisture and oxygen readily available throughout the year. Barriers such as water cover on tailings or disposal of tailings under water would provide an attractive and effective oxygen limiting cover to minimize oxidation processes in such areas. Figure 12 shows a typical management scenario of placement of tailings under a water cover. Figure 13 shows a laboratory lysimeter of tailings under water, designed to measure the transfer flux of various contaminants from tailings solid to the upper lying water column. The results showed that for both, static and continuous moving upper water layer on top of the tailings, the transfer flux J, of contaminants per m^2 per hour, their porewater concentrations Co, and the transfer coefficient K, m/month, all

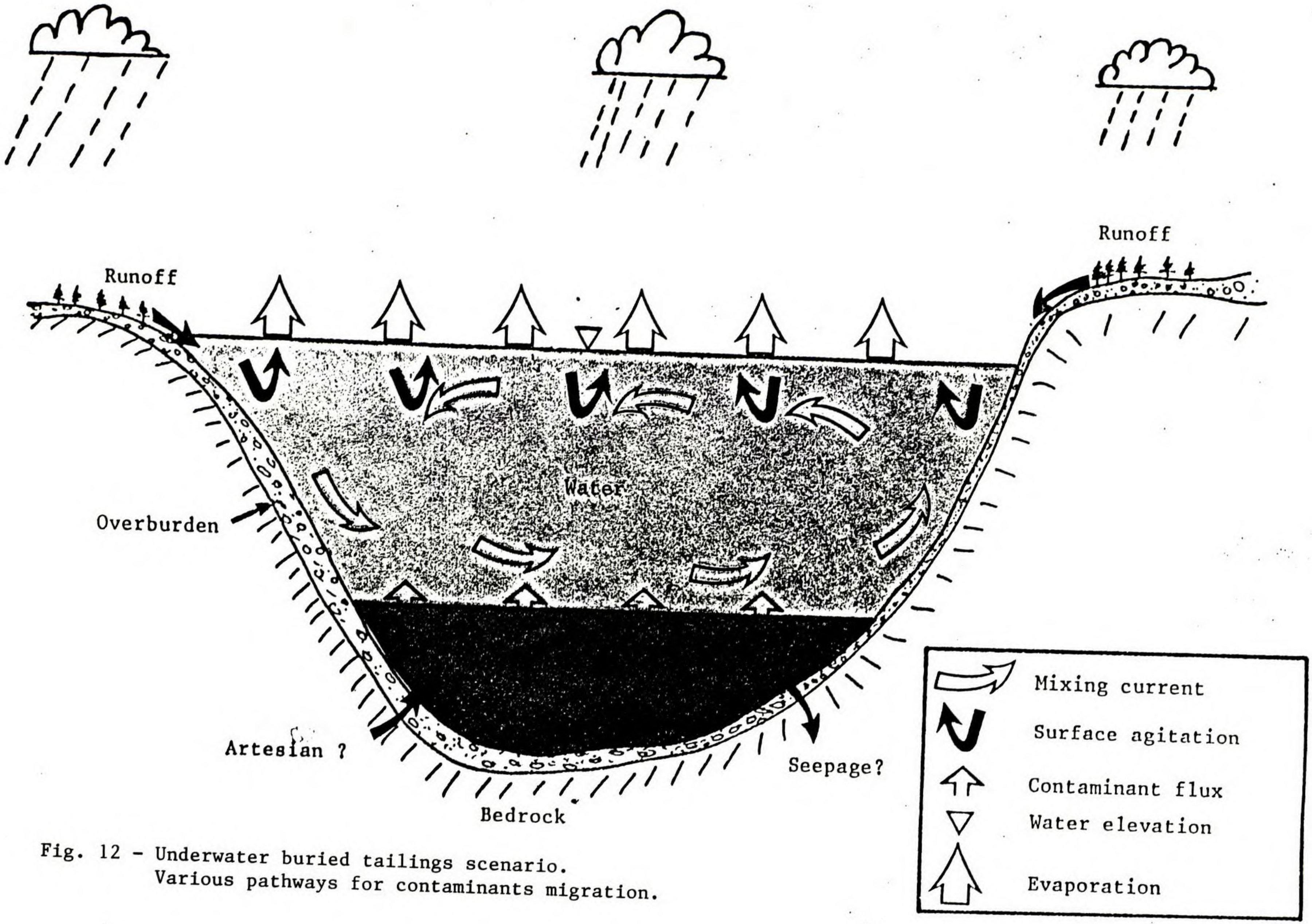

Fig. 12 - Underwater buried tailings scenario.
Various pathways for contaminants migration.

