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JOCK R. SLATER

Date of Birth — Date de naissance

03 AUGUST 1949

Country of Birth — Lieu de naissance

CANADA

Permanent Address — Résidence fixe

1420 BIRCHWOOD DR
MISSISSAUGA, ONTARIO

Title of Thesis — Titre de la thèse

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Name of Supervisor — Nom du directeur de thèse

R.D. MORTON

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SOME RELATIONSHIPS BETWEEN DEFORMATION, MINERALIZATION AND ORE GENESIS AT THE FAY MINE, ELDORADO, SASKATCHEWAN

by

© Jock R. Slater

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
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Supervisor

Date 19 February 1982

ABSTRACT

The Fay Mine is situated in strongly deformed rocks within the fo[illegible] a major fault in the Churchill structural province in northern Saskatchewa[illegible] examination of the wall-rocks indicates that they have undergone seve[illegible] a geochemical examination suggests that there is little elemental varia[illegible] the fault. The uranium ore mineralogy in the lower levels of the [illegible] brannerite-like phase and coffinite in a gangue of ca[illegible] titanium-vanadium hematite and a beryllium silicate. U-Pb geoch[illegible] the mineralization is discordant and was possibly deposited at arou[illegible] [illegible]etic model of the ore-zone suggests that fluids circulating throu[illegible] the shear[illegible] rocks transported elements released during cataclasis into the present [illegible]

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1. INTRODUCTION

The Fay Mine is situated along a major fault zone cutting the Churchill Structural Province of the Canadian Shield in northern Saskatchewan. The mine has produced a total of 16,425 tonnes U_3O_8 since production began in 1953. The Beaverlodge area, surrounding the Fay Mine, was extensively studied up to 1972, at which time interest was shifted to the newly discovered unconformity-type deposits in the Athabasca Basin to the south. These latter deposits have, to date, production and reserves in excess of 150,000 tonnes U_3O_8 (Sibbald *et al.*, 1981)

The Beaverlodge uranium deposits are situated within roughly linear belts of possibly Aphebian sediments that were metamorphosed during the Hudsonian Orogeny. Extensive zones of shearing and cataclasis resulted from the many active fault zones at this time. The Fay Mine is situated in the footwall of one of these fault zones. The orebodies consist of veins and stockworks that show structural and, possibly, lithological control. The veins are usually quite narrow and grade in excess of 0.50 percent U_3O_8, although dilution due to mining generally reduces the mill-head grades to around 0.25 percent. The stockworks, one of which is studied in this report, are associated with more brittle rocks and produce ore grading less than 0.20 percent U_3O_8. They form lenses with dimensions in the order of tens of meters and appear to be more frequent with depth. The orebody is semi-continuous from surface to a depth of 1600m and appears to continue downward.

The vein-type deposits were mined using traditional cut and fill stoping methods. Recently, upon observing that a large percentage of the ore in Fay Winze consisted of the lower grade but large tonnage stockwork-type, mining in these areas was changed to trackless room and pillar methods in an attempt to increase production and reduce costs. In December, 1981, Eldorado Nuclear Ltd. announced that they were stopping production in the Beaverlodge area during 1982 citing low grade and high production costs as the reasons.

This work was initiated while the author was employed for a two-and-a-half year term as an underground mine geologist in the Fay and Fay Winze mines. The study is confined to the Fay Winze Mine, which is the lower extension of the Fay Mine, from 26th to 32nd Levels (1200m to 1600m depth). The area most intensely studied is the 29th

Level because it represented the lower-most part of the ore body being mined at the time of sample collection and because it was the area of the mine most familiar to the author, who performed most of the geological interpretation and ore reserve calculations prior to its development.

Wall-rock sampling consisted of collecting drill-core from a non-mineralized section extending 70m into the footwall from the Saint Louis Fault. These were used for petrographic examination and geochemical analysis. Samples for the determination of ore-and gangue-mineralogy were collected from a working stope in a large stockwork ore zone on the 29th Level of the Fay Winze Mine. These were examined petrographically and quantitative electron microprobe analyses were performed on the uraniferous phases, as well as on several of the gangue minerals. Uranium-lead isotope analyses were done on some of the uranium minerals from these samples.

This work was performed to determine the mineralogy of the low-grade stockwork-type ore zones that constitute a substantial part of the Fay Winze ore reserves; to check the geochemical trends and variations of a number of major-and trace-elements in the unmineralized wall rocks and to determine the time of emplacement of the uranium minerals. These features are examined in the light of recent ideas concerning cataclasis.

Location and Physiography

The Fay Mine is located 11 km east of Uranium City, on the north shore of Beaverlodge Lake, at longitude 108°29'W and latitude 59° 33'N. The property is 50km south of the Northwest Territories border and 870km northeast of Edmonton. It is accessible by boat in the summer, ice road in the winter and aircraft year round.

