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Uranium-Thorium Deposits At The Yates Mine, Huddersfield Township, Québec

by

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A thesis submitted to the School of Graduate Studies
in partial fulfillment of the requirements for the degree
of M.Sc. in Geology

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ABSTRACT

The Yates mine is located 100 km northwest of Ottawa (Lat. 45°55'N, Long. 76°31'W) in the Grenville Province of the Precambrian Shield. It comprises six mineral occurrences known as the Bélanger, Bélisle, Camp, Cliff, Lake and Matte zones. The Camp and the Matte zones, some nearby mica pits and a small radioactive pegmatite were examined in detail because of their good exposure. The zones consist of calc-silicate skarns, or vein-dykes, which are generally in conformable contact with the surrounding biotite and amphibole gneisses. These gneisses have been intruded by pegmatite and diabase dykes. The gneisses represent metamorphic equivalents of sedimentary rocks of the Grenville group.

The deposits are mineralogically zoned with a calcite-rich core mantled by a unit of variable thickness of calc-silicate minerals. Each geological unit is also zoned with respect to grain size. The main radioactive minerals are thorianite, uraninite, thorite and allanite. They generally occur in the core or near the transition between the two units. The mica pits have similar mineralogies and textures to the two zones. The radioactive pegmatite near the Matte occurrence encloses a lens of calcite within its quartz core.

Geochemical analyses indicate that phlogopite, diopside and tremolite reached at least local equilibrium amongst themselves during formation. Uraninite and thorianite occur as discrete grains and as fine mixtures with thorite. The rapid variations in their compositions probably reflect disequilibrium. The allanite from the Matte zone contains more rare-earth elements and less thorium with respect to allanite from the amphibole gneiss.

The genesis of the Yates mine is related to the escape of fluids generated during prograde metamorphism by the reaction of carbonate minerals with available silica forming calc-silicate minerals and volatile constituents, and also by the metamorphism of detrital sediments, which may have been thorium-rich. As the fluids and the volatiles migrated during uplift when the temperature and the load pressure were decreasing, they formed pegmatites if they encountered quartzofeldspathic rocks, or skarns if they encountered calc-silicate rocks. The preferred occurrence of thorianite in calc-silicate rocks in high-temperature metamorphic terrains is probably controlled by a deficiency in silica which limits the formation of thorite. The composition of thorianite from the Camp zone indicates an age of mineralization 1.2 b.yrs. assuming equilibrium of radiogenic daughter elements.

RESUME

Le dépôt Yates se situe à 100 km au nord-ouest de la ville d'Ottawa dans la province de Grenville du Bouclier Canadien (Lat. 45°55'N, Long. 76°31'O). Le dépôt comprend six indices connus sous les noms de zones Bélanger, Bélisle, Camp, Cliff, Lake et Matte. Les zones Matte et Camp, quelques carrières de mica et une pegmatite radioactivite ont été étudiées à cause de leurs affleurements en surface. Les zones Matte et Camp se composent de skarns de minéraux calc-silicates concordant avec les gneiss à biotite et à amphibole environnants. Ces gneiss sont coupés par des filons de pegmatite et de diabase. Les gneiss sont les équivalents métamorphiques des roches sédimentaires du groupe Grenville.

Les gîtes sont zonés granulométriquement et minéralogiquement avec des noyaux riches en calcite entourés de manteaux de minéraux calc-silicates. Les minéraux radioactifs importants sont la thorianite, l'uraninite, la thorite et l'allanite. Ils se retrouvent dans le noyau près du contact gradationnel avec le manteau. Les anciennes carrières de mica ont des minéralogies et textures semblables à ces zones. La pegmatite radioactive près de la zone Matte contient une lentille de calcite dans son noyau de quartz.

Les analyses géochimiques indiquent que la phlogopite, la diopside et la trémolite étaient en équilibre durant leur formation. L'uraninite et la thorianite forment des grains distincts

et des mélanges microscopiques avec la thorite. La variation rapide de leurs compositions reflète un déséquilibre durant leur formation. L'allanite de la zone Matte est enrichie en terres-rares et démunie en thorium par rapport à l'allanite du gneiss à amphibole.

La génèse des gîtes du dépôt Yates est reliée à la libération des fluides générés par la réaction des minéraux carbonates avec la silice formant ainsi des minéraux calc-silicates et des produits volatiles par le métamorphisme de sédiments détritiques thorifères du groupe Grenville durant le métamorphisme régional. Les fluides et les volatiles voyagèrent vers des horizons favorables à leur déposition vers la fin de l'orogénèse durant le soulèvement des roches métamorphisées. Les fluides ont formé des pegmatites ou des skarns dépendant qu'ils ont rencontré soit des roches quartzofeldspathiques ou des roches riches en minéraux calc-silicates. La présence préférentielle de la thorianite dans les roches calc-silicates des régions hautement métamorphisées est contrôlée par leur faible teneur en silice qui limite la formation de la thorite. La composition de la thorianite de la zone Camp indique un âge de 1.2 x 10^9 années pour la minéralisation radioactive. Cette détermination est basée sur l'équilibre des produits de désintégration.

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1. Introduction

The purpose of the thesis is to study by optical, x-ray diffraction and microprobe analysis techniques, the thorium-uranium mineralization and the petrology of a calcite skarn in the Grenville Province of the Canadian Shield, and to attempt to improve the model preferentially proposed for the genesis of this type of radioactive occurrence. Detailed investigations of the mineralogy, the petrology and the geochemistry seem to indicate that the skarns are formed by metasomatism coupled with regional metamorphism (Rowe 1952, Shaw et al. 1963, Hogarth et al. 1972, Villeneuve 1977, Kretz personal communication and 1960) rather than contact metamorphism (Wilson 1924, Currie 1951), or hydrothermal veins related to pegmatites (Ellsworth 1932, Satterly 1957, Semenov 1972) or igneous activity (Spence 1929, Landes 1938, Heinrich 1932). This thesis concentrates on the formation of radioactive minerals to support the model. The Yates Mine was selected because of its distinctive mineralogy, its exposure above and below ground and its accessibility.

1.1 Location

The Yates Mine comprises six radioactive mineral occurrences known as the Bélanger, Bélisle, Camp, Cliff, Lake and Matte zones (Lang et al., 1962, p. 212). These are located in lots 18 and 20 range IV, and in lots 16, 17, 19 and 20 range V of Huddersfield Township (Lat. 45°55'N, Long. 76°31'W) approximately 60 miles (100 km) northwest of Ottawa (Fig. 1).

1.2 History

During the first half of the present century, phlogopite was mined intermittently from pits 300 feet (90 m.) southwest of the Camp zone (Shaw, 1958, p. 39). The discovery of uranothorite in the pits in 1953 led to the incorporation of Yates Uranium Mines Ltd. (Shaw, 1958, p. 39). Low uranium grades caused the cessation of exploration a few years later (Hogarth, personal communication). In 1976 exploration was resumed on the property, for a short period by the present owner, Groundstar Resources (The Northern Miner, vol.62, no. 36; Nov. 18, 1976, p. 23). The mine is well known for fine mineral specimens such as apatite, microcline, salite and scapolite (Sabina, 1970, p: 96).

1.3 Previous work

The first geological investigation of the region was a reconnaissance survey conducted in 1876 by L.R. Ord and H.G. Vennor of the Geological Survey of Canada. A geological report was issued in which the local "red gneisses and syenites" were placed at the bottom of the stratigraphic sequence below crystalline limestone (Vennor 1878, pp. 279-280); no map covering his Huddersfield Township explorations was ever issued. Vennor was followed in 1905 by R.W. Ells, also from the Geological Survey of Canada, who described the region as being characterized by "granite gneiss", crystalline limestone and pyroxenic rocks (Ells 1907, pp. 22-24).

He considered these pyroxenic rocks as "intrusives". Ells' map was published on a scale of 1:253,440 and accompanied the report. De Schmid referred to the deposits as "pyroxenites" (de Schmid, 1912, p. 256) and he emphasized an igneous genesis for their origin. In 1955 D.M. Shaw described the radioactive prospects of Yates Uranium Mines Incorporated as "skarns" (Shaw 1958, pp. 39-41). R. Kretz mapped the area on a 1:63,360 scale the following year (Kretz 1957, p. 6) and he assigned the calc-silicate rocks to the Grenville Group.

1.4 Methodology

In 1976, an area of 5 sq.mi. (13 sq.km.) around the mine was mapped geologically by pace and compass traverses, spaced at 100 ft. (30 m.) intervals, for familiarization purposes. The main zones and the adit of the Yates Mine were investigated in detail. 120 thin sections and 30 polished thin sections were cut from selected samples collected during the field work. At least 2,000 points were counted on each section to determine modal mineral contents. X-ray diffraction patterns were made of minerals not identified by optical techniques. A few selected rock samples were crushed and analyzed for uranium by neutron activation at Atomic Energy of Canada Limited.

Individual minerals were analyzed at Queen's University by an A.R.L. microprobe (Model 4100) coupled with a Nothern (NS-880) computer. The probe was operated in the energy-dispersive mode with an accelerating voltage of 15 KV and a beam current of 0.04 M. Amp. The counting period was set at 120 seconds and drift maintained within 1 percent with a quartz standard. The data were stored on tape and compared later with the standards. These were SiO_2 for silicon, TiO_2 for titanium, UO_2 for uranium, ThO_2 for thorium, Al_2O_3 for aluminum, Y metal for yttrium, RE MIXTURE #3 for lanthanum, Ce metal for cerium, Pr metal for praseodynium, Nd metal for neodynium, $PbCO_3$ for lead, Fe_2SiO_4 for iron, MnO_2 for manganese, MgO for magnesium, $CaAl_2Si_2O_8$ for calcium, $NaAlSi_3O_8$ for sodium and $KAlSi_3O_8$ for potassium. The program TAPE MX2 corrected the data for drift, atomic number, absorption and fluorescence. The accuracy and precision of each oxide analysis was determined (Table 1). The precision obviously controls the lowest detectability. The non-radioactive minerals were analyzed with Dr. Roeder's Program #2 (Queen's University) which reduced the data during analysis.

1.5 Acknowledgements

I thank Dr. D.D. Hogarth for supplying company plans (Yates Uranium Mines Ltd.) and for his comments on the thesis. The project was financially supported by a National Research Council Grant (No. A2122) made out to him. Dr. M. Corlett (Queen's University) made numerous suggestions on the microprobe study and provided the computer program TAPE MX II for data reduction. S. Kalegropoulos (Queen's University) assembled the

standards. Dr. R. Kretz pointed out many of the geological features of the area and supplied unpublished analyses of minerals. Dr. A.G. Plant (Geological Survey of Canada) checked some of the analyses with the microprobe at the Geological Survey of Canada. Dr. R. Lamarche (Ministère des Richesses naturelles du Québec) provided the publications from the M.R.N.Q.. S. Lafontaine, F. Lafontaine and R. Tremblay were helpful assistants in the field. Atomic Energy of Canada Limited made the neutron activation analyses.

Table 1 **Accuracy and Precision of Oxides Analyses with the Queen's University Microprobe**

	Precision	Accuracy
SiO_2	0.2%	0.2 %
TiO_2	0.3	0.1
UO_2	0.8	0.2
ThO_2	0.9	0.2
Al_2O_3	0.2	0.1
Y_2O_3	0.3	0.1
La_2O_3	0.7	0.1
Ce_2O_3	0.4	0.1
Pr_2O_3	0.4	0.1
Nd_2O_3	0.8	0.1
PbO	0.3	0.1
FeO	0.3	0.1
MnO	0.3	0.1
MgO	0.2	0.1
CaO	0.2	0.2
Na_2O	0.2	0.1
K_2O	0.2	0.1

2. The Geological Setting of the Yates Mine

The Yates Mine is situated in the Grenville Province of the Precambrian Shield, specifically within the Central Gneiss Belt of Wynne-Edwards (1972) near its boundary with the Central Metasedimentary Belt to the southeast (Fig. 1). The Central Gneiss Belt is characterized by northwest-trending quartzofeldspathic gneisses; the Central Metasedimentary Belt is characterized by northeast-trending marbles, quartzites, pelitic gneisses and metavolcanics of the Grenville Group, while the boundary is noted for its numerous nepheline syenite bodies (Wynne-Edwards, 1972, p. 313). Kretz (1957 a, p. 1) assigns the metasedimentary rocks near the mine to the Grenville Group after mapping on both sides of the boundary in Western Québec (Kretz 1957 a, 1957 b, 1957 c). The group extends a short distance north of the boundary in this area. Thus the mine is located in rocks either near the base of the group or near the top of the quartzofeldspathic gneisses.

Radiometric dating (Rb/Sr) indicates Archean and Aphebian ages for the rocks within the Central Gneiss Belt (Wynne-Edwards, 1972, p. 284). This and correlations across the Grenville Front imply that the quartzofeldspathic gneisses are probably metamorphic equivalents of the igneous and sedimentary rocks in the Superior and Southern Provinces of the Canadian Shield (Wynne-Edwards, 1972). The Grenville Group renders Helikian ages indicating that it is younger than the quartzofeldspathic gneisses (Wynne-Edwards, 1972, p. 281).

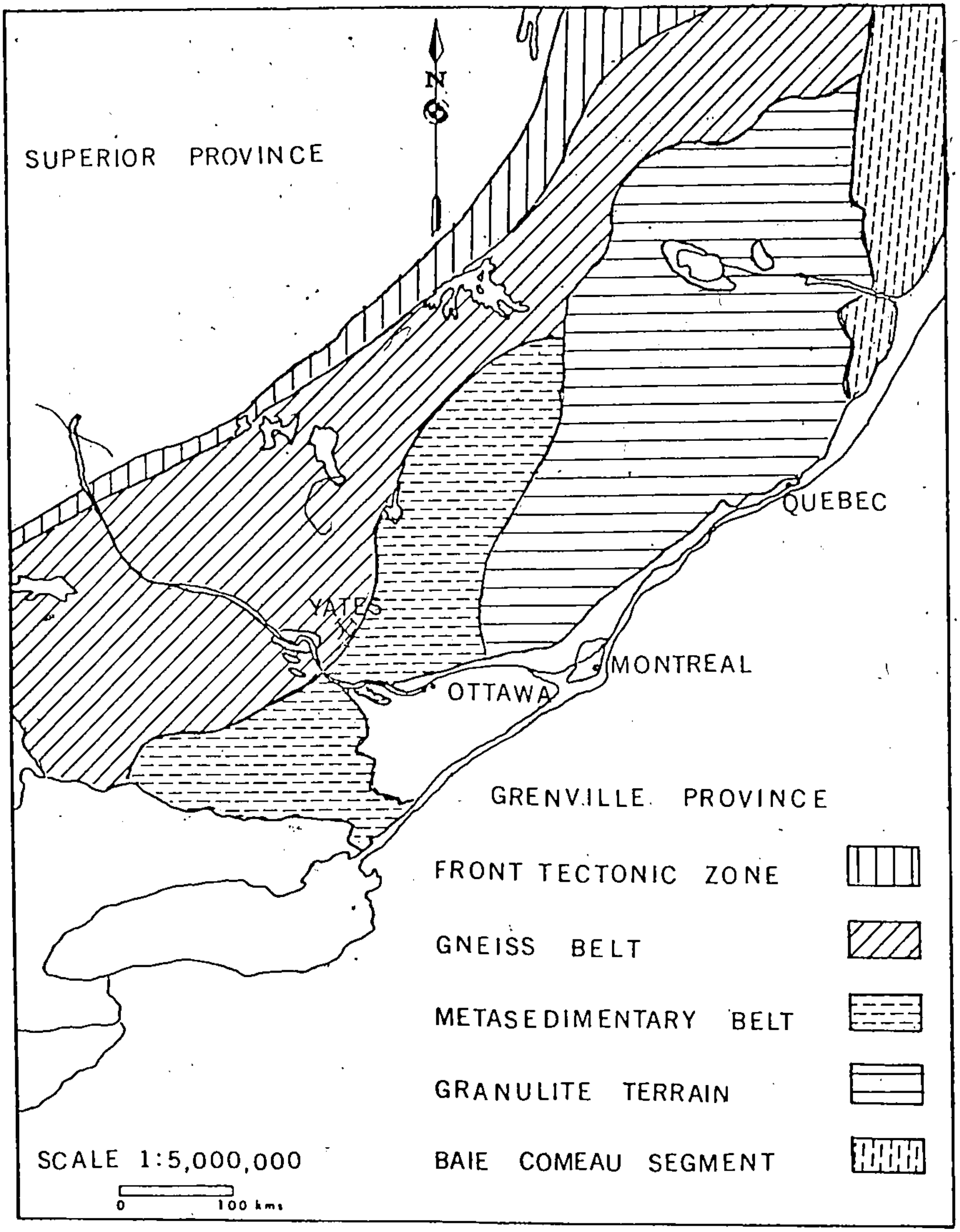

Fig. 1 Location and geological setting of the Yates Mine (Geology after Wynne-Edwards 1972, p. 268)

2.1 Regional Geology

The rock types recognized near the Yates Mine are amphibole gneiss, biotite gneiss, calc-silicate rock, granite pegmatite and diabase (Fig. 2). The amphibole gneiss is grey to black, medium-grained (average grain diameter: 2mm) and foliated. It consists of wide mesocratic bands (meters) alternating with thin leucocratic bands (centimeters). The main minerals are oligoclase (An^{25}), hornblende, quartz and biotite (Table 2). Oligoclase porphyroblasts, up to 10 cm long are encountered in a few outcrops. Microcline, apatite, sphene, hematite, ilmenite and diopside are accessory minerals. Allanite, monazite, calcite, zircon and pyrite occur in trace amounts. Biotite displays pleochroic halos around enclosed grains of allanite or monazite. Exsolution textures of hematite and ilmenite and of feldspars are common. Veinlets of calcite and pyrite cut the foliation.