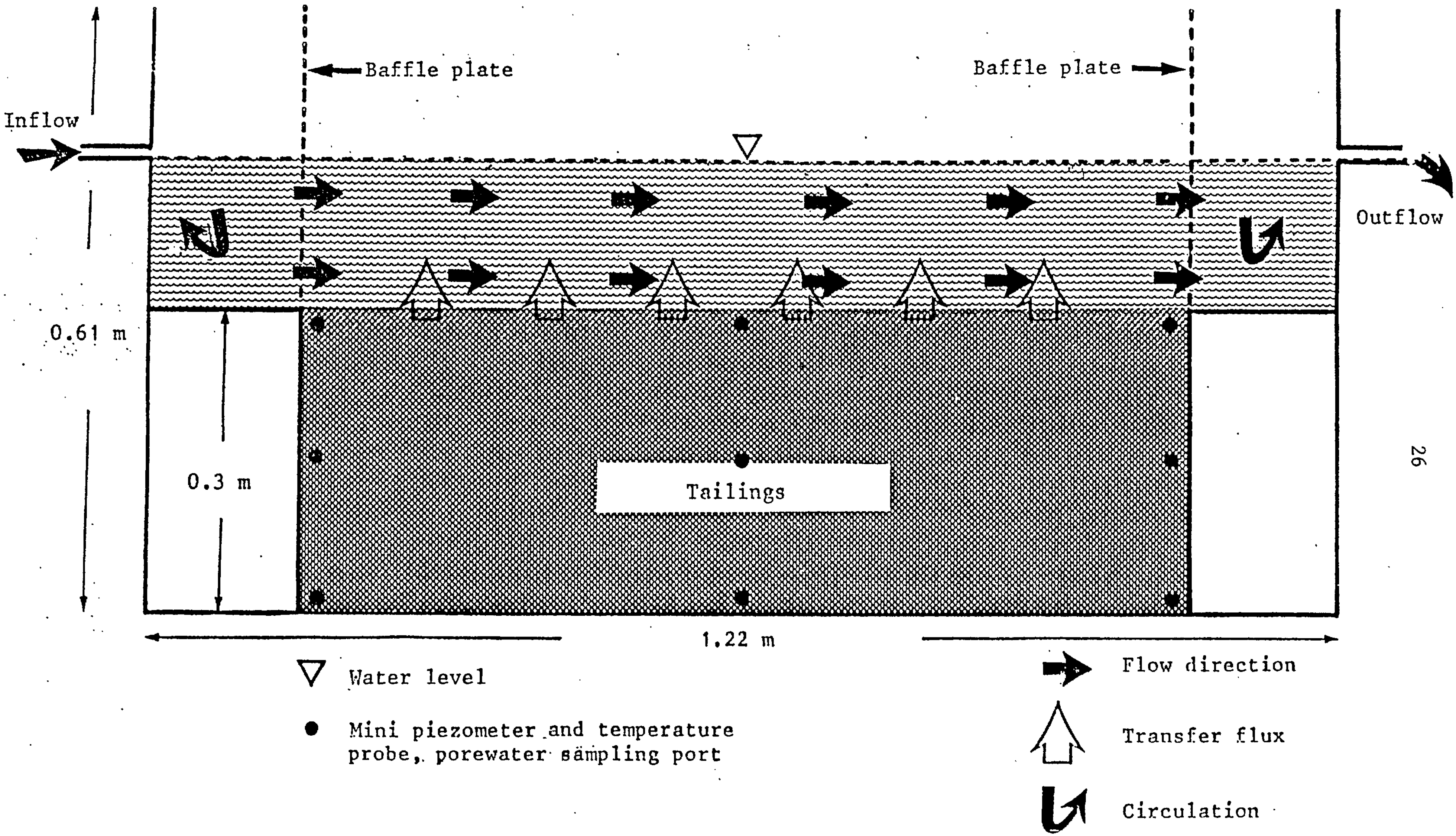

Fig. 13 - Underwater buried tailings lysimeter - constant flow configuration.