The topography is typical of the Canadian Shield with low but rugged relief separating numerous lakes and swamps. Soil development is confined to the low areas and the hills are mostly outcrop. Glaciation moved from northeast to southwest, approximately parallel to the regional strike, and produced striated parallel hills and a pronounced lineation in lakes and drainage. Ablation features consist of occasionally extensive sand plains, kame terraces and eskers. Raised beaches, up to 100m above the present lake level indicate the immense size of the post-glacial lake.

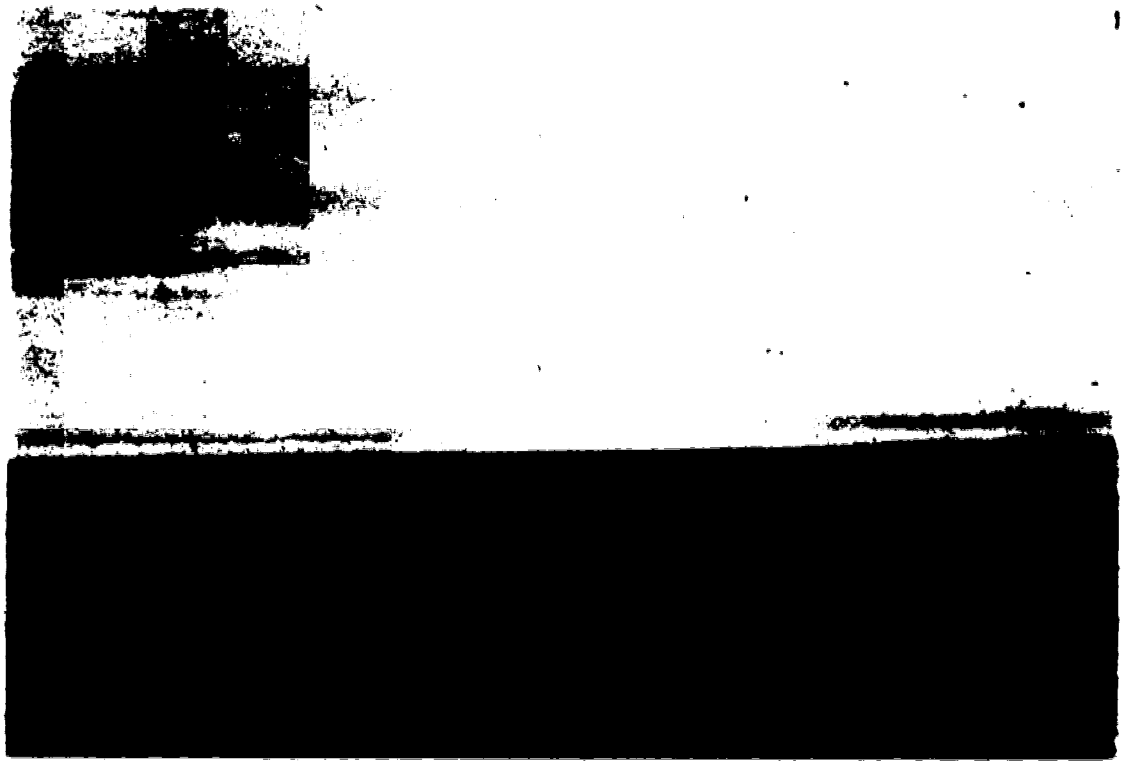


Plate 1 View looking south across Lake Athabasca, showing the typical topography and glacial features of the Beaverlodge area.

History and Previous Work

A great deal of material has been written on the Beaverlodge area from 1892, when J. B. Tyrell performed the initial geological survey of the area (Tyrell, 1895), to 1972 when G. P. Sassano completed his Ph.D. thesis entitled "The Nature and Origin of Uranium Mineralization in the Fay Mine, Eldorado, Saskatchewan". After 1972 exploration and research interest shifted to the unconformity-associated uranium deposits then being discovered around the margins of the Athabasca Basin (see Figure 1). Very little has been written on the Beaverlodge area since then, although several good discussions are included in "Uranium Deposits: Their Mineralogy and Origin" published by the Mineralogical Association of Canada in 1978.

Lake Athabasca was initially explored by Philip Turner in 1790 and David Thompson in 1791. J. B. Tyrell did the first geological mapping one hundred years later in 1892 and reported small patches of sandstone, which he named Athabasca Formation, underlain by extensive areas of granite and gneiss. He also reported the presence of iron formation at Fish Hook Bay on Lake Athabasca approximately 13 km to the south-east of the Fay Mine. This report prompted the initial mineral exploration in the area. Subsequent mapping by the Geological Survey of Canada was performed by Charles Camsell in 1914. He traversed the region between Lake Athabasca and Tazin Lake and called the gneissic and granitic rocks he encountered there the Tazin Formation. A more detailed study of the north shore of Lake Athabasca, including the Beaverlodge area, was done by F. J. Alcock in 1914 and again in 1916 (Alcock, 1914, 1916). Gold mining activity prompted his return in 1935 (Alcock, 1936) to map the Goldfields area, just west of Fish Hook Bay. He named the oldest rocks the Tazin Group, the intermediate ones the Beaverlodge Series and the youngest, the Athabaska Series. Between 1946 and 1948 the Goldfields-Martin Lake area was remapped by A. M. Christie (1953), who dropped the term Beaverlodge Series and placed all of the rocks underlying the Athabaska (now Athabasca) Series into the Tazin Group.