The biotite gneiss is pink to grey and medium-grained (average grain size: 2mm). It consists of weakly foliated, wide leucocratic bands (meters) interlayered with well foliated, thin mesocratic bands (centimeters). Microcline, oligoclase (An^{20}), quartz and biotite are the main minerals (Table 2). Perthitic and antiperthitic textures are common in feldspar. Microcline rims plagioclase. Biotite forms two intersecting foliations in some outcrops. Boudinage and mylonite are encountered in quartz-rich layers. The accessory

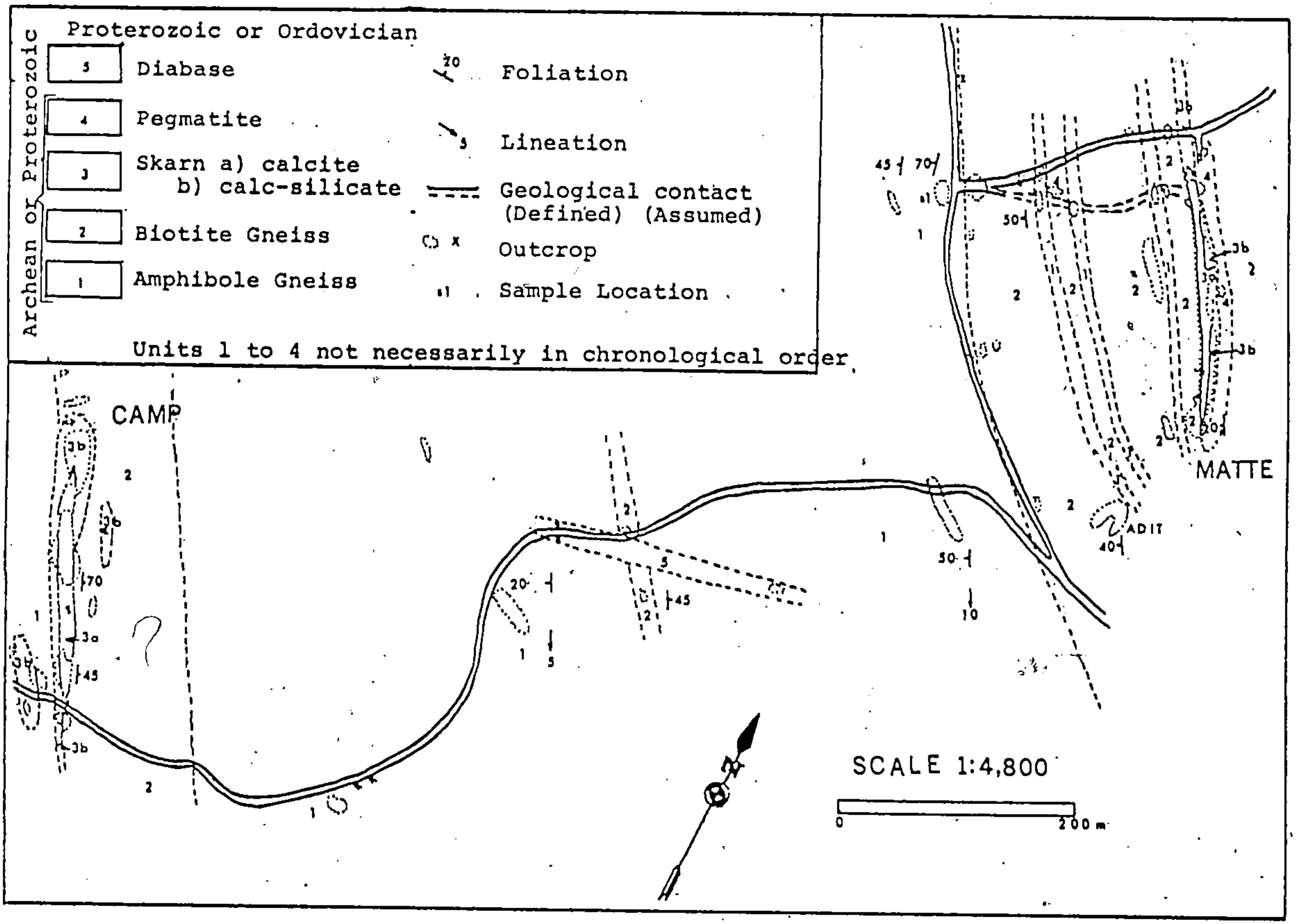

Fig. 2 Geology of the Yates Mine

Table 2 Modal Analyses of Gneisses near the Yates Mine

	Biotite Gneiss (30 specimens)	Amphibole Gneiss (25 specimens)
Quartz	19% (5-35%)	8% (TR-20%)
Plagioclase	34% (10-70%)	45% (13-75%)
K Feldspar	31% (17-60%)	3% (Nil-10%)
Biotite	11% (2-30%)	6% (Nil-20%)
Hornblende	2% (1-10%)	33% (8-60%)
Opaques (Ilmenite, Hematite, Magnetite, Pyrite)	1% (Nil-5%)	2% (TR-5%)
Apatite	1% (TR-5%	1% (TR-5%)
Sphene	TR (TR-2%)	1% (TR-10%)
Allanite	TR (Nil-TR)	TR (Nil-1%)
Monazite	TR (Nil-TR)	TR (Nil-TR)
Zircon	TR (Nil-TR)	TR (Nil-TR)
Calcite	Nil	TR (Nil-1%)
Calcic pyroxene	TR (Nil-5%)	TR (Nil-15%)

Note: Averages calculated from at least 2,000 point counts per specimen minerals are hornblende, apatite, chlorite, magnetite and pyrite. Hornblende is commonly rimmed by biotite. Chlorite and hematized pyrite form veinlets which cut the foliation. Allanite, monazite, sphene and zircon occur in trace amounts and are nuclei for pleochroic halos in biotite. This rock type is commonly cut by dykes and sills of granite pegmatite.

The calc-silicate rock occurs as thin concordant layers, a few centimeters to meters thick, and as small lenses, up to 2 meters long, in biotite gneiss and in pegmatite. This medium to coarse-grained rock is composed of variable proportions of scapolite, salite, sphene, calcite, actinolite and feldspar. A crude foliation is developed in a few outcrops.

Unzoned granite pegmatite, composed of microcline, quartz, perthite and oligoclase, occurs as persistant layers and as small discordant dykes a few meters long in biotite gneiss and rarely in amphibole gneiss. At the contacts, the surrounding gneiss may be coloured pink for distances of up to 3 meters. The accessory minerals are diopside, scapolite, sphene, allanite, biotite, hornblende, zircon, pyrite and calcite.

An east-west diabase dyke cuts the gneisses and is traceable for 170 meters. The contact is exposed in outcrop only and it is marked by a mylonite zone.

2.2 Structure

The foliation in the gneisses generally strikes northwest and dips southwest. The amphibole lineation plunges gently to the southeast. This lineation may represent a southeast plunging fold axis. The diabase is part of an east-west trending dyke swarm in the Grenville Province (Wynne-Edwards, 1972, p. 314) which probably fills a pre-existing fracture system.

3. The Geology of the Zones

Of the six separate mineralized occurrences included in the Yates Mine, the Matte and the Camp zones were selected for a detailed study, because they were the most accessible and best exposed deposits on the property. The mica pits and a small radioactive pegmatite were also examined (Fig. 3, Fig. 4).

3.1 The Camp Zone

During active exploration, the Camp zone was exposed in an area 900 feet (275 meters) long and 100 feet (30 meters) wide (Shaw, 1958, p. 40). Today, this occurrence is exposed for 2/3 of its length and 1/2 of its width. It consists of a carbonate lens, mantled by a body of calc-silicate rock, striking northwest and dipping northeast (Fig. 3). The core is composed mainly of coarse-grained salmon-pink calcite with pale green diopside and amber phlogopite. Thorianite and thorite are found in silicate-rich portions of this assemblage. Thorianite occurs as small cubes, octahedra, dodecahedra, interpenetration cubes with the [111] axis as the twin axis (Stevenson and Stevenson, 1955, p. 107) and as irregular grains. These grains are normally about 0.1 mm in diameter and commonly associated with thorite or calcite. When found in diopside, thorianite is mantled by calcite, and the fractures or cleavages in the pyroxene are filled by carbonate (Plate 1). Thorite occurs as brownish red grains and prismatic crystals of up to

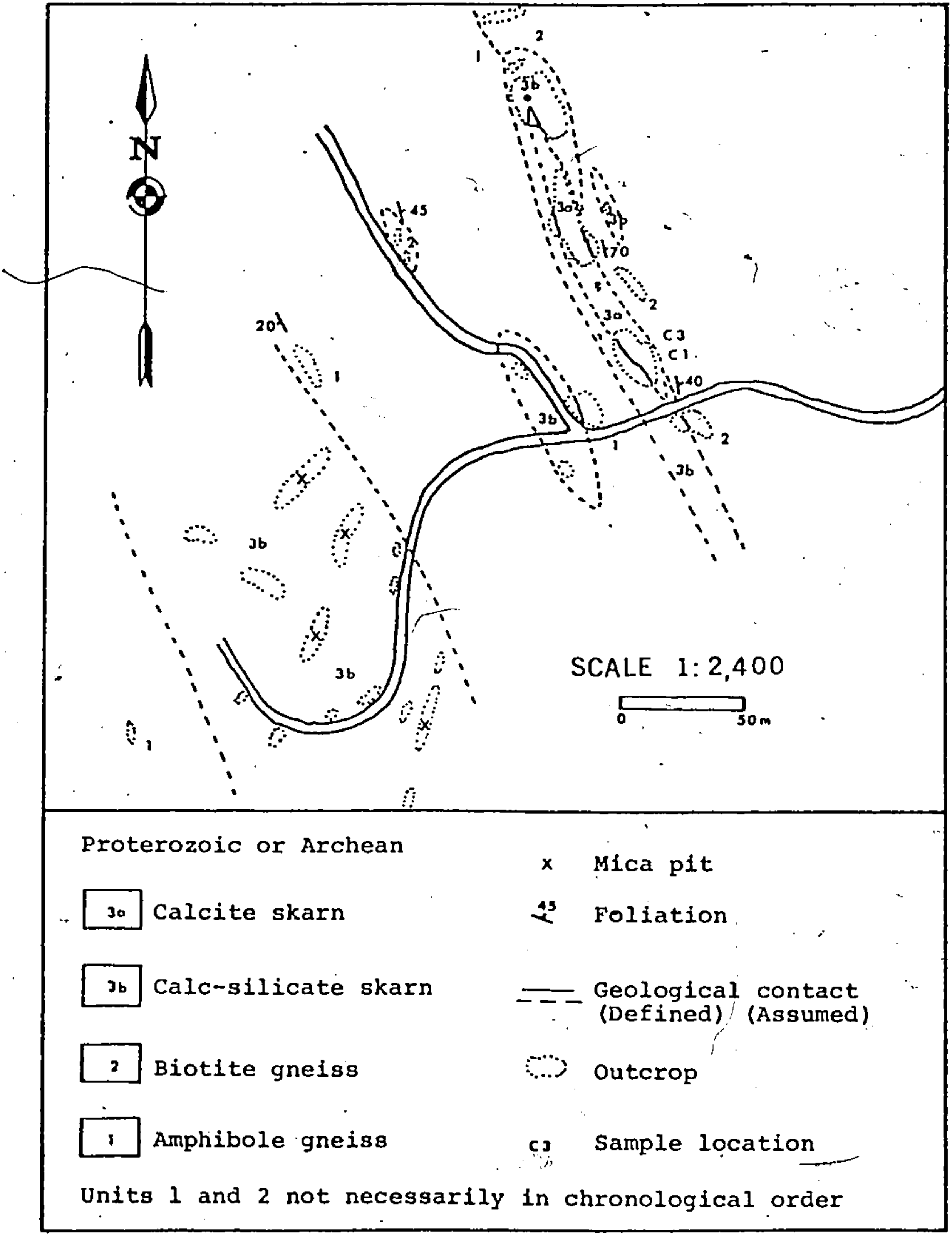

Fig. 3 Geology of the Camp zone and neighboring mica pits

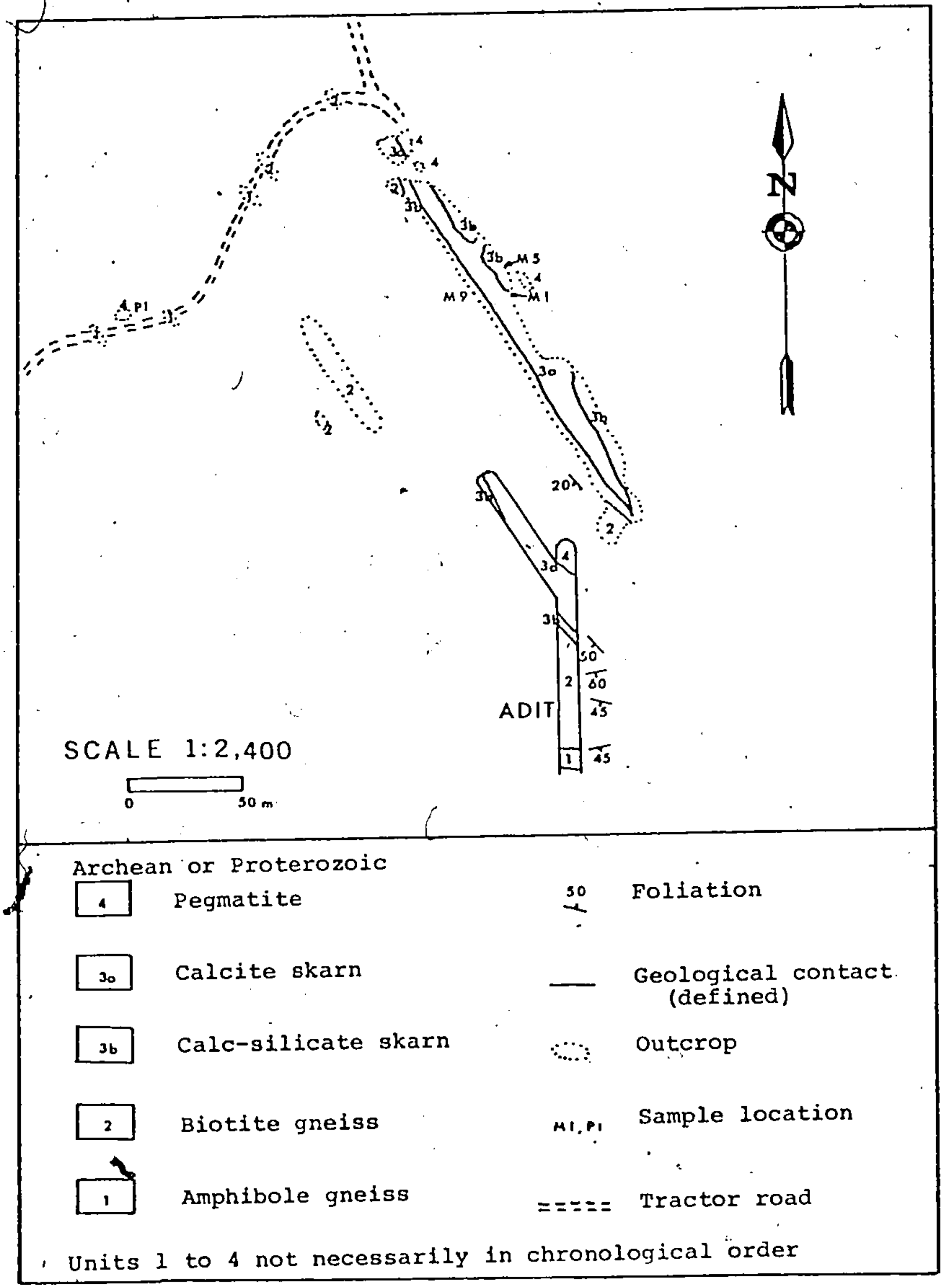

Fig. 4 Geology of the Matte zone. The adit level is 130 feet (39 meters) below the surface exposure of the lens.