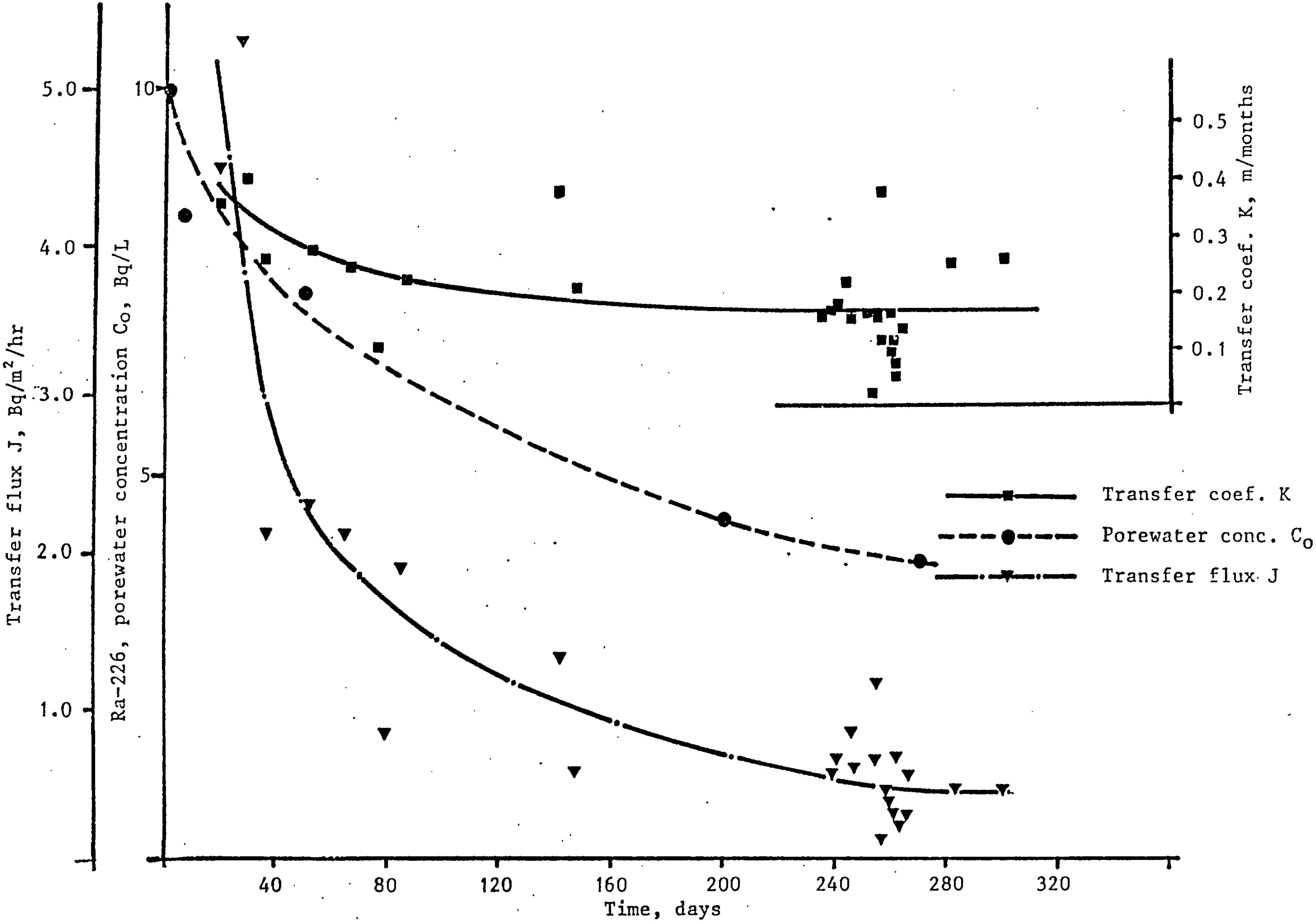

Fig. 14 - Variations of the transfer flux J, porewater concentration C_o and transfer coefficient K for Ra-226 as a function of time.

decreased with time (Figure 14). The decrease was caused by dissolution and diffusion controlled phenomena, where initially the former process dominated the movement of contaminants from solid to the upper lying liquid phase. With time, the solid phase concentration decreased in the tailings upper layer, thereby decreasing the transfer flux and porewater concentration as the diffusional process sets in with the establishment of a steady-state equilibrium condition. The lysimeter was operated for a period of three years with approximately 0.3 m thick water cover on top of the tailings. During that period no oxidation of tailings occurred. The tailings were rather observed to be under highly reducing conditions where sulphate ions were reduced back to sulphides as evidenced by the presence of hydrogen sulphide gas throughout the tailings column.