Uranium exploration in this area by the Crown Corporation, Eldorado Mining and Refining Ltd., commenced in the 1940's after an examination of the radioactive mineralization previously reported at the Nicholson property just west of Fish Hook Bay. During the initial uranium mining activity, detailed studies of the uranium mineralogy were done by S. C. Robinson (1955) and wall rock alteration by K. R. Dawson (1956). Studies also done at this time by C. E. B. Conybeare and C. D. Campbell (1951) showed that the rocks forming the 'red-alteration' zones, common to most deposits in the area, are mylonites. L. P. Tremblay (1972) mapped the Beaverlodge area from 1952 to 1957 and produced the most comprehensive work to date, "The Geology of the Beaverlodge Mining Area, Saskatchewan". He has retained the units defined by Christie and added the Martin Formation, which contains the undeformed sediments and volcanics unconformably overlying the Tazin granites and gneisses, and which were thought to be different from the Athabasca Formation occurring to the south. Tremblay provides descriptions of most of the deposits in the Beaverlodge area and proposes a genetic model that involves the mobilization of uranium from granitized Archean sediments followed by the remobilization into ore bodies during cataclasis.

L. S. Beck (1969) working out of Uranium City from 1960 to 1964, reported his observations in "Uranium Deposits of the Athabasca Region". His descriptions are extensive and detailed and include some of the earliest geochronological studies of the granitic rocks of the area. His report also includes uranium-lead geochronology of a number of ore samples as well as illustrated descriptions of most of the deposits and showings. He provides interpretations of the regional tectonic setting and ore petrogenesis.

The most extensive geochronological study of the Beaverlodge area was done by V. Koeppel (1967) who analysed a number of ore samples from the Fay Mine as well as the surrounding area using, for the first time, a solid-source mass spectrometer and isotope dilution techniques. These permitted a tight control of the samples and a reduction of the discordance previously observed in samples from this area. A summary of his findings is included in the section on geochronology in Chapter V.

G. P. Sassano (1972) whose studies were based upon several years as a mine geologist at Eldorado, reported on the stratigraphy, structure, stable isotopes, mineralogy and geochronology. He arrived at a genetic interpretation, different from that of both Tremblay and Beck, which suggested that prograde metamorphism of uraniferous pelitic sediments could concentrate pitchblende into the deposits presently being mined.

Production History

Prospectors working for Eldorado Mining and Refining Ltd. discovered several occurrences of pitchblende along the surface trace of a major fault (later named the Saint Louis Fault) in 1946. Geiger-counter surveys, trenching and drilling were sufficiently encouraging to justify underground exploration and the Ace shaft was sunk in 1949 at an inclination of 50 degrees, parallel with the Saint Louis Fault. By 1950 enough ore had been outlined to warrant going into production and the 5 compartment Fay shaft was collared and completed to a depth of 365m by 1952. A 500 ton per day carbonate-leaching treatment plant was built near the Fay shaft and the mine went into production in March, 1953.

Ore discovered to the east of the Ace shaft resulted in the sinking of the Verna shaft in 1953 which eventually reached a depth of 410m. The combination of the Ace, Fay and Verna shafts permitted production over a distance of more than 4.3km of the Saint Louis Fault. The Ace and Fay shafts serviced the same ore body, which eventually was serviced by the Fay shaft and Fay Winze. The Verna shaft, and eventually the Verna Winze allowed access to a large low-grade ore body in the hanging wall of the Saint Louis Fault.

Exploration from the bottom Fay levels, at a depth of 1220m, in the late 1960's indicated that the ore body continued downward. The Fay Winze was collared on the 23rd Level and sunk 520m, resulting in a total vertical development on the Fay orebodies of 1600m. Ore from the Fay Winze was hauled over 2km to the Fay shaft where it was taken to surface for treatment. Production started in 1977 on the 26th Level and by 1979 on the 29th Level, Fay Winze.

Production from the Ace-Fay-Verna complex has totaled about 16,425 tonnes U_3O_8 (1981 est.) at an average grade of about 0.22 percent U_3O_8. In December, 1981, Eldorado announced the suspension of its Beaverlodge operation in June 1982. High production costs, low ore grade and a declining uranium price were cited as the reasons for this action.