Plate 1 Thorianite from the Camp zone

Thorianite (T) mantled by calcite (C) is embedded in diopside (D). (Magnification 400 X)

Transmitted Light

1.5 cm in length. They frequently contain inclusions of diopside and calcite. Yellow uranophane occurs as a secondary coating after thorianite. Beta-uranophane (Lang et al., 1962, p. 213), lessingite (Robinson and Sabina, 1953, p. 627) and allanite (Shaw, 1958, p. 40) have been reported at this occurrence. The core forms veins and plugs in the adjacent calc-silicate rock.

The calc-silicate shell which mantles the core, is of variable thickness (centimeters to meters) and of variable composition. Commonly it consists of scapolite, salite, phlogopite and actinolite. Locally this assemblage is replaced by diopside and actinolite. The calc-silicate rock is medium-grained (2 mm) near the country rocks and coarse-grained (some crystals are up to 0.5 meters long) near the core. White calcite, norbergite and sphene are found in minor amounts. Actinolite and phlogopite are more common near the core, and fluorite occurs in trace amounts. Zoned veins, consisting of scapolite and salite at the edges and of phlogopite at the center (Plate 2), cut the country rocks. At the contact with biotite gneiss, salite encloses scapolite poikilitically. Calcite is rimmed by plagioclase near microcline.

Diamond drilling reveals that the surficial rocks of the Camp zone are underlain by numerous bodies of calc-silicate rock and silicated marble enclosed in pyroxene-bearing biotite gneiss. The biotite gneiss

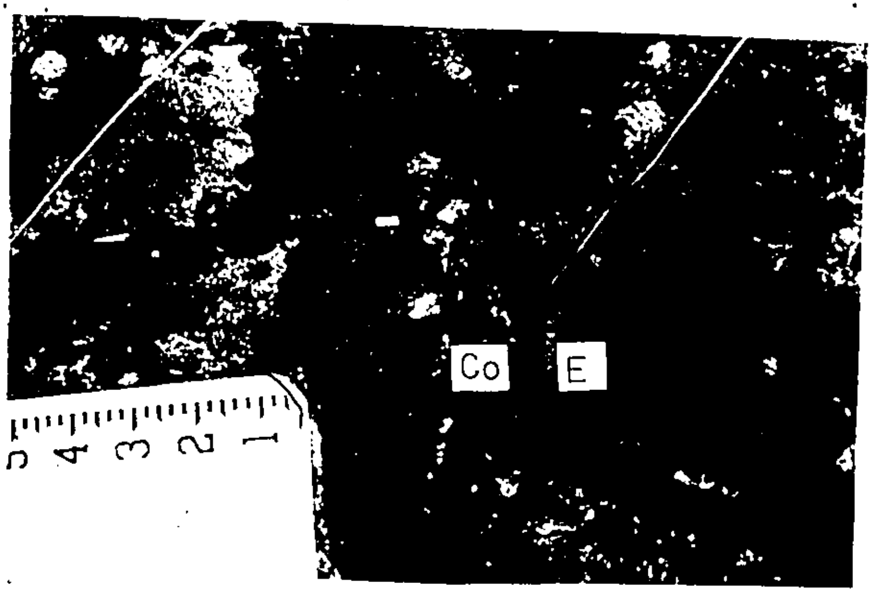

Plate 2 Calc-silicate vein cutting the country rocks at the Camp zone.

A phlogopite core (Co) grades into a scapolite-pyroxene assemblage at the edge (Scale 1:10) overlies amphibole gneiss (Shaw, 1958, p. 40). The relationship between the rocks of the Camp zone and the country rocks is unclear because of the lack of exposure. Shaw (1958, p. 40) reports that the zone forms a shallow syncline.

The skarn rocks at the mica pits are similar to those of the Camp zone. They commonly consist of a salmon-pink calcite-rich coarse-grained core or vein cutting through calc-silicate rock (Plate 3). Salite, phlogopite and green apatite, as crystals up to 40 cm, occur in the core. The calc-silicate rock is composed of varying proportions of salite, scapolite, sphene and phlogopite. The radioactive minerals reported from these pits are uranothorite (Shaw, 1958, p. 39) and allanite (de Schmid, 1912, p. 134). The surrounding rock is a pyroxene and sphene-bearing biotite gneiss.

3.2 The Matte Zone

The Matte zone is 30 feet (10 meters) wide and 600 feet (183 meters) long on surface. It is a concordantly zoned occurrence which strikes northwest and dips 30° southwest (Fig. 4). The core consists of coarse-grained salmon-pink calcite. At the contact, the calcite core contains rounded blocks, up to 3 feet (1 meter) long, of medium-grained scapolite-salite-sphene rock (Plate 4). These blocks are always rimmed by a layer of coarse-grained calc-silicate minerals (Plate 5). Deep purple fluorite, green apatite, salite,

Plate 3 The calcite-rich core of a mica pit. The calcite-rich core (Co) mantled by a calc-silicate edge (E) cuts the country rocks (CR). (Scale 1:40).

Plate 4 Rounded blocks of calc-silicate minerals occurring in the calcite core of the Matte zone (Scale 1:5).

Plate 5 Calc-silicate rim on a calc-silicate block at the Matte zone. A coarser-grained scapolite-salite rim (R) on a scapolite-salite block (B) embedded in coarse-grained calcite (C) at the Matte zone (Scale 1:5).

scapolite, black sphene, phlogopite, microcline, peristerite, thorite, allanite, pyrite and chalcopyrite occur with calcite. Fluorite layers curve around crystals of salite. When apatite crystals are in contact with one another, they are commonly fractured, broken and ground. The fractures are filled by carbonate. Similar fillings occur in fractures and cleavages in salite. Twin lamellae in calcite are frequently bent at grain boundaries. Thorite occurs as slender prisms which form penetration twins (Plate 6). The calcite surrounding these crystals is white, forming pockets in the pink carbonate. Thorite appears to be zoned and commonly occurs in fluorite and allanite (Plate 7). Allanite normally mantles feldspars. Stilbite, heulandite and cerite are reported from cavities in the calcite (Sabina, 1970, p. 96). Near the edge of the core, veinlets of quartz cut calcite and fluorite.

The carbonate core grades into and cuts the adjacent calc-silicate rock which is composed of scapolite, salite, brown sphene, white calcite, brown apatite and phlogopite. Fluorite, pyrite and molybdenite occur in trace amounts. This unit is locally banded with alternating pyroxene-rich and-poor layers. Quartz pods rimmed by salite, up to 30 cm in diameter, are found near the calcite core. Fractures perpendicular to the axis of the zone are filled with salite (Plate 8). These veins exhibit, in some cases, zoning

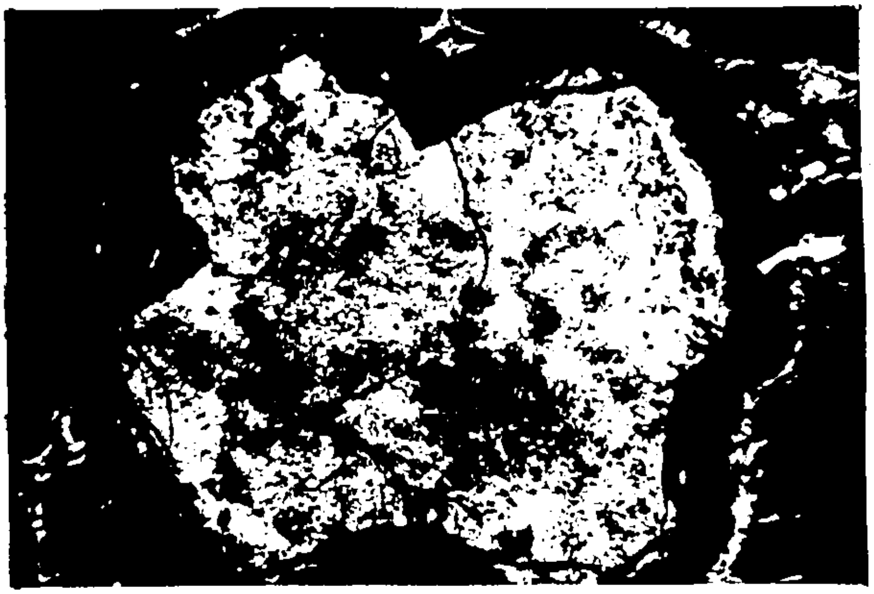

Plate 6 Thorite penetration twins from the Matte zone.

Possible thorite (Th) penetration twin surrounded by fluorite. (Magnification 100 X).

Transmitted Light

Plate 7 Zoned thorite from the Matte zone. Crystalline thorite (Th 1) occurring in metamict thorite (Th 2). (Magnification 100 X). Transmitted Light

Plate 8 Salite-filled fractures at the Matte zones
Salite-filled (Sa) dilation fractures perpendicular to the axis of the Matte zone. (Scale 1:10).

and inward-facing crystals. The zone is in contact with pink biotite gneiss at the hanging-wall and with pyroxene-bearing pegmatite at the footwall. These contacts are exposed in further detail in the adit. The Matte zone is penetrated at a depth of 130 feet (40 meters) below the surface expression of the vein by a drift from an adit which cuts through the hanging-wall rocks. These are dominantly amphibole and biotite gneisses which contain small lenses and layers of calc-silicate rock that are more common near the zone (Fig. 4). These lenses and layers are regularly zoned with calcite-rich cores enclosed by a scapolite-salite-sphene assemblage. The gneiss adjacent to the zone contains abundant scapolite and pyrite. The deposit consists of a calc-silicate rock enclosing a calcite breccia. Calcite and fluorite veins cut the underlying pegmatite. Diamond drilling reveals that the rocks below the deposit are dominantly pyroxene-bearing gneiss (Shaw, 1958, p. 41). The Lake zone which is located 2,500 feet (760 meters) along strike, is probably an extension of the Matte zone (Shaw, 1958, p. 41).

A small zoned radioactive pegmatite is exposed, 400 feet (120 meters) west of the north end of the Matte zone, along an old tractor road (Fig. 4). This pyroxene-bearing pegmatite which grades into a coarse-grained graphic granite, is in contact with biotite gneiss. The quartz core encloses a lens of calcite-fluorite-phlogopite rock with traces of sphene, apatite, salite, epidote and hornblende (Fig. 5). The radioactive minerals are zircon and allanite. Zircon displays euhedral metamict overgrowths surrounding rounded crystalline cores.

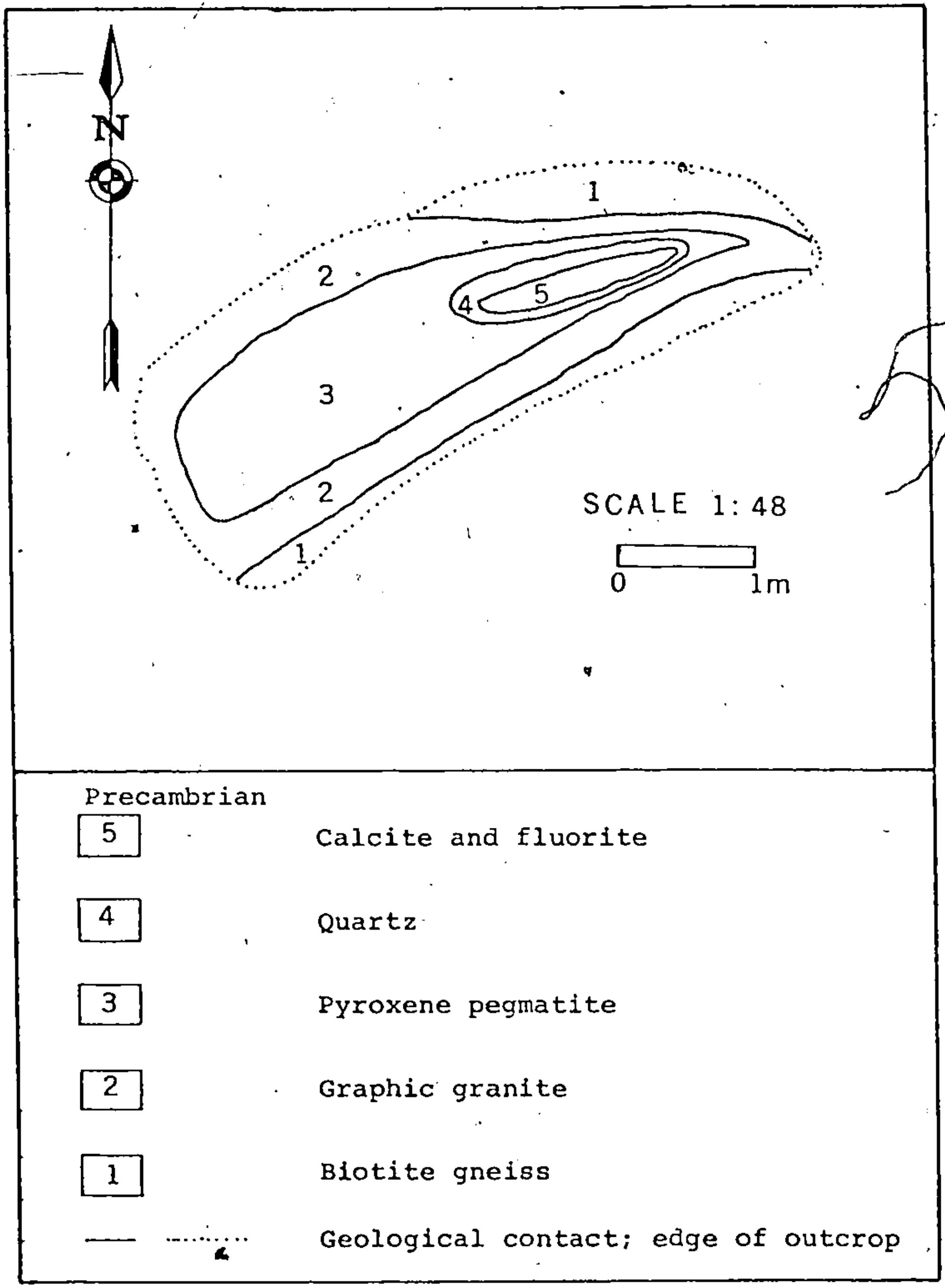

Fig. 5 Radioactive pegmatite near the Matte zone

4. The Geochemistry of the Minerals from the Matte and Camp Zones

Because of the variable and coarse-grained nature of the deposits, it was for all practical purposes impossible to obtain representative rock samples for analysis. Accordingly individual minerals were analysed by microprobe. The accuracy and the precision of the analyses (Table 1) must be borne in mind when considering the results.

4.1 Non-Radioactive Minerals

4.1.1 Amphibole

Hornblende from an amphibole gneiss (Specimen S1, Fig. 2) was analysed to compare it with tremolite from the Camp zone (Table 3). The tremolite is depleted in iron, aluminum, titanium, manganese, potassium and sodium, while being enriched in magnesium and calcium with respect to the hornblende. The compositions of the amphiboles reflect the geochemistry of the parental rocks.