With the vegetative cover on the tailings for the past 8 to 10 years, a definite soil-like profile is developing on the top upper layer, approximately 10 to 20 cm thick, consisting mainly of decomposed organic matter. The vegetation cover has reduced the effect of wind and water erosion and probably reduced, to some extent, the amount of water that annually infiltrates to the water table of the tailings.

Within tailings and vegetation ecosystems, some uptake of metals and radionuclides (uranium tailings) by the established vegetation, meadow voles (Microtus pennsylvanicus), grasshoppers (Orthoptera Acrididae), black cut-worm larvae (Agrotis ipsilon), snowshoe hares (Lepus americanus), muskrats (Ondatra zibethicus), beavers (Castor canadensis), and otters (Lutra canadensis) is observed. Tables 6, 7 and 8 give the average concentrations of various metals and radionuclides in the substrate, vegetation and animal/insect tissues. It is seen from these results that higher substrate levels of Cu, Ni and Fe from nickel and copper mine tailings resulted in elevated levels of Ni and Fe in vegetation and an internal body burden of Fe in kidneys and bones of meadow

Table 6 - Metals (μg/g) and radionuclide levels (mBq/g) in substrate, vegetation (mixed species) and tissues of Microtus pennsylvanicus from tailings and control sites (dry weight basis)

Site	Cu	Ni	Fe	Co	Zn	Pb	Ra-226
<u>Ni-Cu Tailings</u>							
Substrate	405±66	368±59	107,600±4,700	47±4	90±26	64±9	0
Vegetation	16.5±5	18±9	186±81	0.8±0.5	13±4	0.7±0.2	0
M. pennsylvanicus tissues							
Total body	21±3	21±6	1,073±398	2.3±0.2	86±11	5±1	0
Kidneys	20.5±2	<3.5	666±187	<3.9	72±7	<0.9	0
Bones	6.4±0.8	7.4±0.3	228±33	6.8±0.2	132±18	17±5	0
<u>Uranium Tailings</u>							
Substrate	38±8	7±0.5	8,133±3,156	10±2	6±0.9	189±62	6550±1924
Vegetation	18±13	2.4±0.9	66±16	0.7±0.3	11±1.4	1±0.9	370±166
M. pennsylvanicus tissues							
Total body	15±3.6	7±1.1	262±34	1.7±0.1	89±5	4.5±0.4	259±110
Kidneys	18±3.5	<2.8	290±80	<5.6	69±12	<0.8	0
Bones	6.5±1.2	7.6±0.6	176±13	6±0.3	160±2	14.2±0.5	1406±555
<u>Control</u>							
Substrate	27±8	38±5	25,800±600	26±0.6	78±21	29±6	0
Vegetation	6±2	1.2±0.1	59±8	0.6±0.1	19±6	<0.5	0
M. pennsylvanicus tissups							
Total body	9.7±0.3	5.4±0.1	388±84	2.4±0.1	101±7	4.1±0.2	0
Kidneys	26±1.7	<2.3	238±16	<5.7	79.5±0.7	<1.1	0
Bones	5.2±0.1	10±1.3	153±4	6.1±0.3	162±14	12±0.3	0

Table 7 - Radionuclide concentrations based on dry weight in substrate and vegetation samples collected at various uranium tailings in Elliot Lake (± analytical precision).