II. REGIONAL GEOLOGY OF NORTHERN SASKATCHEWAN

General

The Fay Mine is situated on a major fault zone in the Western Craton subdivision (Lewry and Sibbald, 1978) of the Churchill Structural Province (Fig. 1). The area was folded and metamorphosed during the Aphebian and subsequently covered by supracrustal rocks of the Athabasca Formation during Helikian times. The predominant lithology at the mine is mylonite which is strongly to moderately developed adjacent to most of the major fault zones in this area of Northern Saskatchewan (Blake, 1951;Christie, 1953;Tremblay, 1972).

Lithostructural Domains

The Precambrian Shield area of Northern Saskatchewan has been subdivided into several lithostructural domains (Fig. 1), defined as Hudsonian orogenic belts analogous in both character and position to younger plate tectonic orogenic belts seen elsewhere (Lewry and Sibbald, 1980). These domains have been grouped into crustal units consisting of the *Western Craton*, the *Cree Lake Zone* (containing the Wollaston Domain), the *Rottenstone Complex* and the *Southeastern Complex*.

The *Western Craton*, containing the Fay Mine, is the only one of these lithostructural domains discussed in detail. It is made up of relatively massive granulite facies areas separated by linear belts of lower grade metamorphism (the "mobile zones" of Lewry *et al.*,(1979) or the "fold-linear" belts of Beck, (1969), possibly representing Hudsonian reworking of older sedimentary and volcanic rocks, including the Tazin Complex of the mine area.

The Western Craton extends into northeastern Alberta and possibly includes much of the north-western part of the Churchill Province in the Northwest Territories (Sibbald, *et al.*, 1981). The area is interpreted as a cratonic foreland to the west of the main Hudsonian mobile belt (Cree Lake Zone, etc) and comprises catazonal Archean continental crust on which Aphebian stable platform supracrustals are locally preserved. Sutton(1976) feels that the Proterozoic tectonics were characterised by small rigid blocks a few hundred kilometers in size enveloped in a network of mobile belts. Present day tectonic styles, he states, did not evolve until the Hadrynian, when larger continental masses resulted in continental break-up and collision.