4.1.2 Apatite

X-ray diffraction, optical data and chemical analyses (Trzcienski *et al.*, 1974; Cruft *et al.*, 1965) identify the apatite from the Bélisle and the Matte zones as fluoroapatite (Table 4). The material for the analysis from Trzcienski *et al.* included brown and green crystals, while the material analysed by Cruft *et al.* was a large green crystal. The two analyses are similar

Table 3 Amphibole from the Yates Mine

		Gneiss (S1)	Camp Zone (1)
	SiO_2	44.4%	
	TiO_2	1.3	0.03%
	Al_2O_3	9.2	0.03
(2)	FeO	17.4	1.23
	MnO	0.3	0.05
	MgO	10.6	22.96
	CaO	11.5	15.01
	Na_2O	1.6	0.84
	K_2O	1.3	0.34
(3)	H_2O	2.0	
	Total	99.6%	40.49%
(4)	Fe*	47.88	2.93

Ions calculated on basis	Gneiss (S1)	Camp Zone (1)
	a) 46 charges	a) 46 charges
	b) 8 atoms of Si & Al in tetrahedral sites	b) 8 atoms of Si per formula
		c) all Al octahedral

	Gneiss (S1)		Camp Zone (1)	
Si	6.70	8.00	8.00	8.00
Al	1.30		0.00	
Al	0.34	5.11	0.01	4.72
Ti	0.15		----	
Mg	2.39		4.56	
Fe	2.19		0.14	
Mn	0.04		0.01	
Ca	1.85	2.57	2.14	2.44
Na	0.47		0.22	
K	0.25		0.06	

Note:
(S1) This study
(1) R. Kretz (personal communication)
(2) All iron as Fe O
(3) Calculated on basis of 2 OH per formula of 46 charges
(4) Fe* = (Fe/Fe + Mg) x 100

Table 4 Apatite from the Yates Mine

	Matte (1)	Bélisle (2)	Ions based on 25 positive charges				
				Matte		Bélisle	
UO_3		0.10%	P	2.72		2.96	
SO_3	0.72%		C	0.10	3.02	----	2.98
P_2O_5	38.26	38.37	Si	0.15		0.02	
CO_2	0.88	2.10	S	0.05		----	
SiO_2	1.76	1.07					
Fe_2O_3	0.13	0.04	Ca	4.84		4.82	
Y_2O_3	0.15	0.18	Sr	0.01		0.01	
Ce_2O_3	1.23	0.96	Y	0.01		0.01	
La_2O_3	0.44	0.35	Ce	0.04	4.97	0.03	4.89
Nd_2O_3		0.44	La	0.01		0.01	
Al_2O_3		0.03	Nd	----		0.01	
CaO	53.91	53.98	Na	0.05		----	
SrO	0.28	0.27	Fe	0.01		----	
MgO		0.02					
MnO		0.01	F	1.04	1.20	0.95	1.02
Na_2O	0.28		OH	0.16		0.07	
H_2O	0.29	0.14					
F	3.92	3.30					
Cl		0.02					

Notes: (1) Source: Trzcienski *et al.*(1974

(2) Source: Cruft *et al.* (1965)

except for some minor elements which may be impurities. The presence of oxidized iron could be responsible for the brown color of apatite from the calc-silicate rock. In both analyses cerium is the main rare-earth element.

4.1.3 Calcite

Calcites from the core of the Camp zone and from the breccia of the Matte zone (Specimens C1 and C3, Fig. 3; specimens M1 and M5, Fig. 4) were studied (Table 5). The results indicate that the Matte calcite contains less magnesium but more iron and calcium than the Camp calcite. Another study of these carbonates support these observations (Kretz, personal communication, Table 5).

Shaw _et_ _al._ (1963, p. 594) demonstrate that there is a decrease of aluminum, silicon and magnesium, coupled with a general increase of strontium, iron, manganese and boron during the recrystallization of calcite from sedimentary limestones to skarns (Table 6). If we apply this concept to the analyses and assume that the skarns were derived from parental rocks of similar compositions, the iron and magnesium imply that the skarn is further evolved at the Matte than at the Camp zone. However the analyses may also reflect a difference of composition of the wall rocks.

Table 5 Partial Analyses of Calcite from the Yates Mine

		Camp Zone		Matte Zone	
		(2 grains) C1 & C3 Average	Kretz (1)	(2 grains) M1 & M5 Average	(3 grains) Kretz (1) Average
	CaO	52.3%	56.5%	54.7%	55.1%
	MgO	1.1	0.78	0.3	0.29
	MnO	TR	0.09		0.12
	FeO	TR	0.19	0.3	0.48
	SrO	D	0.26	D	0.24
	BaO		0.19		0.20
(2)	Fe*	7.1	12.0	36.2	48.2
Ions calculated on basis of 1 cation					
	Ca	0.972	0.970	0.988	0.977
	Mg	0.028	0.019	0.008	0.007
	Fe	0.0	0.003	0.004	0.007
	Mn	0.0	0.001		0.002
	Sr		0.002		0.002
	Ca		0.001		0.001

Notes:
(C1, C3, M1, M5) This study
(1) R. Kretz (Personal communication), Analyst: D. Garrett
(2) Fe* = (Fe/Mg + Fe) x 100
TR Some values above detectability but average below
D Detected but not analysed

Table 6 Compositions of Calcites from Skarn Rocks, Grenville Marbles and Paleozoic Limestones

	Skarn Average of 19	Marble Average of 10	Limestone Average of 13
B	21 ppm	18 ppm	8 ppm
Ti	21	15	41
Mn	1490	190	150
Sr	2350	300	310
Pb	22	2	---
Ba	53	42	4
Si	2470	3410	3450
Al	400	390	740
Mg	4430	34100	7630
Fe	3910	1680	970

Notes: Source: Shaw et al. (1963) p. 593

4.1.4 Phlogopite and Biotite

Pale amber phlogopite from the core of the Camp zone, brown phlogopite from the carbonate breccia of the Matte zone and biotite from an amphibole gneiss (Specimen S1, Fig. 2) were analysed by microprobe (Table 7). The Matte phlogopite is depleted in magnesium and enriched in iron when compared to the Camp phlogopite. These skarn phlogopites contain more magnesium and silicon, and less titanium, iron and aluminum than the gneiss biotite.

4.1.5 Pyroxene

Pyroxene coexists with calcite and phlogopite in the skarns at the two localities. The Matte pyroxene is richer in iron, sodium, aluminum and manganese, and poorer in magnesium with respect to the Camp pyroxene (Table 8). These plot in the salite and diopside fields defined by Tröger (1956) as shown in Fig. 6.

A detailed study of trace elements in skarn pyroxenes reveal that they contain less chromium, titanium, nickel, copper, vanadium, zirconium, yttrium, strontium, barium and rubidium than igneous pyroxene (Shaw _et_ _al._, 1963, p. 589). Also the iron content of skarn pyroxenes can be generally correlated with the intensity of the green color (Shaw _et_ _al._, 1963, p. 587). This generalization applies to the Yates mine

Table 7 Phlogopite and Biotite from the Yates Mine

	Camp Zone (C1 & C3) (Average of 5 grains)	Matte Zone (M1 & M5) (Average of 2 grains)	Gneiss (S1) (Average of 2 grains)
SiO_2	41.9%	41.1%	36.7%
TiO_2	Tr	0.4	4.2
Al_2O_3	10.7	11.1	14.1
MgO	27.6	21.1	12.0
MnO	0.0	0.0	0.0
(1) FeO	1.5	8.4	18.4
CaO	0.0	0.0	0.0
Na_2O	0.4	0.4	0.0
K_2O	9.4	10.0	9.5
Total	91.5%	92.5%	94.9%
(2) Fe*	2.8%	18.3%	44.6%

Ions calculated on basis of 22 charges

	Camp Zone		Matte Zone		Gneiss	
Si	3.06	3.98	3.08	4.00	2.88	4.00
Al	0.92		0.92		1.12	
Al	—	3.09	0.07	2.98	0.18	3.04
Ti	—		0.02		0.25	
Fe	0.09		0.53		1.21	
Mg	3.00		2.36		1.40	
Na	0.06	0.93	0.06	1.02	—	0.95
K	0.87		0.96		0.95	

Notes: All analyses made during this study
(1) all iron as FeO
(2) Fe* = (Fe/Fe + Mg) x 100

Tr Some values above detectability limit but average value below

Table 8 **Pyroxene from the Yates Mine**

		A Camp Zone (C1 & C3) (Average of 6 grains)	B Matte Zone (M1 & M5) (Average of 3 grains)	C Matte Zone (1)	Ions based on 12 charges and 4 cations	A Camp Zone		B Matte Zone		C Matte Zone	
	SiO_2	54.1%	52.5%	52.20%	Si	1.96	1.98	1.96	2.00	1.96	2.00
	TiO_2	----	----	0.06	Al	0.02		0.04		0.04	
	Al_2O_3	0.4	1.1	1.31							
(2)	Fe_2O_3	1.8	2.9	1.72	Al	0.00		0.01		0.02	
(2)	FeO	0.0	7.4	8.49	Fe^{3+}	0.05		0.08		0.05	
	MgO	17.7	12.1	11.89	Fe^{2+}	0.00	1.02	0.23	1.00	0.27	1.01
	CaO	24.9	23.7	23.10	Mg	0.97		0.67		0.66	
	MnO	----	0.3	0.28	Mn	----		0.01		0.01	
	Na_2O	0.3	0.8	0.65							
	K_2O	----	----	0.06	Ca	0.98	1.00	0.95	1.01	0.93	1.00
	H_2O	----	----	0.18	Na	0.02		0.06		0.07	
	H_2O	----	----	0.16							
	F	----	----	0.04							
	Cl	----	----	0.03							
	O=(F, Cl)	----	----	0.02							
	Total	99.2%	100.8%	100.15%							
(3)	Fe*	5.0	31.7	31.7							

Notes: (C1, C3, M1, M5) This study
(1) Source: Shaw et al. 1963, Analyst: C.O. Ingamells
(2) Calculation of Fe^{3+} and Fe^{2+} based on the methods of Essene and Fyfe (1967)
(3) Fe* = (Fe/Fe + Mg) x 100

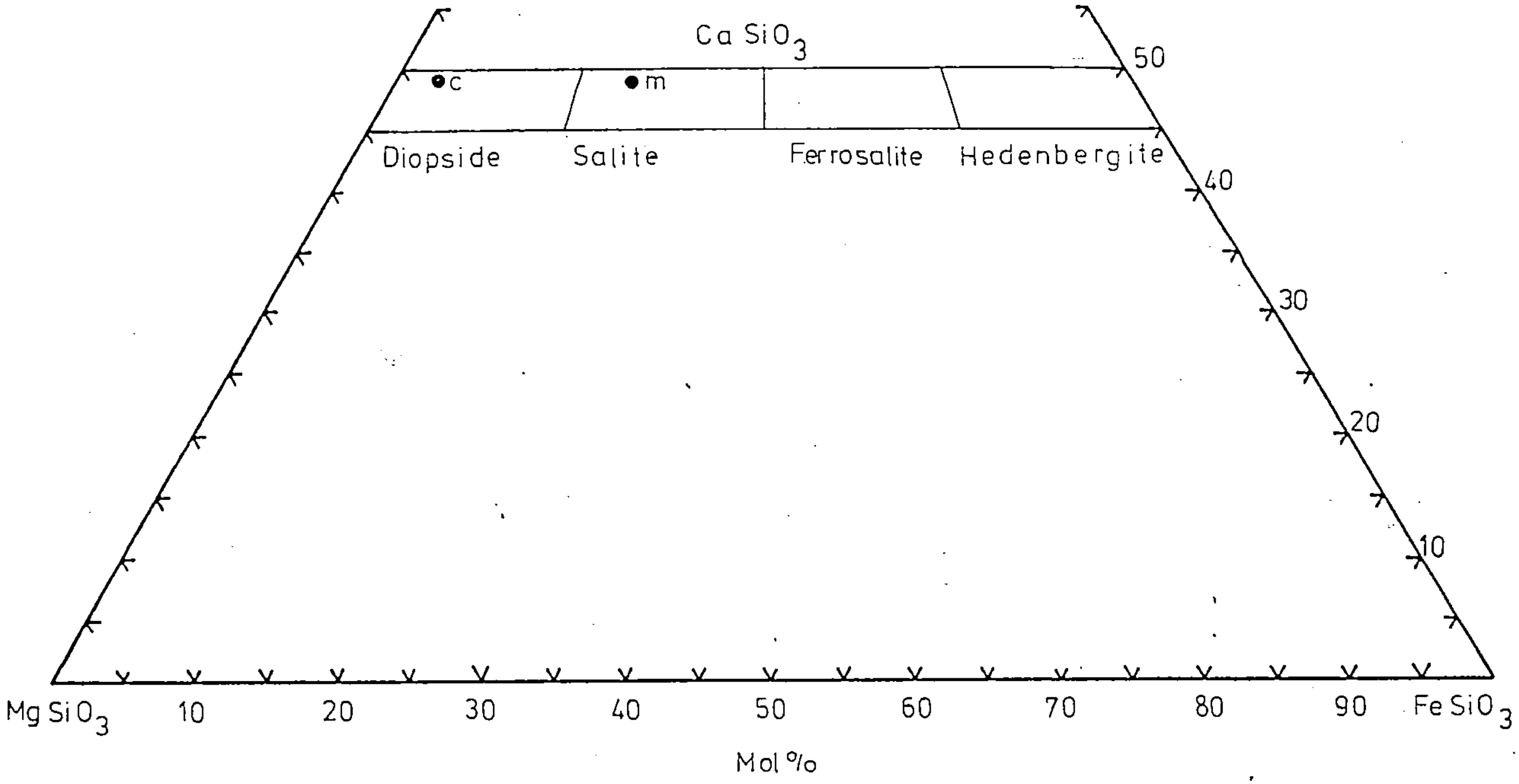

Fig. 6 Molar composition of pyroxene from the Camp zone (C) and the Matte zone (M). Pyroxene fields are those of Tröger (1956).

pyroxenes, since the Matte salite is much darker green than the Camp diopside. If this assumption is also true for the pyroxenes from the amphibole gneiss, then these much darker pyroxenes would plot in the ferrosalite or hedenbergite fields.

4.1.6 Scapolite

Analyses of scapolite from the Matte and the Camp zones are given in Table 9. The Camp scapolite (Haughton, 1971, p. 885) is richer in calcium, carbon and aluminum, and poorer in silicon, sodium and chlorine than the Matte scapolite (Shaw *et al.*, 1963, p. 582). A partial microprobe analysis of scapolite from the Matte zone (Table 9) differs in calcium and sodium contents from the previously reported analysis which is explainable by chemical variations within the deposit or, perhaps, within a single crystal.

4.1.7 Sphene

Sphene was studied from the Matte zone, the radioactive pegmatite and an amphibole gneiss (Specimens M1, M5 and P1, Fig. 4; specimen S1, Fig. 2). The compositions of skarn and pegmatite sphenes are remarkably alike but richer in aluminum and poorer in titanium than the gneiss sphene (Table 10).