Element	Site	Substrate	Grasses (Whole Plant: Mixed spp.)	Trefoil (Whole Plant)	White Birch (*B. papyrifera* Marsh)		Trembling Aspen (*P. tremuloides* Michx)	
					Branches	Leaves	Branches	Leaves
Ra-226 mBq/g	Lacnor	5032±222	425±26	259±19	–	–	–	–
	Nordic Main	8732±315	696±33	237±15	518±30	1021±37	148±15	100±7
	Nordic West Arm	15133±426	144±11	7±4	633±37	943±30	85±7	126±11
	Quirke	436±30	311±9	130±11	–	–	–	–
	Spanish American	4403±148	11±4	133±7	–	–	–	–
	Stanrock	15022±407	–	–	237±7	499±22	70±11	81±7
	Williams Lake	326±30	303±19	70±11	130±7	222±19	111±15	33±7
Ra-223 mBq/g	Lacnor	1554±111	30±4	15±4	–	–	–	–
	Nordic Main	2201±130	122±11	48±7	144±19	≤4	33±11	22±11
	Nordic West Arm	5717±204	30±4	96±15	63±15	118±11	19±4	33±7
	Quirke	170±22	15±4	11±4	–	–	–	–
	Spanish American	1036±74	≤4	≤4	–	–	–	–
	Stanrock	5180±185	–	–	67±4	159±15	56±15	67±11
	Williams Lake	115±19	15±4	11±4	15±4	26±7	11±7	≤4
Pb-210 mBq/g	Lacnor	3515±185	85±26	107±26	–	–	–	–
	Nordic Main	7863±352	44±26	41±26	104±30	59±30	26±22	30±26
	Nordic West Arm	12961±555	22±22	22±22	255±33	92±30	22±22	37±26
	Quirke	296±44	196±30	81±26	–	–	–	–
	Spanish American	2923±148	22±22	81±26	–	–	–	–
	Stanrock	11285±481	–	–	70±26	78±26	22±22	115±30
	Williams Lake	200±41	33±22	22±22	48±26	30±26	22±22	26±22
Th-232 mBq/g	Lacnor	118±26	≤4	≤4	–	–	–	–
	Nordic Main	196±33	≤4	≤4	≤4	≤4	≤4	≤4
	Nordic West Arm	202±26	≤4	≤4	≤4	≤4	≤4	≤4
	Quirke	70±15	7±4	≤4	–	–	–	–
	Spanish American	455±48	≤4	≤4	–	–	–	–
	Stanrock	570±56	–	–	≤4	≤4	≤4	≤4
	Williams Lake	81±15	≤4	≤4	≤4	≤4	≤4	≤4
Th-230 mBq/g	Lacnor	555±74	≤4	≤4	–	–	–	–
	Nordic Main	1647±111	≤4	7±4	≤4	≤4	≤4	≤4
	Nordic West Arm	1887±111	≤4	≤4	≤4	≤4	≤4	7±4
	Quirke	237±26	22±4	19±4	–	–	–	–
	Spanish American	707±63	≤4	≤4	–	–	–	–
	Stanrock	1813±111	–	–	≤4	7±4	≤4	11±4
	Williams Lake	181±22	7±4	≤4	≤4	≤4	≤4	≤4
Th-228 mBq/g	Lacnor	74±37	≤4	≤4	–	–	–	–
	Nordic Main	333±74	≤4	≤4	≤4	≤4	≤4	≤4
	Nordic West Arm	168±61	≤4	≤4	≤4	≤4	≤4	≤4
	Quirke	48±22	≤4	≤4	–	–	–	–
	Spanish American	1406±74	≤4	≤4	–	–	–	–
	Stanrock	777±74	–	–	≤4	≤4	≤4	≤4
	Williams Lake	74±37	≤4	≤4	≤4	≤4	≤4	≤4

Table 8 - Ra-226 levels in: skeletal tissues of Snowshoe hares (Lepus americanus), Beavers (Castor Canadensis), Muskrats (Ondatra zibethicus, whole body of Grasshoppers (Orthoptera Acrididae), and Black cutworm larvae (agrotis ipsilon).

Animal Tissue/Insect	Ra-226 Concentration, mBq/g dry weight		
	Uranium Tailings Site	Control Sites	
		Local	Distant
1. Snowshoe hare (Lepus americanus) bone.	275±94	30±10	<3.7
2. Beaver (Castor Canadensis) bone.	10-892	28-70	10-27
3. Muskrat (Ondatra zibethicus) bone.	22-4600	24-296	3.7-36
4. Grasshoppers (Orthoptera Acrididae) whole body.	57-378	6.4±4	-
5. Black cutworm larvae (Agrotis ipsilon) whole body.	117±7	-	-

voles. For uranium tailings, elevated levels of Ra-226 were only found in vegetation and bones of animals, though both Pb and Ra-226 were higher in the substrate. The average vegetation to tailings concentration was 0.03 for both Ra-226 and Pb-210.

Figure 15 shows Ra-226 concentrations in blueberries (Vaccinium angustifolium Ait.) near a uranium tailings site in relation to the prevalent wind direction. Elevated levels of total Ra-226 ranging between 20-290 mBq/g (dry weight) were observed in samples collected within 500 m from the tailings. Highest levels, ~285 mBq/g, were observed in a sample collected on a tailings spill. For sites located more than 500 m away in the upwind direction, and those situated at distances greater than 1 km downwind from the waste pile, the total Ra-226 concentrations approached background levels which were measured as 2 to 6 mBq/g. Blueberry wine has a concentration of 400 mBq/L $\simeq$5 mBq/g dry weight of blueberries. Approximately 17% of the total Ra-226 measured was removable by washing the samples with distilled water. Wind dispersal of the tailings material and its deposition in the form of dust on blueberries was believed to be responsible for the external contamination. Based on the ICRP recommended dose limits for oral intake of Ra-226, it was calculated that approximately 160 kg/a, 3350 kg/a and 47 kg/a of washed blueberries (wet weight) from inside (less than 500 m), and outside (greater than 1 km downwind) the influenced zone, and from the tailings spill site (where the highest Ra-226 levels in blueberries were measured), respectively, would need to be consumed before the individual annual limit for the general public was exceeded.