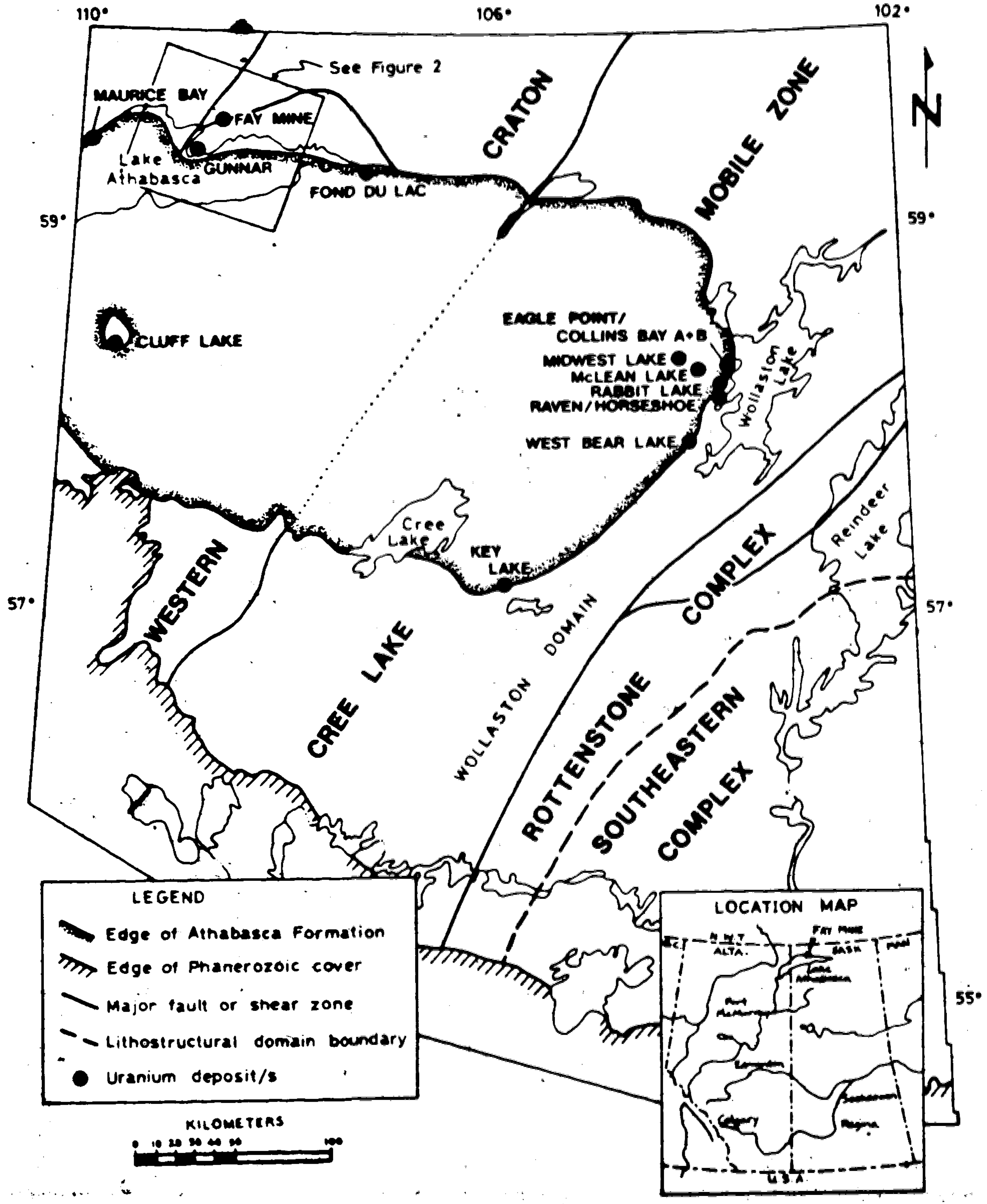


Figure 1 Regional geology and principal mineral showings of northern Saskatchewan.

TABLE 1: Precambrian nomenclature based on K-Ar and U-Pb methods (after Stockwell, 1964)

EON	ERA	SUB-ERA	OROGENY	AGE OF BOUNDARY m.y.
PROTEROZOIC	HADRYNIAN			570
	HELIKIAN	NEOHELIKIAN	GRENVILLIAN	975
		PALEOHELIKIAN	ELSONIAN	1440
	APHEBIAN		HUDSONIAN	1800
ARCHEAN			KENORAN	2560

These ideas are summarised by Irving and McGl[illegible]976). In a discussion of the tectonic evolution of the Churchill Province they conclude

> "...by the end of Aphebian time, there almost certainly existed a large continental mass, comprising several Archean blocks and a large area of somewhat deformed Archean crust with internal belts of deformed Aphebian sediments which were partly ringed by marginal geosynclines."

The rocks deposited in the marginal geosynclines are the Helikian supracrustals such as the Martin Formation and the increasing stability of the Proterozoic crust is indicated by the weak metamorphism and folding seen in these younger rocks.

The age of the Tazin Complex is a subject of considerable discussion. McDonald (1980) says it should be "provisionally" regarded as 'reworked' Archean craton. Morton and Beck (1978) believes this area is analogous to the rocks of the Wollaston Domain to the southeast and is composed of metamorphosed Aphebian sediments with occasional granitic to granodioritic gneiss-domes representing inliers of Archean granitic basement. The Aphebian age has also been proposed by Krupicka and Sassano (1972) and Sassano, *et al.*, (1972), who place the base of the Tazin Complex (the Foot Bay Gneiss) in the Archean and the upper units (the Donaldson Lake Gneiss and the Fay Mine Complex) in the Aphebian, with an unconformity separating the two. Tremblay (1972) does not recognize this unconformity and thinks that the Tazin Complex is totally Archean. Lewry and Sibbald (1978) feel that more detailed metamorphic studies are required in order to separate Archean from Aphebian supracrustal rocks in the 'craton'.

The Wollaston Domain is the principal area to be considered within the *Cree Lake Zone*. Ray and Wanless (1980) define this as an Archean granitoid basement overlain by Aphebian supracrustals consisting of metasediments, metavolcanics, volcaniclastics and gneisses which have been metamorphosed during the Hudsonian to amphibolite facies. Most of the major uranium deposits discovered in the Athabasca area occur within this domain. In contrast to the Western Craton, Hudsonian orogenesis in the Wollaston domain resulted in remobilization and ductile interaction of the Archean basement and the overlying Aphebian cover (Sibbald, *et al.*, 1981).

The Rottenstone Complex, to the southeast of the Wollaston Domain, is characterised by widespread partial melting resulting in extensive plutonism, mainly represented by the Wathaman batholith, dated by Ray and Wanless (1980) at 1865±10

Ma (U-Pb from zircon). The La Renge Domain, within the *Southeastern Complex*, contains metavolcanics, metasediments and volcaniclastics, probably Aphebian in age (Sangster, 1978).

Intrusive Activity

Intrusive rocks of late-Archean to early-Aphebian age have been reported in the Beaverlodge area by Tremblay (1972) and Beck (1969) who return dates of 2000 to 2200 Ma using U-Pb, K-Ar and Rb-Sr methods. Lewry and Sibbald (1978) suggest that the plutonic bodies in the north part of the Rottenstone Complex are a result of 'post-Kenoran continental rifting'. Godfrey (1978) reports Rb-Sr dates of 2500 Ma from granitic rocks of northeast Alberta, although later reworking has obscured much of this event.