Table 9 Scapolite from the Yates Mine

	Matte Zone (M1)	Matte Zone (1)	Camp Zone (2)	Ions based on 12 (Si Al)						
					Matte Zone (M1)		Matte Zone (1)		Camp Zone (2)	
SiO_2	53.3%	52.10%	50.14%	Si	7.88	12.00	7.80	12.00	7.61	12.00
TiO_2	----	0.02	0.00	Al	4.12		4.20		4.39	
Al_2O_3	23.6	23.79	24.57							
Fe_2O_3	----	0.23	0.03	Ca	1.59		1.79		2.04	
MgO	----	0.18	0.06	Na	2.18	3.92	1.99	3.95	1.68	3.90
MnO	----	TR	0.00	K	0.15		0.17		0.18	
CaO	10.0	11.13	12.56							
Na_2O	7.6	6.86	5.70	CO_3			0.44		0.63	
K_2O	0.8	0.87	0.93	Cl			0.47		0.39	
H_2O	----	0.07	0.07	SO_4			0.09	1.12	0.13	1.22
H_2O	----	0.10	0.22	F			0.05		0.00	
CO_2	----	2.14	3.04	OH			0.07		0.07	
Cl	----	1.85	1.56							
SO_3	----	0.80	1.16							
F	----	0.11	0.00							
Total	95.3	100.25	100.04							
O:(Cl, F)		0.46	0.35							
Total		99.79	99.69							
(3) Me	40.5	46.2	52.6							

Notes:
(M1) This study
(1) Source: Shaw et al. (1963), Analyst: C.O. Ingamells
(2) Source: Haughton 1971
(3) Me = (Na / Ca + Na + K) x 100

Table 10 Sphene from the Yates Mine

		Matte Zone (M1 & M5) Average of 2 grains	Pegmatite (P1)	Gneiss (S1)
	SiO_2	30.4%	30.3%	32.8%
	TiO_2	30.0	29.6	36.8
	Al_2O_3	5.6	5.6	1.9
	CaO	27.7	27.5	27.6
	MgO	0.3	0.2	0.5
(1)	FeO	1.5	1.9	1.0
	Na_2O	0.0	0.2	0.0
	Total	95.5	95.3	100.6

Ions calculated on basis of 5 oxygens

	Matte Zone		Pegmatite		Gneiss	
Si	1.00		1.00		1.04	
Ti	0.74	1.00	0.73	1.01	0.88	1.00
Al	0.22		0.22		0.07	
Mg	0.01		0.01		0.02	
Fe	0.04		0.05		0.03	
Ca	0.98	0.98	0.97	0.98	0.94	0.94
Na	0.00		0.01		0.00	

Notes: (1) all iron as FeO

All analyses made during this study

4.1.8 General Considerations

Although the distribution of iron with respect to magnesium in minerals should be considered following the equation Kd $= \frac{x^a\ (1-x^b)}{(1-x^a)\ x^b}$ where x^a and x^b represent Fe^{2+} and Mg^{2+}, an attempt is made to qualify the chemical zoning within the skarn by using Fe* ratios which include Fe^{3+}. Bearing in mind the chemical analyses, we can observe the following:

1) Fe* ratios (Fe*=Fe/Fe+Mg x 100)

   a) Fe* calcite > Fe* diopside > Fe* actinolite > Fe* phlogopite in the core of the Camp zone, Fe* calcite > Fe* salite > Fe* phlogopite in the carbonate breccia of the Matte zone and Fe* hornblende > Fe* biotite in the amphibole gneiss.

   b) Fe* calcite / Fe* diopside from the Camp zone (1.42) $\neq$ Fe* calcite / Fe* salite from the Matte zone (1.14), Fe* diopside / Fe* phlogopite of the Camp zone (1.79) $\approx$ Fe* salite / Fe* phlogopite of the Matte zone (1.73) and Fe* phlogopite / Fe* actinolite of the Camp zone (0.96) $\approx$ Fe* biotite / Fe* hornblende of the amphibole gneiss (0.93). These Fe* ratios do not agree with those that R. Kretz found in skarns minerals of the Grenville Province. He found Fe* px/Fe* amphibole $\approx$ 1 and Fe* amphibole / Fe* mica $\approx$ 0.6. But if we calculate $\frac{x^a}{(1-x^a)}\ \frac{(1-x^b)}{x^b}$ values we obtain similar values to those computed by Kretz in 1970 for gneisses.

c) Fe* biotite from the amphibole gneiss > Fe* phlogopite from the Matte zone > Fe* phlogopite from the Camp zone.

d) Fe* of the minerals from the Matte zone > Fe* of the minerals from the Camp zone.

2) The Me content of the scapolite from the Camp zone > Me content of the scapolite from the Matte zone.

3) The compositions of the sphenes from the radioactive pegmatite and the Matte zone are similar.

These observations may indicate that:

1) a) Iron is preferentially concentrated to magnesium in the carbonate with respect to the silicates.

   b) Equilibrium possibly exists between the silicates but not between the carbonate and the silicates. The relative availability of the elements is controlled by the rates of metasomatism and nucleation. The silicates are formed by similar reactions whose rates and sequence are controlled by the geochemical environment at a specific time. The carbonate formed under different conditions at a later time.

   c) The availability of the elements depends on the chemistry of the parental rocks.

2) The Me content of scapolite also reflects the chemistry of the parental rocks and on the rates of metasomatism of elements.

4.2 Radioactive Minerals

4.2.1 Allanite

Allanites from the Matte zone and an amphibole gneiss were analysed (Table 11; specimen S1, Fig. 2 and specimen M1, Fig. 4). The Matte zone allanite contains more rare-earth elements, magnesium and silicon, and less aluminum, iron, titanium and thorium than the gneiss allanite. In both cerium is the main rare-earth element. The Matte zone allanite has twice the rare-earths content of the amphibole gneiss allanite and a similar enrichment in thorium in the Matte zone allanite might be expected, since thorium behaves similarly geochemically to the cerium family of rare-earth elements (Gabelman, 1977). The occurrence of thorite as inclusions in allanite from the Matte zone offers an explanation for its low thorium content. The earlier nucleation of thorite depleted the concentration of thorium in the geochemical environment for the formation of allanite.

4.2.2 Thorianite

Seventeen grains of thorianite were analysed from two localities, 10 meters apart, at the Camp zone (Specimens C1 and C3, Fig. 3). The average composition of these grains is a

Table 11 Allanite from the Yates Mine

		Matte Zone (M1)	Gneiss (S1)
	SiO_2	34.3%	32.9%
	TiO_2	0.0	1.0
	ThO_2	1.2	2.1
	Al_2O_3	16.9	19.9
	La_2O_3	6.0	3.0
	Ce_2O_3	9.9	5.2
	Pr_2O_3	3.2	1.5
	Nd_2O_3	2.5	1.6
(1)	Fe_2O_3	0.4	7.0
(1)	FeO	8.8	10.0
	CaO	13.2	13.5
	MgO	1.5	0.5
(2)	H_2O	1.6	1.8
	Total	99.5%	100.0%

Ions based on 8 cations	Matte zone		Gneiss	
Si	3.17	3.17	2.91	3.00
Al	0.00		0.09	
Al	1.84	2.76	1.98	3.33
Fe^{3+}	0.03		0.47	
Fe^{2+}	0.68		0.74	
Mg	0.21		0.07	
Ti	0.00		0.07	
Ca	1.31	2.07	1.28	1.69
Ce	0.34		0.17	
La	0.20		0.10	
Pr	0.11		0.05	
Nd	0.08		0.05	
Th	0.03		0.04	

Notes: (1) Fe^{3+} and Fe^{2+} calculated on basis of 25 charges and 8 cations

(2) calculated on basis of 1 OH per formula

All analyses by microprobe, made during this study uranian thorianite (Table 12). The grains are generally speckled with microscopic inclusions which explains the presence of at least some of the silicon, aluminum, iron and calcium in the analyses as impurities. X-ray diffraction patterns and microprobe analyses indicate that uraninite occurs as blebs near thorianite and thorite. The Th/U ratios of the 17 grains analysed give two population maxima (Fig. 7). Assuming that sampling has been sufficiently complete, these peaks suggest that uraninite and thorianite occur as distinct species at the Camp zone with limited interspecies solution (Table 13). Locally, the nucleation of thorite may have hindered the formation of thorianite. Little variation exists between the cores and the rims of uraninite and thorianite (Table 14). The rims are generally richer in silicon and have a higher Th/U ratio than the cores. This indicates an increase of impurities with possibly the formation of secondary uranium silicates and leaching of uranium because of its oxidation to the hexavalent state (U^{+6}; Gabelman, 1977) at the rims. Calcium may be considered, either as an impurity because calcite is embedded in uraninite and thorianite, or as a constituent because it replaces uranium in the uraninite structure (Morton and Sassano, 1972). Compositions plot close to a 1.2 by line (Fig. 8) in the uraninite and thorianite

Table 12 Thorianite from the Yates Mine

		Camp Zone (C1 & C3) Average of 17 grains	Camp Zone (1)	Bélisle Zone (1)
	U_3O_8	----	36.8%	25.0%
(2)	UO_2	37.8%		
	ThO_2	44.1	40.1	55.5
(2)	CeO_2	1.5		
	SiO_2	1.7		
	Pr_2O_3	Tr		
	Nd_2O_3	1.5		
	Al_2O_3	0.4		
	PbO	9.1	7.7	6.8
	CaO	2.0		
	MgO	0.4		
(2)	FeO	Tr		
	Total	98.5	84.6	87.3
	Molar U/Th	0.84	0.88	0.43

Ions calculated on basis of 1 cation

	Camp Zone (C1 & C3)		Camp Zone (1)		Bélisle Zone (1)	
U	0.38	0.99	0.41	1.00	0.27	1.00
Th	0.46		0.49		0.64	
Ce	0.02		----		----	
Nd	0.02		----		----	
Pb	0.11		0.10		0.09	

Notes: (C1, C3) This study

(1) Source: Robinson and Sabina (1955)

(2) Assumed Valencies of U, Ce and Fe

Tr Some values above detectability but average below

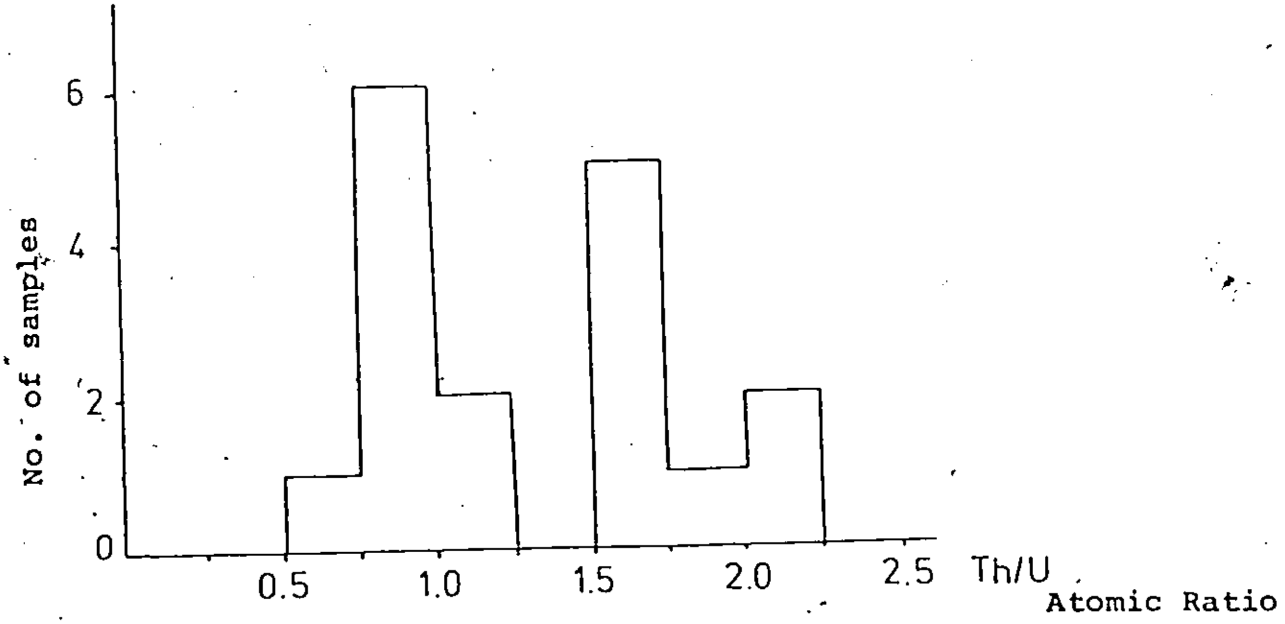

Fig. 7 The distribution of Th/U ratios in thorianite from the Camp zone

Table 13 Uraninite and Thorianite from the Camp Zone

		Uraninite (Average of 9 grains)	Thorianite (Average of 8 grains)
(1)	UO_2	44.4%	30.5%
	ThO_2	36.9	52.3
(1)	CeO_2	1.6	1.4
	SiO_2	1.4	2.0
	Pr_2O_3	Tr	Tr
	Nd_2O_3	1.6	1.5
	Al_2O_3	0.4	0.3
	PbO	9.4	8.7
	CaO	2.3	1.7
	MgO	0.4	0.4
(1)	FeO	Tr	Tr
	Total	98.4	98.8

Ions calculated on basis of 1 cation

	Uraninite		Thorianite	
U	0.45	1.01	0.31	1.00
Th	0.38		0.54	
Ce	0.03		0.02	
Nd	0.03		0.02	
Pb	0.12		0.11	

Notes: (1) Assumed Valencies for U, Ce, Fe

Tr Some values above detectability limits but average below

All analyses by microprobe, made during this study

Table 14 Analyses of Cores and Rims of Uraninite and Thorianite from the Camp Zone

	Uraninite-Thorianite		Thorianite	
	Core	Rim	Core	Rim
(1) UO_2	40.3%	37.2%	33.4%	29.7%
ThO_2	39.1	39.4	50.2	53.5
(1) CeO_2	1.8	1.3	1.3	1.4
SiO_2	1.4	2.9	1.4	2.3
Pr_2O_3	0.4	Tr	Tr	Tr
Nd_2O_3	1.6	2.1	1.4	1.3
Al_2O_3	0.5	0.4	0.3	0.3
PbO	9.8	9.3	8.6	8.5
CaO	2.5	2.9	1.7	1.3
MgO	0.3	0.3	0.4	0.4
(1) FeO	Tr	Tr	Tr	Tr
Total	97.7	94.8	98.7	98.7
Molar Th/U	0.98	1.10	1.53	1.83

Ions calculated on basis of 1 cation

U	0.41	1.00	0.39	1.00	0.34	1.01	0.30	0.99
Th	0.40		0.43		0.52		0.55	
Ce	0.03		0.02		0.02		0.02	
Pr	0.01		0.00		0.00		0.00	
Nd	0.03		0.04		0.02		0.02	
Pb	0.12		0.12		0.11		0.10	

Notes: (1) Assumed Valencies for U, Ce, Fe

TR Some values above detestability limits but average below

All analyses by microprobe made during this study

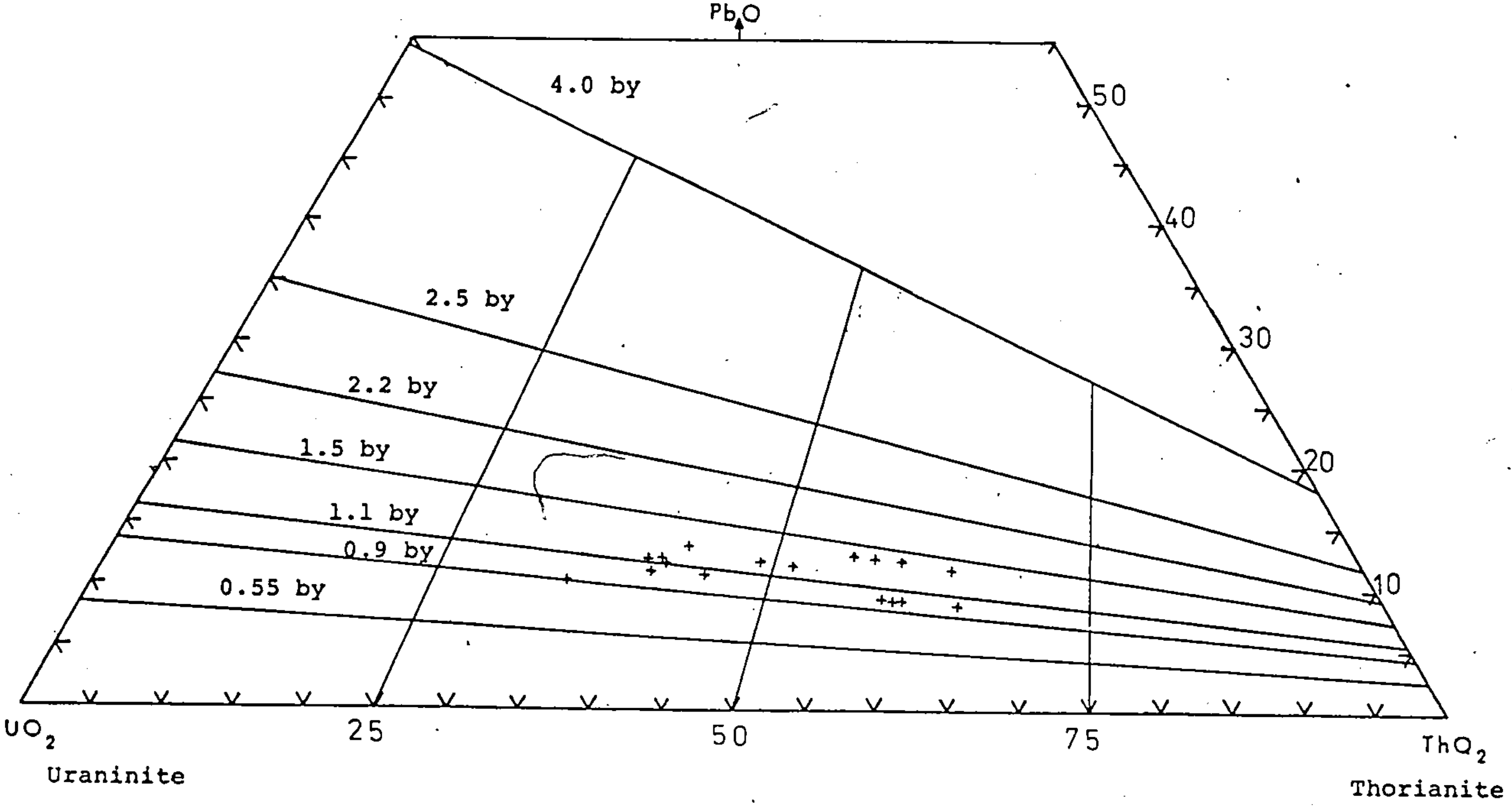

Fig. 8 The molecular compositions of thorianite-uraninite minerals from the Camp zone (Specimens Cl & C3)

fields (Appendix 1). The variation of the molecular compositions of the minerals is tremendous (Fig. 8) considering that thorianite is a few mm away from uraninite (Appendix 3; grains laa from the same slide). This probably reflects disequilibrium during their formation.