EVALUATION OF TAILINGS COVERS

As discussed previously, the vegetative cover on tailings has provided greater surface stability by controlling erosion and has improved the general

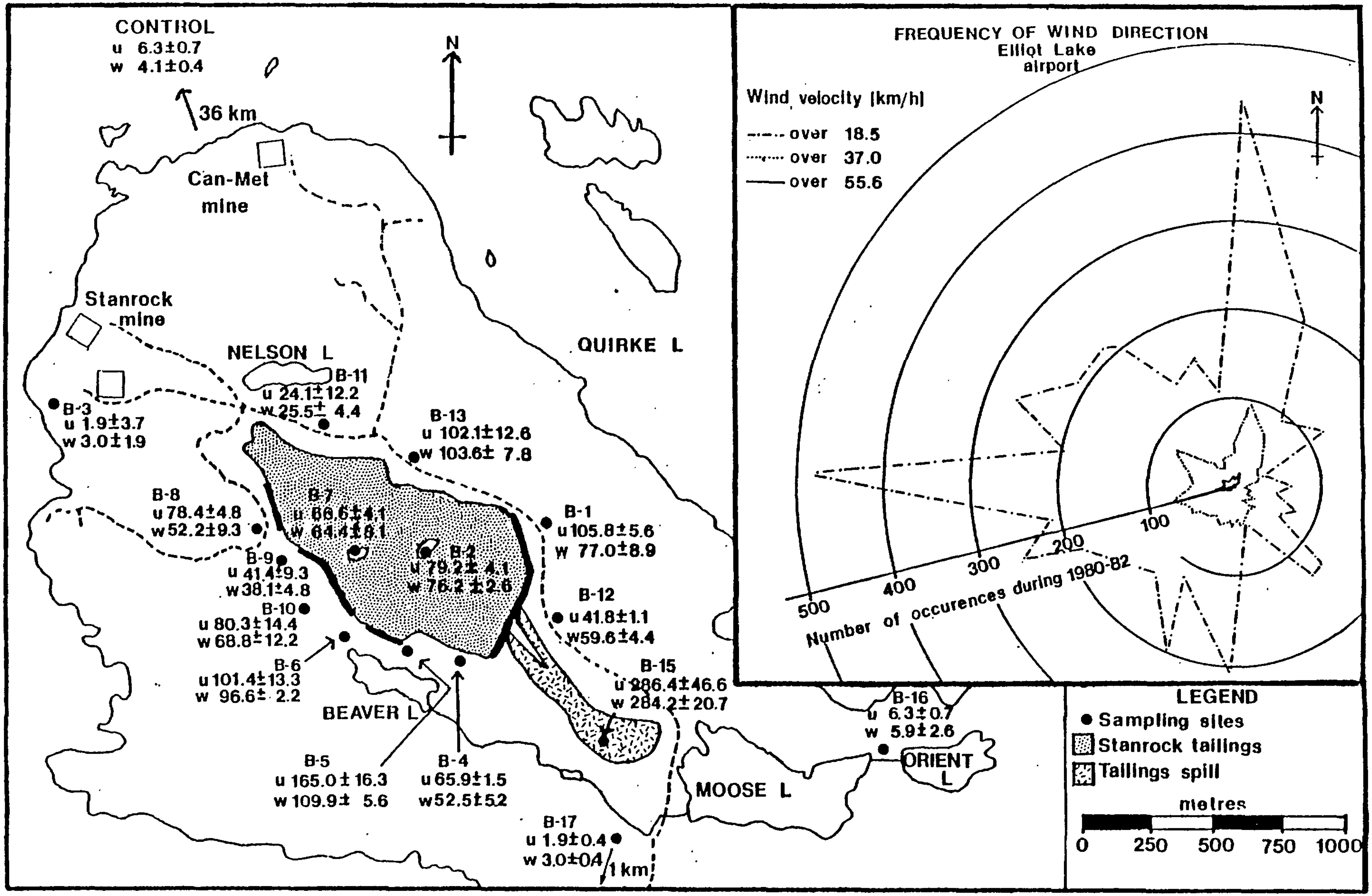

Fig. 15 - Ra-226 concentration in blueberries near a uranium tailings site in relation to the prevalent wind direction.

aesthetics of the area. Its overall effect on the acid generation and the tailings area water quality, however, cannot be established to date. There has been no evidence of improvement in the quality of water that leaves a tailings area though the site that has been vegetated for the last ten years. A water cover on tailings or disposal of tailings under water on the other hand showed promising results in limiting the available oxygen and thereby minimizing pyrite oxidation. Evaluation of other dry and wet barriers are being undertaken as a part of the RATS program.