Hudsonian igneous activity in the Beaverlodge area includes granites dated at 1820±100 Ma by Rb-Sr methods (Beck, 1969) and volcanic flow rocks dated by K-Ar methods at 1630 Ma (Wanless, *et al.*, 1965). In northeast Alberta, Godfrey (1978) recognises a 'fresh' granite, possibly Hudsonian in age, showing no signs of Kenoran alteration. Lewry and Sibbald (1978) report late Hudsonian, post-kinematic plutons in the Black Lake Fault Zone and date the Wathaman batholith in the Rottenstone Complex at 1865±10 Ma.

The latest intrusive activity in the Beaverlodge area consists of widespread northeast and northwest trending diabase dykes that have been dated by K-Ar methods at 1490 Ma (Wanless *et al.*, 1965). To the south, similar basic intrusives cutting the Athabasca Basin have returned dates of 1000 to 1360 Ma (method unknown) (Wanless,*et al.*, 1965). Rb-Sr dates of 1428±30 Ma and 1513±24 Ma from vitric ash-fall tuffs of the Wolverine Point Formation are reported by Ramaekers (1980). Sassano (1972) describes cross-cutting pegmatites within the Tazin Complex at the Fay Mine, which he believes to be the youngest rocks in the immediate study area.

Supracrustal Rocks

Helikian supracrustal rocks have been preserved at many locations in and around the Beaverlodge area. These have been subdivided into four 'successor' basins by Langford (1980) which consist of, from oldest to youngest: the Thluicho Formation, the Martin Formation, Charlot Point Formation and the Athabasca Group. They all consist of fine-to medium-grained clastics with minor interbedded volcanics in the Martin Formation and pyroclastics in the Athabasca Group. They are all non-metamorphosed and relatively undeformed. The two units most important to this work are the *Martin Formation* and the *Athabasca Group*.

The *Martin Formation* consists of late Aphebian to Helikian red-beds occupying several fault-bordered basins in the Beaverlodge area (Tremblay, 1972). It is made up of shallow-water red arkoses, siltstones and conglomerates with some interbedded plateau-type basaltic flow rocks. The source of deposition is to the northeast (Tremblay, 1972). The red coloration is from pink feldspar clasts and hematite cement (Sibbald and Lewry, 1980). The base of the Martin Formation does not show the development of a regolith zone, which is typical of the Athabasca basin to the south. The contact of the Martin Formation and the Tazin Complex is characterised by either an angular unconformity or a layer of coarse basal conglomerate which is locally derived from the underlying gneisses (Tremblay, 1972). Potassium-argon dating of the dykes cutting the Martin Formation returns an age of 1630 to 1830 Ma (Fahrig, 1961,Tremblay, 1972).

The Athabasca Group has been sub-divided by Ramaekers (1980), into structural sub-basins that are possibly related to movement on the major shear zones and faults in the area. These basins are filled with four, transgressive deposits of marine origin which are separated by unconformities, and include one regressive, fluvial deposit near the base. Dating (Rb-Sr) of the ash-fall tuffs and associated sediments of the Wolverine Point Formation of the Athabasca Group have returned dates of around 1500 Ma (Ramaekers, 1980).

The basal Athabasca is chronologically close to the Martin Formation, which is not suprising if Hudsonian-related block-faulting is considered to be the source of the basins and sediment-shedding highlands. Ramaekers (1980) states that the sediments of the Athabasca basin reflect a "major episode of uplift and erosion in the Wollaston Belt and areas to the east; as well as repeated uplift, subsidence, and erosion in the Athabasca region". In drawing a present day analogy, Ramaekers compares the Athabasca basin to the Parana Basin of Argentina which, with the Andes to the west, opens to the Atlantic in the south and southeast.

Orogenic History of the Beaverlodge Area

The rocks of the study area have undergone three periods of orogeny. The earliest was the Kenoran (about 2560 Ma) which could have produced the gneiss-domes and granulites seen at the core of the Donaldson Lake anticline. Emplacement of the earliest (syngenetic) uraninite in rocks such as the Viking Lake granite is thought to have occurred at this time (Koeppel, 1967).

The Hudsonian orogeny (about 1800 Ma ago) has had the most obvious effect on the area. Morton and Beck (1978) believes that it caused the metamorphism of the Aphebian sediments of the Tazin Complex; Lewry and Sibbald (1978), on the other hand, feel that the effects of the Hudsonian have been overprinted on pre-existing Archean metamorphics. Metamorphism related to the Hudsonian orogeny appears to have been as high as almandine-amphibolite facies (Tremblay, 1972) although alteration during the waning stages has resulted in widespread mineralogy of the greenschist facies. Intrusive activity related to the early phases of the Hudsonian orogeny caused the emplacement of granites dated at 1860± 100 Ma by Rb-Sr methods (Beck, 1969).

The Hudsonian orogeny was a period of very active mountain-building, both in the Beaverlodge area (Tremblay, 1972) and in the Wollaston Domain to the southeast (Ramaekers, 1980). The formation of these highlands with concommitant block faulted basins, is responsible for much of the Helikian sedimentation (i.e. Martin Formation and parts of the Athabasca Group) seen in northern Saskatchewan.