4.2.3 Thorite

The thorites from the Matte and the Camp zones can be referred to as uranothorite (Lang et al., 1962, p. 48) since they contain more than 5 percent uranium (Table 15). These analyses represent uranothorites from two different localities from both zones (Specimens C1 and C3, Fig. 3; specimens M1 and M5, Fig. 4). The Matte uranothorite contains more uranium, calcium and lead, and less silicon and cerium than the Camp uranothorite. In both uranothorites, cerium is the main rare-earth element. A few thorite analyses (Appendix 4) had low concentrations of silica and they probably represent mixtures of thorianite and thorite. These grains generally show wide variations of their silica content compared to the other uranothorites which show little if not no variations. Analyses of Robinson and Abbey (1957) of uranothorites from other localities in the Grenville Province listed in Table 16 show that uranothorites from calcite skarns are generally richer in rare-earths than uranothorites from pegmatites and granites. The Yates mine uranothorites are also rich in rare-earths (0.6 - 1.0 RE) and therefore agree with this generalization.

Table 15 Uranothorite from the Yates Mine

		Matte Zone (M1 & M5) (Average of 12 grains)		Camp Zone (C1 & C3) (Average of 6 grains)	
ThO_2		58.7%		59.3%	
UO_2	(1)	8.4		5.7	
SiO_2		16.4		18.4	
Ce_2O_3	(1)	0.6		1.0	
PbO		Tr		Tr	
Nd_2O_3		Tr		Tr	
Al_2O_3		0.3		0.3	
PbO		3.9		3.2	
CaO		4.4		3.3	
FeO	(1)	0.6		0.5	
		93.9%		92.4%	

Ions calculated on Basis of 1 Si Al

Si		0.98	1.00	0.98	1.00
Al		0.02		0.02	
Th		0.80	1.26	0.71	1.04
U		0.11		0.07	
Ce		0.01		0.02	
Nd		0.00		0.00	
Pr		0.00		0.00	
Pb		0.06		0.05	
Ca		0.28		0.19	

Notes: All analyses by microprobe, made during this study

(1) Assumed Valencies of U, Ce, Fe

Tr Some values above detectability limit but average below

Table 16 Uranothorite from the Grenville Province

	1	2	3	4	5	6	7	8	9
SiO_2	19.73%	20.84%	17.62%	17.80%	19.32%	19.20%	20.40%	19.18%	21.06%
PbO	1.58	3.16	1.27	1.46	0.50	0.64	3.62	1.23	3.98
U_3O_8	13.94	12.31	5.78	11.32	10.83	11.72	10.73	9.00	15.09
ThO_2	46.78	43.49	57.55	49.08	48.29	51.56	49.92	52.42	39.46
RE	3.99	0.2	1.69	1.66	2.05	0.2	0.41	0.2	0.2
Fe_2O_3	0.36	2.70	3.89	3.42	2.40	3.96	2.44	2.74	2.26
CaO	5.75	3.29	2.42	2.30	2.59	2.16	2.79	2.37	3.88
H_2O	9.72	11.1	9.54		11.1	9.3	9.48	9.75	11.08
C		0.24				0.1	0.31	0.59	
CO_2		0.04					0.19	0.26	

Note: Source - Robinson and Abbey (1957)

Specimens 1, 3, 4, 5 are from skarn rocks or calcite lenses in pegmatite

Specimens 2, 6, 7, 8, 9 are from pegmatites or granites

4.3 Neutron Activation Analyses

Three rock samples were carefully selected to be free of uranium-rich minerals and were submitted to Atomic Energy of Canada Limited for uranium analyses by neutron activation. The samples are an amphibole gneiss, a pink biotite gneiss near the Matte zone and the calcite core of the Matte zone (Table 17; Specimen S1, Fig. 2; Specimens M4 and M1, Fig. 4). The uranium contents of the calcite core of the Matte zone is much higher than those reported for sedimentary carbonate rocks and marbles by Rogers and Adams (1969). Marble generally contains less uranium than sedimentary carbonate rocks, indicating that metamorphism tends to lower the uranium contents in rocks (Rogers and Adams, 1969, p. 92 N-1) by remobilizing it to more favorable environment of deposition. The amphibole gneiss also indicates an enrichment of uranium with respect to a hypothetical gabbroic source rock. The uranium content of the biotite gneiss is within the acceptable norms reported for Precambrian granites (2-6 ppm). The enrichment of uranium in the Matte zone and in the amphibole gneiss can be explained, either by intrusions of pegmatites and granites into sedimentary rocks, or by regional metamorphic processes which would have mobilized the uranium in a sedimentary rock and caused it to migrate into the skarns and amphibole gneisses of the Yates mine.

Table 17 Uranium in Rocks from the Yates Mine and from selected localities

	U (PPM)	
This study (1)		
Calcite core Matte zone (M1)	17.3	
Amphibole gneiss (S1)	8.9	
Biotite gneiss near Matte zone (S2)	2.5	
Rogers and Adams (1969)		
Carbonate rocks	2.2	(0-7)
Shales	3.2	(1-6)
Greywacke	2.1	
Marble (Grenville Province)	0.4	
Gneiss	2.8	
Biotite Hornblende Schist	4.7	
Granitic rocks (Precambrian)	2.2	(2-6)
Gabbroic rocks	0.8	(0.1-1.5)
Roscoe (1969)		
Radioactive conglomerate (Elliot Lake)	16.9	(16.9-15,000)
Subarkose (Elliot Lake)		(5.0-13.0)

Note: (1) Neutron activation analyses by Atomic Energy of Canada Limited.

4.4 General Observations

Data can be summarized as follows:

1) Radioactive minerals at the Yates Mine are generally thorium- and cerium-rich.
2) Allanite from the skarn is richer in rare-earths and poorer in thorium than the allanite from the amphibole gneiss. Also it contains numerous inclusions of thorite.
3) Thorianite includes poikilitic impurities (probably calcite, quartz, diopside), varies compositionally from thorian uraninite to uranian thorianite, is in contact with thorite or calcite and occurs as minute inclusions in thorite at the Camp zone.
4) Thorite from the Camp zone contains less uranium than the thorite from the Matte zone.
5) Calcite bearing skarn is richer in uranium than the regional amphibole gneiss, which in turn is richer in uranium than its sedimentary protolith (the average graywacke of Table 17). Biotite gneiss contains considerably less uranium than the amphibole gneiss.

These data suggest:

1) The source rock was anomalously high in thorium and cerium rare-earths since these elements tend to migrate together (Gabelman, 1977).
2) Allanites from amphibole gneiss and skarn were formed under different conditions and at the Matte zone the thorium content was apparently depleted

by the development of entrapped thorite.

3) The nucleation of thorite after thorianite and/or possibly the formation of thorianite itself depleted the thorium supply which led to the formation of uraninite. The rapid variation of the molecular composition probably reflects disequilibrium conditions.

4) The uranium - and thorium - bearing metasomatic fluids reacted dominantly with carbonate rocks, or rocks that had been derived from them during metamorphism.

5. The Genesis of the Yates Deposits

The occurrence of radioactive and/or molybdenum-bearing skarns (Satterly 1957, Vokes 1963, Shaw et al. 1963, Kretz personal communication) or vein-dykes (Ellsworth 1932, Hogarth et al. 1972) or apatite-phlogopite occurrences (Semenov 1972) are widely distributed in space and time (Aldan and Slyudyanka, U.S.S.R., Archean; Saskatchewan, Canada, Aphebian; Ontario and Québec, Canada, Helikian; Ceylon, Cambrian; Madagascar, Cambrian). The occurrences in the Grenville Province of Ontario and Québec have been considered as igneous dykes (Spence 1929, Landes 1938, Heinrich 1966), as hydrothermal veins related to pegmatites (Ellsworth 1932, Satterly 1957, Semenov 1972), as products of contact metamorphism (Wilson 1924, Currie 1951), and as products of regional metamorphism coupled with metasomatism (Rowe 1952, Shaw et al. 1963, Hogarth et al. 1972, Villeneuve 1977, Kretz personal communication and 1960).

5.1 Geological Characteristics

The model proposed for the formation of the Yates skarns should explain observations made at the mine and perhaps also at similar occurrences. The mine is located within a sedimentary pile which has been metamorphosed to the upper amphibolite or granulite facies (Wynne-Edwards, 1972) and intruded by granitic, syenitic and gabbroic plutons and diabase dykes. The deposits and other calc-silicate layers and lenses are interbedded with quartzofeldspathic biotite gneiss and amphibole gneiss. These gneisses contain trace amounts of apatite, monazite and zircon. The alteration of hornblende to biotite, of biotite to chlorite and of feldspar to epidote, and possibly also the occurrence of calcite, pyrite and chlorite veinlets indicate that the gneisses were affected by retrograde metamorphism. A radioactive pegmatite occurs near the Matte zone. The pegmatite is zoned and contains a calcite-fluorite lens in its quartz core.

The deposits of the Yates mine are mineralogically zoned; they each possess a calcite core, with or without fluorite and apatite, which grades into and locally replaces an enveloping pyroxene-rich zone, with or without scapolite, phlogopite and sphene. Each assemblage is also zoned with respect to grain size; the outer edge is finer-grained than the inner edge or core. The deposits appear to be generally concordant with the gneisses, but are locally discordant. Similarly zoned calc-silicate veins occur adjacent to the deposits filling dilated fractures and cutting the country rocks. Some of these veins contain voids and inward-facing crystals. The mineralogies and the textures of the cores of the deposits reflect the abundance of volatiles (CO_2, F, P_2O_5) during the skarn-forming process and their mobility during or after their formation (blocks of calc-silicate embedded in a calcite matrix, ground and broken crystals of apatite, calcite filling and replacement along fractures and cleavages in minerals, flowing of fluorite layers around pyroxene porphyroblasts, bending of twin planes at the rims of calcite grains). The radioactive minerals are generally concentrated at the transition between the cores and the edges. Thorianite occurs as discrete crystals, sometimes accompanied by uraninite, as inclusions in thorite and in contact with no silicate other than thorite. Amphibole locally replaces pyroxene. Lenses of quartz occur within the calc-silicate assemblage. The very coarse-grained nature of the deposits is characteristic of pegmatites. Calcite, pyroxene, phlogopite, amphibole and epidote (allanite) are common to both the skarns and the nearby marbles suggesting that these two rock types may ha[illegible] been formed under the same thermal regime (Kretz, 1960). The geochemistry indicates an enrichment of uranium and thorium in the deposits in contrast to the norms for marbles and sedimentary carbonate rocks. This enrichment is preferentially localized in the skarns. Constant Fe* ratios between pyroxene, phlogopite and amphibole, and the decreasing intensity of the color of pyroxene from the edges to the cores of the deposits suggest a variation of iron with respect to magnesium in the compositions of these silicates. These minerals tend to develop lower Fe/Mg ratios towards the core of the deposits. The color of calcite grades from white at the edges to salmon-pink at the core and this indicates that the iron content increases towards the core

(Shaw et al., 1963). The Fe* ratios suggest that a possible local equilibrium exists between the silicates but not with calcite. The trace element contents of pyroxene and calcite from skarns differ from those of igneous pyroxene, sedimentary and metamorphic calcites (Shaw et al., 1963). Pyroxene, phlogopite and calcite from the Matte zone are richer in iron and poorer in magnesium than the same minerals from the Camp zone; this may reflect more intense iron metasomatism at the Matte zone, or a difference in geochemical environment. Fluoride and phosphate complexes may have been vehicles of metasomatic transport as evidenced by the abundant fluorite and fluorapatite at the Matte zone.

Elsewhere stable isotope ratios have been determined from vein-dykes or skarns. Powell (1965) demonstrated that strontium isotope ratios in vein-dykes from the Bancroft area are intermediate between sedimentary limestones and carbonatites (Fig. 9). Currie (1951) found carbon isotope ratios for a marble and a vein-dyke from southeastern Ontario to be similar, thereby excluding the possibility of igneous or hydrothermal origin for the carbon (Table 18).

The parameters of formation of skarns in the Grenville Group can be estimated by considering the formation of marbles, which have similar mineralogies, and associated rocks in the group. Measurements made with a

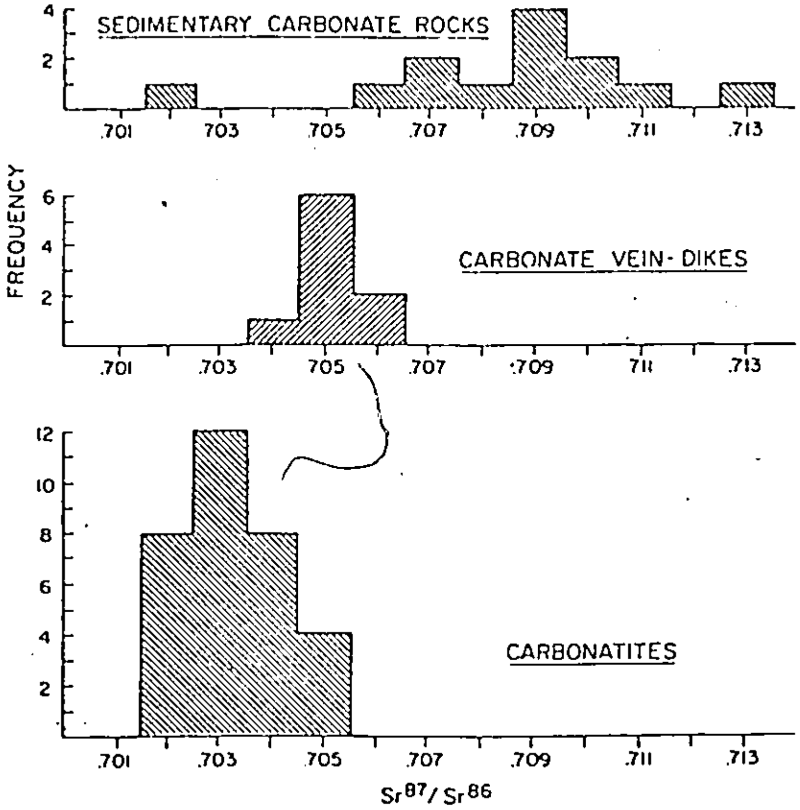

Fig. 9 Frequency distribution of Sr^{87}/Sr^{86} ratio in carbonatites, vein-dykes and sedimentary carbonate rocks (Powell, 1965).

C^{12}/C^{13} RATIOS.

	Type of material	Values of C^{12}/C^{13}
1	Meteoric carbon	89.5 to 92.0
2	Igneous carbon	89.0 to 90.2
3	Calcium carbonate from limestone	87.9 to 89.5
4	Pink calcite from North Burgess Twp.	84.90 (±0.1%)
5	Limestone from North Burgess Twp.	85.02 (±0.1%)

Values 1, 2 and 3 as given by Rankama (12, p. 204).
Values 4 and 5 from analysis by J. Macnamara, McMaster University, Hamilton, 1950.

Table 18 Carbon isotope ratio from a vein-dyke (Currie, 1951).

sphalerite geobarometer at four localities in southeastern Ontario and adjacent western Québec indicated pressures ranging from 4.75 to 6.0 Kbars during the metamorphism of the group (Ewert, 1977). The nearest locality to the Yates mine, the New Calumet mine, indicated pressures of 5.5 to 6.0 Kbars. If these values are applied to the rocks near the Yates mine, they imply burial depths reaching 20 to 22 km. Hutcheon and Moore (1973) measured temperatures in marbles of the amphibolite facies in southeastern Ontario ranging from 400° to 597° C. by the calcite-dolomite geothermometer. Ewert (1977) using the same geothermometer and invariant points estimated temperatures of 540° to 630° C. for pyroxene-bearing marbles also in southeastern Ontario. He demonstrated that the presence of chondrodite limits the partial pressure of CO_2 to a maximum value of 0.25.