For uranium tailings, the suitability of various dry and wet covers in controlling radon release rates from tailings was also investigated. Measurements were taken using activated charcoal cartridges for various surface covers consisting of bare, vegetated, acidophilic moss with a high degree of water saturation, compacted crushed rock and gravel, and winter snow.

The results (Figure 16) showed that at a given site, there was no significant difference in radon emanation rates between various tailings covers and bare tailings. The flux ranged from 40 to 200 atoms/cm^2/sec. In particular, no increase in radon emanation rates from vegetated areas compared to bare tailings was observed. The release rates varied spatially depending on the tailings grain size, porosity, moisture content and on pressure and water table variations. The emanation rates were higher for tailings with low water contents compared to those for wet and moss covered tailings (Figure 17).

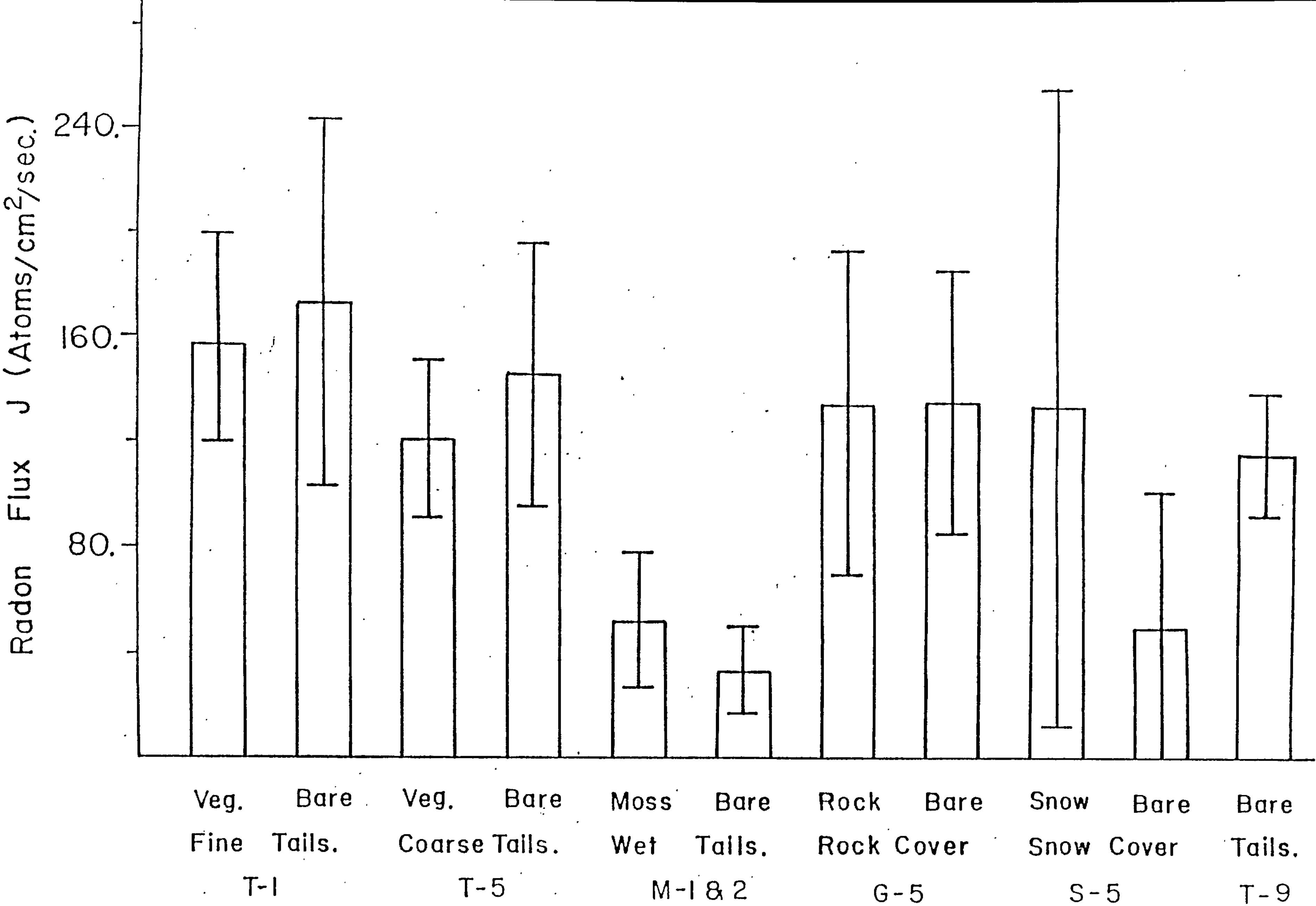

Fig. 16 - Radon emanation fluxes for various tailings covers at different sites.

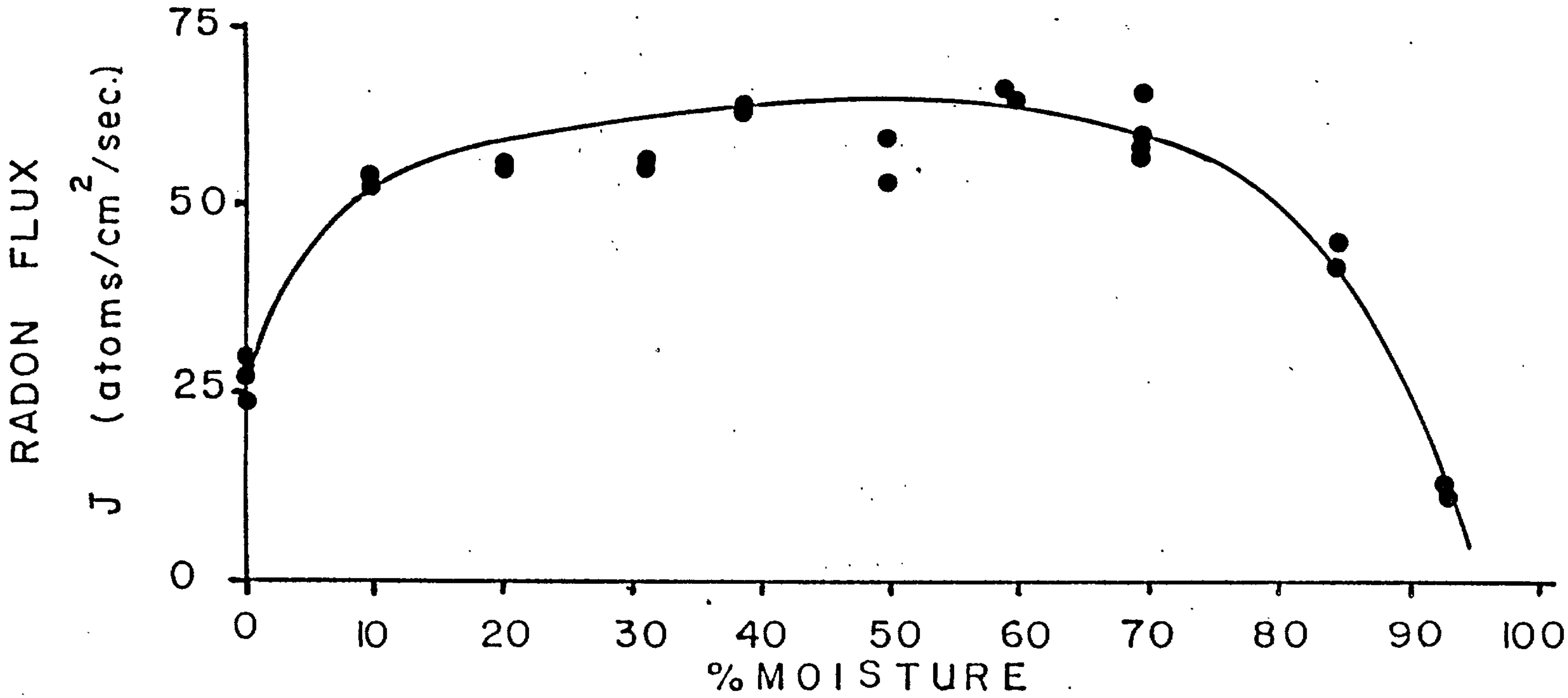

Fig. 17 - Moisture dependence of radon flux from uranium tailings.

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