The waning phases of the Hudsonian orogeny caused the activation (or reactivation?) of several major fault zones in Northern Saskatchewan. Those in the Beaverlodge area include the Black Bay Fault and the Saint Louis Fault. Strain adjacent to these fault zones was responsible for the often considerable thickness of mylonite and the initial deposition (or remobilization) of the primary phase of pitchblende at the Fay Mine (Tremblay, 1972; Beck, 1969; Sassano, 1972; Koeppel, 1967; Lewry and Sibbald, 1979).

The final phase of the Hudsonian orogeny saw the eruption of volcanic rocks, dated at 1630 Ma (K-Ar method), within the Martin Lake successor basin (Wanless, *et al.*, 1965). Ramaekers (1980) has suggested that these volcanics represent a higher level or less eroded equivalent of the 'late' intrusives exposed in the Virgin River-Black Lake shear zone to the east.

The Grenville orogeny (about 1000 Ma) had little major tectonic effect on the Beaverlodge area. It was not responsible for the generation of the northwest trending diabase dyke swarms which are dated at 1400 Ma in the Beaverlodge area but 1000 to 1360 Ma in the Athabasca basin to the south (Ramaekers, 1980). The most obvious result of this orogeny may have been the widespread remobilization of uranium and resetting of pitchblende dates at a commonly recorded 1100 Ma (Tremblay, 1972; Koeppel, 1967).

III. LOCAL GEOLOGY

General

The local geology of the Beaverlodge area, as shown in Fig. 2, consists of metasedimentary and metavolcanic rocks of the Tazin Complex, quartzites, calc-silicates and schists of the Murmac Bay Formation and coarse clastics and interbedded volcanics of the Martin Formation. All of the Tazin Complex rocks immediately north of the Saint Louis Fault have been moderately to strongly mylonitized. All rocks below the volcanics of the Martin Formation are cut by gabbroic dykes.

Uranium mineralization occurs in veins and stockworks in the uppermost meta-sedimentary rocks of the Tazin Complex and occurs in cross-cutting veins within [illegible] Martin Formation. The mineralization in the Tazin Complex occurs as either sheet-like vein systems in the more schistose rocks or as lensoidal stockworks in the more fractured siliceous mylonites. All of the Tazin-hosted mineralization in the Fay and Fay Winze Mines is confined to the footwall of the Saint Louis Fault.

Lithology

Tazin Complex

The Tazin Series was first described by Camsell (1916). The name was changed to Tazin Group by Alcock (1936), a name used by Tremblay (1972) and Sassano (1972) and was recently changed to Tazin Complex by MacDonald (1980) on a new edition of the geological map of Saskatchewan.

Tremblay (1972) describes the Tazin Complex as a "thick succession (greater than 10,000m) of interbedded greywackes, shale, feldspathic sandstone and basic tuff, now represented by feldspathic-quartzite, amphibolite, garnet-biotite-feldspar rocks and quartzo-feldspathic gneisses in all stages of granitization, and metamorphic granites".

All rocks seen underground are part of the Tazin Complex. Going up-section, these consist of: the *Foot Bay Gneiss*, the *Donaldson Lake Gneiss*, and the *Fay Mine Unit* which contains in descriptive mine terminology, *epidotic argillite*, *mylonitic mica schist* and *orange porphyroclastic mylonite*. These terms are retained in this work for historical reference. Equivalent terms used in other studies are shown in Table 2. The following descriptions are primarily lithogical although the mode of occurrence of uranium mineralization is included where appropriate. A more detailed description of petrology