5.2 The Model

The model proposed for the formation of the Yates mine must also account for the genesis of similar vein-dykes or skarns. The mineralogical differences between the deposits are caused by the chemistry of the country rocks (Hogarth *et al.*, 1972) and by the type and degree of metasomatism and remobilization.

The sequence of events leading to the formation of the Yates deposits have begun by the introduction of uranium and thorium in the basin as resistate minerals such as possibly uraninite, thorianite, monozite, thorite, allanite, zircon and apatite, as precipitates such as coffinite and as absorbed ions during the deposition of the arkosic, psammitic, pelitic and carbonate sediments of the Grenville Group. A partial separation of uranium and thorium may occur during sedimentation because the precipitates are dominantly uranium minerals and the resistates are commonly thorium minerals. Differentiation would necessarily occur during diagenesis since water, being expelled from the sediments because of the loss of pore space, would transport uranium as U^{6+} in soluble complexes at low temperatures and pressures (Gabelman, 1977) while thorium remains immobile. In this form uranium could migrate along fractures and through pore spaces in sedimentary rocks to favorable horizons of deposition.

During prograde metamorphism clay minerals recrystallize to micas and finally to aluminous silicates producing water which may be expelled from the rocks since the specific volume of water increases with increasing temperature and pressure (Norris and Henley, 1976) leading to hydraulic fracturing of the rocks. If a volume of rock follows a path as described by Norris and Henley (1976) during metamorphism (Fig. 10), water could escape during prograde metamorphism and in the early stages of uplift. During prograde metamorphism, impure carbonate rocks produce CO_2, following the general reaction: carbonate minerals

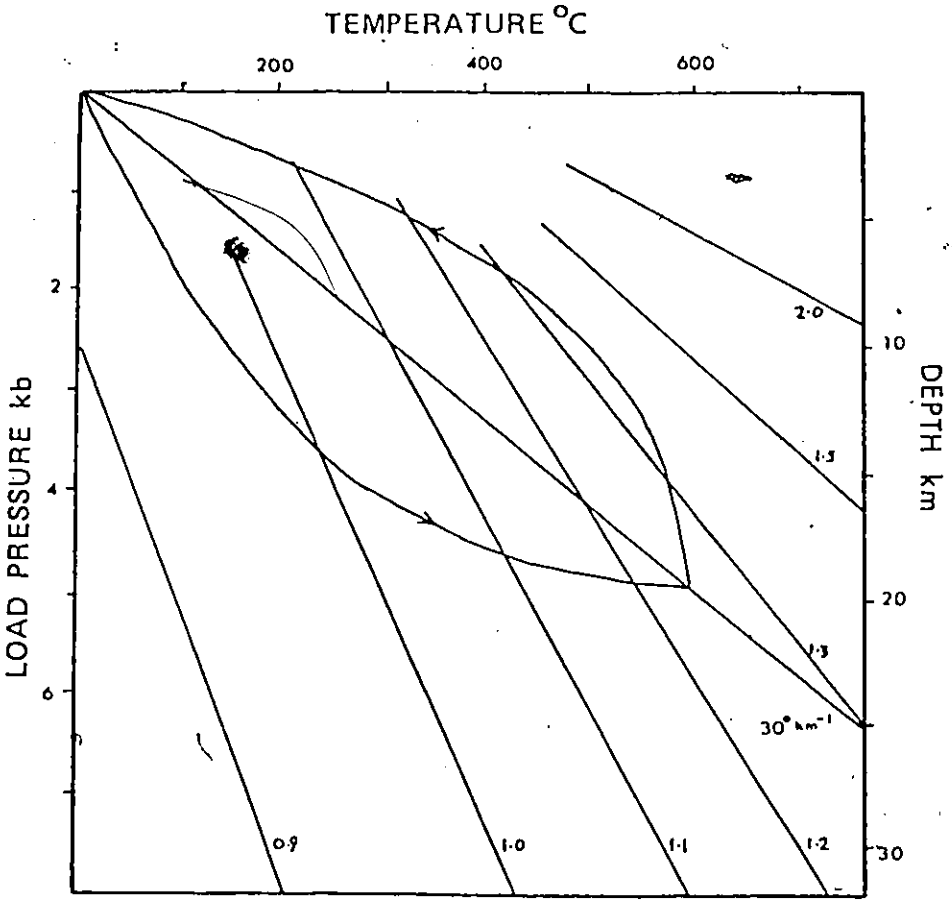

Fig. 10 Trajectories of a small volume of rock of a pile of sediments during metamorphism after Norris and Henley (1976). The slanting lines represent specific volumes of water ($cm^{3} gm^{-1}$). The geothermal gradient is assumed to be $30^{o} km^{-1}$ and the depth equivalents are calculated from an average rock density of 2.6 gm cm^{-3}.

+ silicate minerals = calc-silicate minerals + CO_2 (Table 19). At the peak of metamorphism, metasomatism of elements such as silicon can occur over short distances near contacts of carbonate beds with the surrounding rocks. Thus thin carbonate beds could be extensively silicated. At temperatures of 600°C. and pressures of 4 to 5 Kbars, uranium, thorium and rare-earths form soluble salts (fluorides and chlorides) and complexes (Gabelman, 1977) after the decomposition of resistate minerals such as thorite, allanite, monazite, thorianite and apatite. Thus the resultant metamorphic fluids, rich in volatiles, actinides and lanthanides may be retained at depth until the early stages of uplift (Norris and Henley, 1976).

During early stages of uplift of the metamorphosed sediments, the metamorphic fluids expand and migrate along fractures and weak planes because of the release of the overlying pressure. When the fluids encounter quartzofeldspathic rocks melting may occur to form pegmatites. Should the fluids encounter carbonate or calc-silicate rocks, such rocks may be mobilized and calc-silicate minerals may form with an accompanying increase in CO_2 partial pressure. With the depletion of silica, calcite, calcium fluorides and phosphates crystallize. The reaction of thorianite

Table 19 Possible Reactions Involved in the Formation of Minerals of Calc-Silicate Rocks at the Yates Mine

1) Dolomite + microcline + water $\rightleftharpoons$ phlogopite + calcite + CO_2

$3\ CaMg\ (CO_3)_2 + K\ Al\ Si_3O_8 + H_2O \rightleftharpoons K\ Mg_3Al\ Si_3O_{10}\ (OH)_2 +$

$3\ Ca\ CO_3 + 3\ CO_2$

2) Dolomite + Quartz + Water $\rightleftharpoons$ Talc + Calcite + CO_2

$3\ Ca\ Mg\ (CO_3)_2 + 4\ SiO_2 + H_2O \rightleftharpoons Mg_3Si_4O_{10}\ (OH)_2 + 3\ CaCO_3 + 3CO_2$

3a) Talc + Calcite + Quartz $\rightleftharpoons$ Tremolite + CO_2 + Water

$5\ Mg_3Si_4O_{10}(OH)_2 + 6CaCO_3 + 5SiO_2 \rightleftharpoons Ca_2Mg_5Si_8O_{22}(OH)_2 +$

$6\ CO_2 + 2H_2O$

3b) Dolomite + Quartz + Water $\rightleftharpoons$ Tremolite + Calcite + CO_2

$5\ CaMg\ (CO_3)_2 + 8SiO_2 + H_2O \rightleftharpoons Ca_2Mg_5Si_8O_{22}\ (OH)_2 + 3CaCO_3 +$

$7\ CO_2$

4a) Tremolite + Calcite + Quartz $\rightleftharpoons$ Diopside + CO_2 + Water

$Ca_2Mg_5Si_8O_{22}\ (OH)_2 + 3\ CaCO_3 + 2SiO_2 \rightleftharpoons 5\ CaMgSi_2O_6 + 3\ CO_2 +$

H_2O

4b) Dolomite + Quartz $\rightleftharpoons$ Diopside + CO_2

$CaMg\ (CO_3)_2 + 2\ Si\ O_2 \rightleftharpoons Ca\ Mg\ Si_2O_6 + 2CO_2$

5) Calcite + Plagioclase $\rightleftharpoons$ Scapolite

$CaCO_3 + 3\ Ca\ Al_2Si_2O_8 \rightleftharpoons Ca_4Al_6Si_6O_{24}(CO_3)$.

6) Calcite + Rutile + Quartz $\rightleftharpoons$ Sphene + CO_2

$CaCO_3 + TiO_2 + SiO_2 \rightleftharpoons Ca\ Ti\ SiO_5 + CO_2$

7) Thorianite + Quartz = Thorite

$ThO_2 + SiO_2 = Th\ Si\ O_4$

with silica producing thorite may or may not go to completion depending on the available silica. The fluids become progressively depleted in thorium by the nucleation of thorianite, and enriched in uranium and rare-earths which may form discrete uranium and RE minerals depending on sufficient concentration. In the final stages a high CO_2 partial pressure may cause the fracturing and replacement of existing minerals and veining such as at the Matte zone. In this fashion fluids, originally rich in water and capable of generating very coarse-grained quartzofeldspathic rock, become progressively enriched in CO_2 forming calc-silicate minerals and carbonates. This theory may explain the almost simultaneous formation of syenite pegmatites, pegmatites with carbonate cores and vein-dykes, aided by the release of volatile components generated during high-grade regional metamorphism of a sedimentary sequence. It also may explain the preferred occurrence of thorianite in calc-silicate rocks which lack the silica supply of pegmatites (Appendix 2).

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Appendix 1 The Uraninite-Thorianite Solid Solution

The mineral names uraninite and thorianite are generally used to denote the uranium-and thorium-rich end-members of the uraninite-thorianite solid solution (Palache et al., 1944; Lang et al., 1962; Rogers and Adams, 1969). Uranium isotopes decay more rapidly to lead than the main thorium isotope (U^{238}½ life = 4.5×10^9 yrs, U^{235}½ life= 7.1×10^8 yrs, Th^{232}½ life= 1.39×10^{10} yrs; Rogers and Adams, 1969). For this reason the analytical data do not correspond to the original compositions of the minerals at the time of their formation. It could be argued that non-radiogenic lead (Pb^{204}) is incorporated in large concentrations in minerals. However, in over one hundred determinations of lead isotopes from uraninite and thorianite reported in the literature, non-radiogenic lead represents less than 0.25 percent of the total lead content in more than 90 percent of the analyses (Collins et al., 1954; Zykov et al., 1961; Choudari et al., 1967; Koeppel, 1968; Roscoe, 1969), and in one case only did it exceed 1 percent of the total lead content. Thus for practical purposes, radiogenic lead is the only lead present in uraninite and thorianite.

Thus considering the variations of the decays and the ratios of uranium, thorium and radiogenic lead isotopes, it is possible to construct a triangular diagram which expresses the composition of uraninite-thorianite minerals by the molecular proportions of UO_2 ThO_2 and PbO components (Fig. A1). This diagram can be subdivided into the uraninite and thorianite fields while

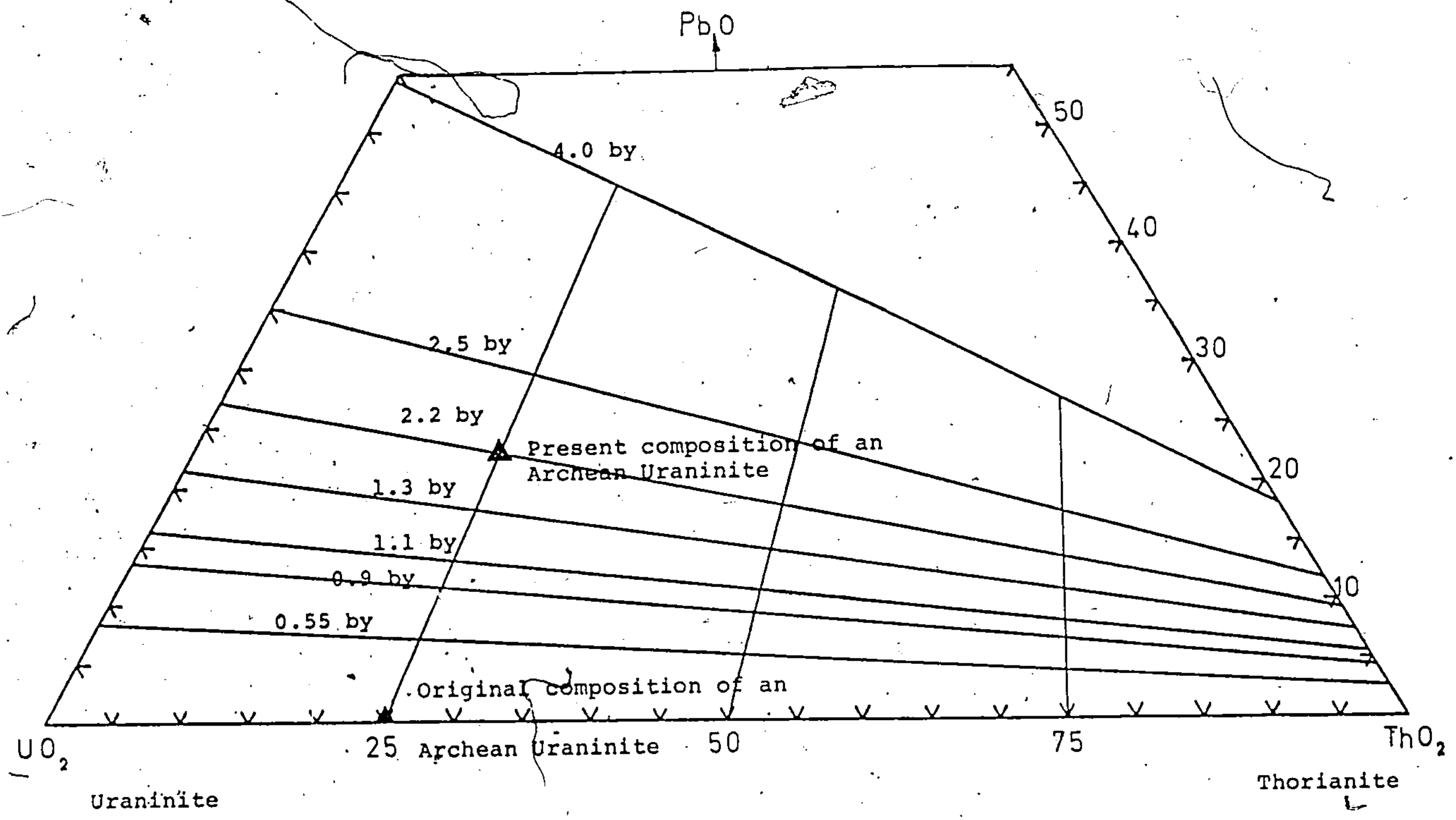

Fig. A1 The molecular variation of thorianite and uraninite through geological time.

considering the compositional variations of the boundary with respect to time. Pitchblende, a cryptocrystalline variety of uraninite which contains low concentrations of thorium and rare-earths, generally plots in a narrow field along the UO_2-PbO line. In the diagram (Fig. A1), the steeply inclined lines represent the variations in compositions of minerals with respect to time, and the subhorizontal lines represent the uraninite-thorianite solid solution formed at a specific geological time. The variation in composition can be illustrated by an Archean uraninite (2.5 b.yrs. old) which shows an increase of ThO_2/UO_2 ratio with respect to time (Fig. A1). Age estimates from the compositions of dated uraninites and thorianites (Table A1) tend to be accurate when they occur in pegmatites and skarns while showing appreciable losses of lead from sedimentary occurrences. This suggests an application of uraninite-thorianite composition to the geochronology of pegmatites and skarns.

Experimental work suggests that the uraninite-thorianite solid solution is complete at high temperatures (Mumpton and Roy, [illegible]). A continuous range of composition also appears to exist in nature (Fig. A2). However, in certain fields very few analyses bridge important gaps, but if gaps do occur within the solid solution, they are probably of very minor extent. Analyses have been taken from Hidden and MacKintosh (1889), Hildebrand (1890, 1891), Dunstan and Blake (1905), Dunstan and Jones (1906), Lacroix (1922), Wells (1930), Ellsworth (1932), Wells et al. (1933), Ellsworth and Osborne (1934), Lanbintzov (1939),

Table A1 Measured and Estimated Ages of Uraninites and Thorianites

	Mineral	Locality	Age Determined (my)	Estimated (my)
(1)	Uraninite	Richardson, Property, Cardiff Township, Bancroft area	1032	975
(2)	Uraninite	Rajasthan pegmatite, India	906	900
(3)	Thorianite	Cardiff Uranium Mines Ltd., Cardiff Township, Bancroft area	1070	1050
(3)	Thorianite	Camex Ltd., Monmouth Township, Bancroft area	1000	1000
(3)	Thorianite	Norminco Mines Ltd., Dungammon Township, Bancroft area	1040	1025
(3)	Thorianite	Nu-Age Uranium Mines Ltd., Cardiff Township, Bancroft area	955	1100

Notes:
(1) Source: Collins *et al.* (1954)
(2) Source: Choudari *et al.* (1967)
(3) Source: Robinson (1961)

Ages estimated from Fig. A1.

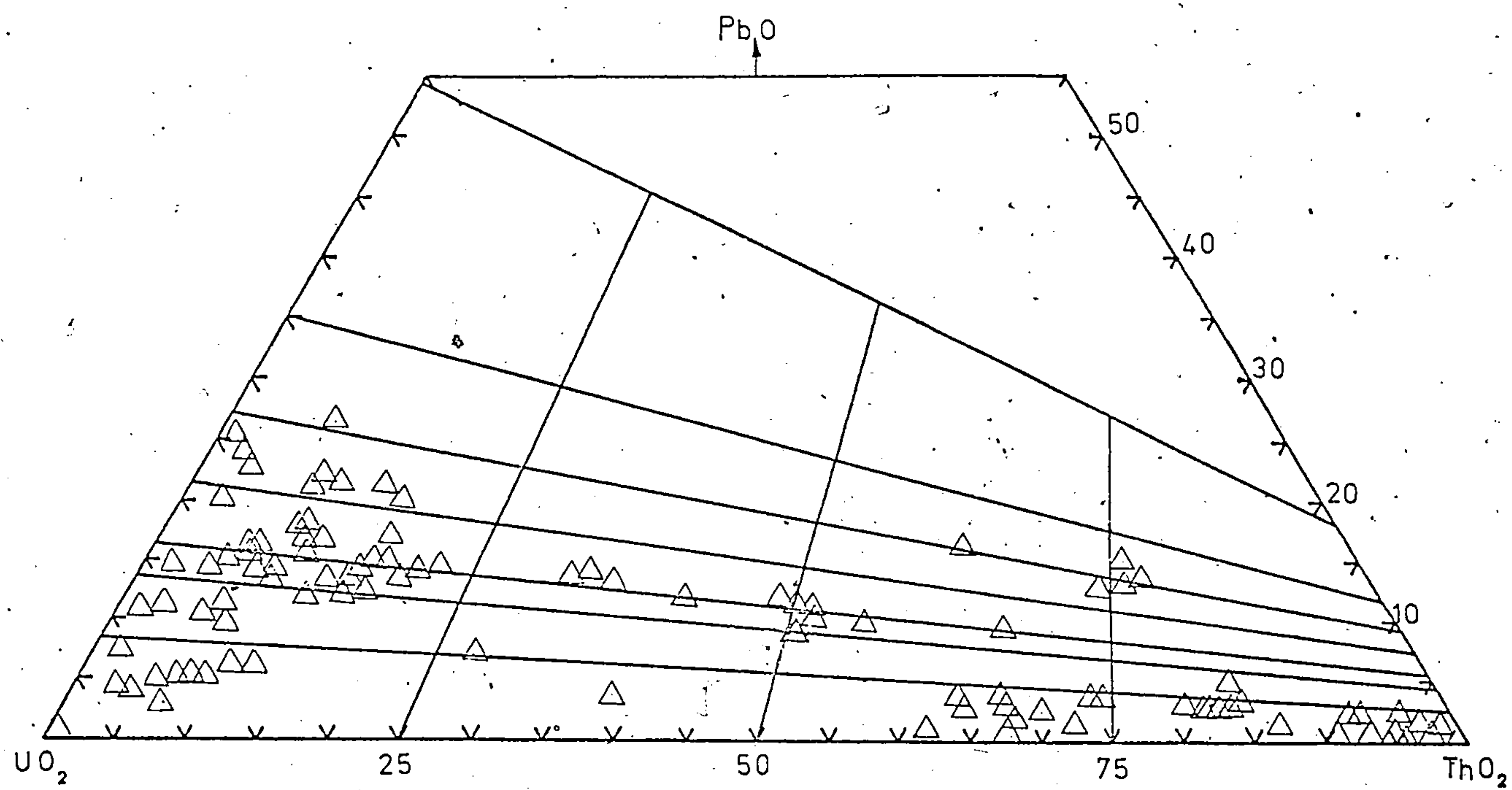

Fig. A2 The molecular compositions of uraninites and thorianites according to the references cited in text.

Russell <u>et al.</u> (1954), Robinson and Sabina (1955), Satterly (1957), Berman (1937), Makarov and Lipova (1962), Moreau (1963), Lima de Faria (1964), Hanekam <u>et al.</u> (1965), Choudari <u>et al.</u> (1967), Heimstra (1968), Ranchin (1971), Traill (1970), Morton and Sassano (1972), Herath (1975), Rimsaite (1977), Semenov (1977).

Appendix 2 The Occurrence of Uraninite and Thorianite

The classification of radioactive deposits has been discussed by numerous authors (see summary by Rùzicka, 1970). Uraninite and thorianite are reported in numerous types of mineral deposit (Table A2).

Thorianite was originally thought to occur dominantly in granite pegmatites (Palache et al., 1944). After an extensive survey of the literature (Dunstan and Blake, 1905; Dunstan and Jones, 1906; Herath, 1975; Lacroix, 1925; Moreau, 1963; Makarov and Lipova, 1962; Satterly, 1957; Russell et al., 1954; Robinson and Sabina, 1955; Semenov, 1977; Well et al., 1933), only the Ceylon occurrences seem to be situated in this rock type. The other thorianite analysed occur in metasomatites (calc-silicate skarns and vein-dykes), in carbonatites and associated alkalic complexes, and in sediments (placers) derived from these rocks (Fig. A3). The favoured occurrence of thorianite in these rocks can be explained by their poor silica content with respect to quartzofeldspathic metamorphic rocks and granitic igneous rocks. In such high temperature environments early formed thorianite may have the tendency to react with free silica producing thorite ($ThO_2 + SiO_2 = Th\,SiO_4$, Mumpton and Roy, 1961). Thus silica-rich igneous and metamorphic rocks are unfavourable hosts for thorianite.

Table A2 Geological Classification of Uranium Deposits

after V. Ruzicka (1971)

Syngenetic types	
Pegmatitic granites and syenite	Uraninite (Thorianite-Ceylon)
Effusive sedimentary	Uraninite (pitchblende)
Ancient conglomerates	Uraninite
Placers	Uraninite Thorianite
Phosphatic sediments	
Caustobioliths, organic shales, etc.	
Syngenetic deposits in limestones, clays and sandstone	
Graphitic shales and schists	Uraninite
Argillaceous, micaceous and black shales	Uraninite (pitchblende)
Metamorphic disseminations	Uraninite (pitchblende)
Granulites	Uraninite (pitchblende)
Epigenetic types	
Migmatites and metasomatic deposits	Uraninite Thorianite
Alkalic metasomatism in ferrigenous rocks	Uraninite
Fenites (carbonatites)	Thorianite
Contact metasomatic (skarns)	Uraninite
Pyrometasomatic deposits in intrusive or extrusive rocks	Uraninite
Veins	Uraninite (pitchblende)
Blanket	Uraninite (pitchblende)
Roll	Uraninite (pitchblende)
Infiltration deposits in lignites or coals	

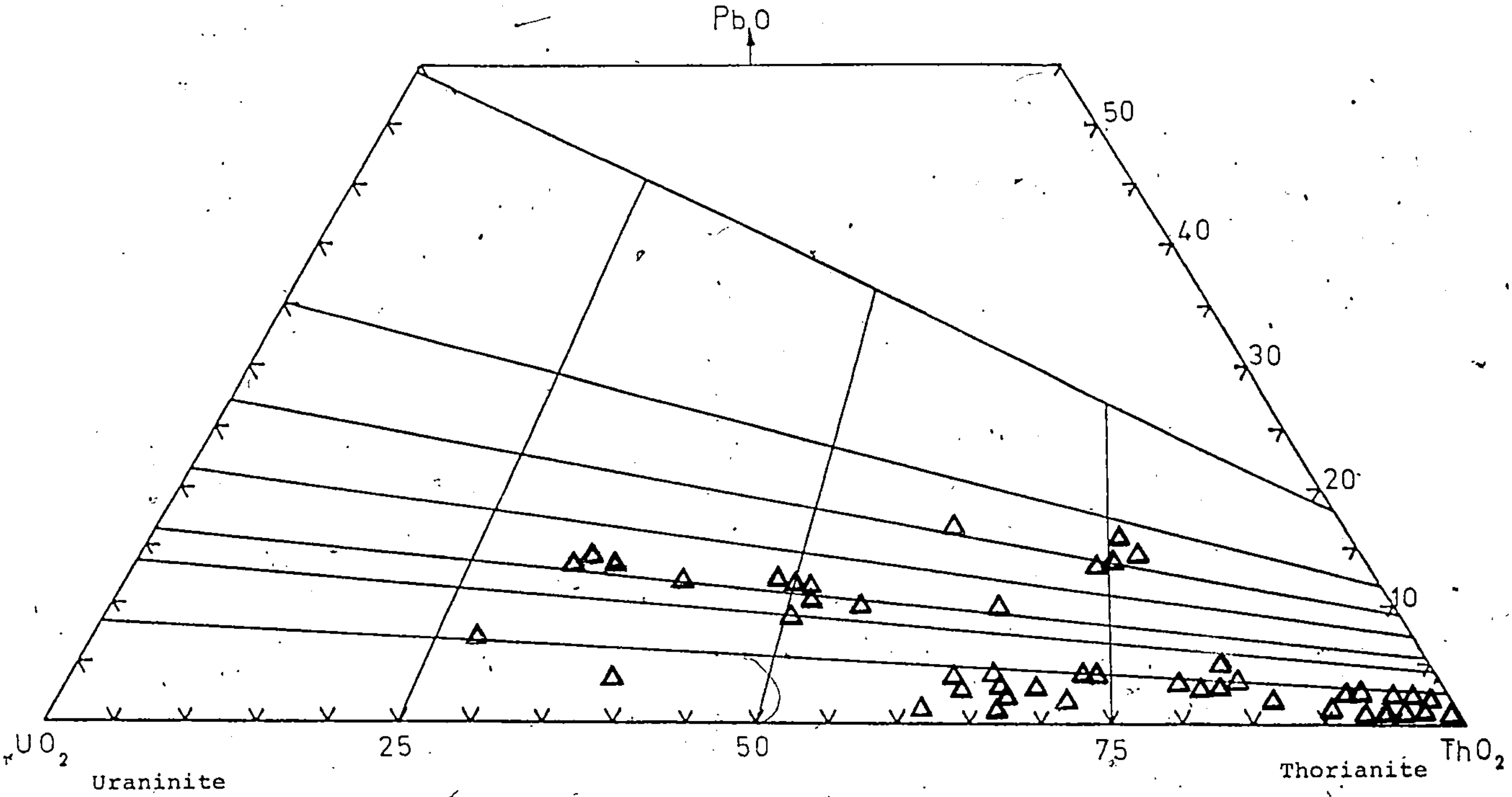

Fig. A3 The molecular composition of thorianite and thorium-rich uraninite with respect to host rock occurrence

Note:
△ : Alkalic complexes
△ : Carbonatites
△ : Skarn

Appendix 3 Average Compositions of Thorianite from the Camp Zone, Microprobe Analyses

Grain No.	MgO	Al_2O_3	SiO_2	PbO	ThO_2	UO_2 (1)	CaO	CeO_2 (1)	Pr_2O_3	Nd_2O_3	FeO (1)	Total
111	0.3%	0.3%	0.0%	9.0%	40.6%	44.7%	1.8%	1.5%	0.4%	0.0%	0.0%	98.6
121	0.5	0.3	1.2	8.6	34.8	46.5	2.6	1.3	0.0	1.9	0.3	98.0
131	0.3	0.3	0.7	8.8	29.5	52.1	1.6	2.9	0.4	2.2	0.0	98.8
141	0.4	0.3	3.2	9.0	52.2	24.9	2.7	2.3	0.4	2.4	0.0	97.8
151	0.4	0.3	1.2	8.0	54.0	33.9	0.3	0.7	0.0	0.0	0.0	98.8
161	0.3	0.4	1.6	10.1	36.5	43.3	3.5	1.5	0.0	1.2	0.0	98.4
171	0.6	0.5	0.0	10.0	36.0	47.2	2.4	1.5	0.0	0.0	0.3	98.5
181	0.2	0.4	1.4	9.6	35.5	45.7	1.9	1.6	0.4	2.1	0.0	98.8
191	0.3	0.5	3.1	9.2	43.2	35.6	2.2	1.7	0.5	2.6	0.0	98.9
201	0.5	0.4	0.4	7.9	55.0	33.7	0.4	1.0	0.0	0.0	0.0	99.3
211	0.4	0.3	0.4	7.7	54.9	32.8	0.4	1.2	0.0	1.1	0.0	99.2
221	0.5	0.4	0.3	7.4	60.3	29.4	0.2	0.7	0.0	0.0	0.0	99.2
231	0.4	0.4	4.4	9.4	45.6	29.3	3.5	1.8	0.0	1.9	0.0	96.7
241	0.6	0.5	2.6	9.6	40.7	38.5	2.3	1.7	0.0	2.2	0.0	98.2
251	0.4	0.3	4.1	10.1	45.8	31.1	2.3	1.9	0.0	2.1	0.0	98.1
261	0.2	0.3	2.0	9.7	35.7	45.6	2.3	1.4	0.0	1.3	0.0	98.5
271	0.5	0.2	1.9	9.7	50.2	28.6	3.7	1.6	0.0	2.3	0.0	98.7

Notes (1) Assumed valencies of U, Ce, Fe

A value of 0.0% has been assigned for all average determinations below detectability limits

Appendix 4 Average Composition of Thorite from the Yates Mine, Microprobe Analyses

Grain No.	MgO	Al_2O_3	SiO_2	PbO	ThO_2	UO_2 (1)	CaO	Ce_2O_3 (1)	Pr_2O_3	Nd_2O_3	FeO (1)	Total
Camp Zone												
111	0.6%	0.2%	19.8%	2.3%	62.8%	2.7%	3.2%	1.6%	0.4%	0.0%	1.7%	95.3
121	0.7	0.4	14.9	5.0	43.3	18.2	3.2	3.3	0.0	2.1	0.0	91.1
131	0.7	0.4	20.1	3.1	63.8	2.6	3.5	0.4	0.0	0.0	0.0	94.6
141	0.6	0.4	20.3	3.1	63.3	1.6	3.6	0.6	0.0	0.0	0.3	93.8
151	0.5	0.2	19.8	2.9	61.4	2.2	3.5	0.5	0.4	0.0	0.3	91.7
161	0.5	0.0	15.5	2.5	61.1	7.0	2.6	0.0	0.0	0.0	0.0	89.2
Matte Zone												
111	0.4	0.2	16.9	3.0	61.8	8.5	5.6	0.0	0.0	0.0	0.0	96.4
121	0.4	0.8	15.6	5.2	55.8	10.0	1.9	0.6	0.0	1.2	0.5	92.0
131	0.4	0.2	15.8	7.1	55.7	7.0	5.4	0.0	0.0	0.0	0.0	91.6
141	0.4	0.2	10.9	5.1	66.2	1.6	4.6	0.0	0.0	0.0	0.9	89.9
151	0.6	0.3	17.1	4.5	52.1	12.4	2.9	3.3	0.0	1.4	0.4	95.0
161	0.7	0.0	20.5	3.4	62.4	2.8	2.0	1.8	0.0	2.3	0.4	96.3
171	0.4	0.7	18.5	2.0	55.1	12.6	5.4	0.0	0.0	0.0	0.4	95.1
181	0.6	0.5	18.1	4.0	59.5	6.1	5.1	0.0	0.0	0.0	1.4	95.3
191	0.5	0.2	17.3	2.4	59.4	10.7	4.4	0.0	0.0	0.0	1.1	96.0
201	0.5	0.0	16.8	3.0	62.9	9.8	4.8	0.0	0.0	0.0	0.0	97.8
211	0.4	0.2	16.0	2.3	56.2	11.7	5.4	0.0	0.0	0.0	1.3	93.5
212	0.5	0.5	13.4	5.1	57.5	7.2	4.9	0.0	0.0	0.0	0.0	91.0

Notes: (1) Assumed Valencies of U, Ce, Fe
A value of 0.0% has been assigned for average determinations below the detectability limits.