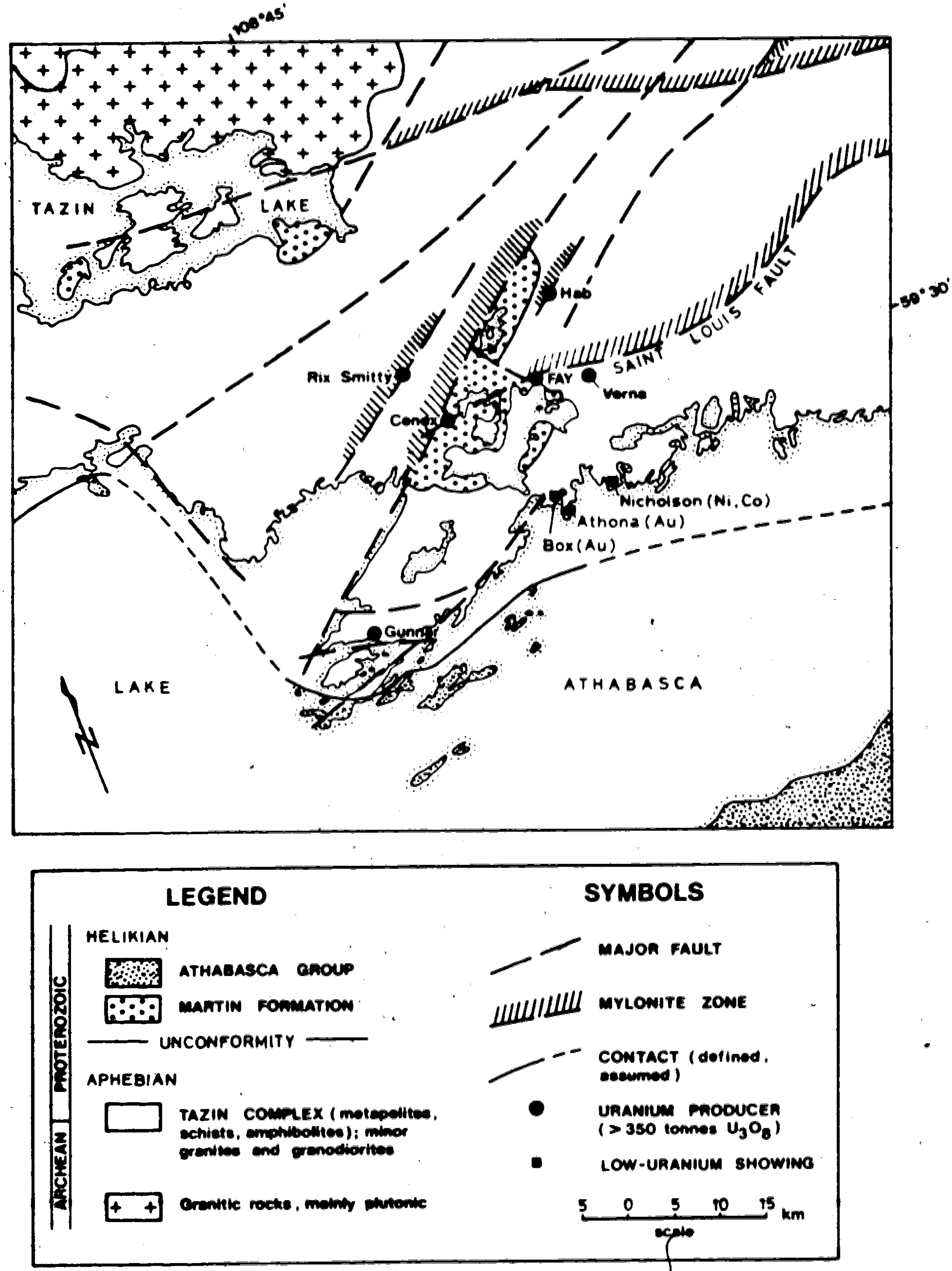


Figure 2 Local geology and major uranium producers of the Beaverlodge area.

and mineralogy is found in Chapters IV and V.

Foot Bay Gneiss

This unit is structurally and stratigraphically below the mineralized units and is not encountered in normal mining operations. It is characterised by greenish-grey to dark grey layers alternating with wider bands of white to orange-red rock and is commonly cut by veins of epidote, calcite and anhydrite (Sassano, 1972). Compositionally it varies from leucocratic gneiss to amphibolite. A distinctive feature commonly seen in this unit is irregular bands of plagioclase (oligioclase) augen up to 10cm in diameter occurring in a quartzo-feldspathic matrix.

Two periods of cataclasis and deformation have been recognised in the Foot Bay Gneiss (Morton and Sassano, 1972). Ultramylonite grading upward into cataclasite at the contact with the overlying unit was thought by Sassano (1972) to represent an erosional gap between the Archean Foot Bay Gneiss and the Aphebian Donaldson Lake Gneiss. Tremblay (1972) does not recognize this unconformity.

Donaldson Lake Gneiss

This unit has been variously described as metasomatic granite, alaskite and leucocratic granite by Eldorado geologists. Sassano (1972) concluded that the 'puzzling and controversial' rocks called Donaldson Lake Gneiss on surface are the cataclastic equivalents of less deformed gneiss seen underground, although a mechanism for this transition is not proposed.

The Donaldson Lake Gneiss in the study area is generally light greenish-grey to brown to orange-brown. Tight ptygmatic folds and layers and lenses of pink quartzo-feldspathic migmatite are characteristic of this unit. The gneiss becomes increasingly porphyroclastic approaching the Saint Louis Fault (Sassano, 1972) although it is the observation of the writer that the intensity and location of the porphyroclastic zones is only partly controlled by the major fault and is possibly a function of original lithology. The quartzo-feldspathic layers appear to be more susceptable to the development of microcline porphyrblasts, an observation consistent with studies of the mylonitization process and described in Appendix 1.

Sassano (1972) observed that in addition to 'regular' deformation textures and mineralogy, the Donaldson Lake Gneiss has chlorite (penninite) developed at the expense

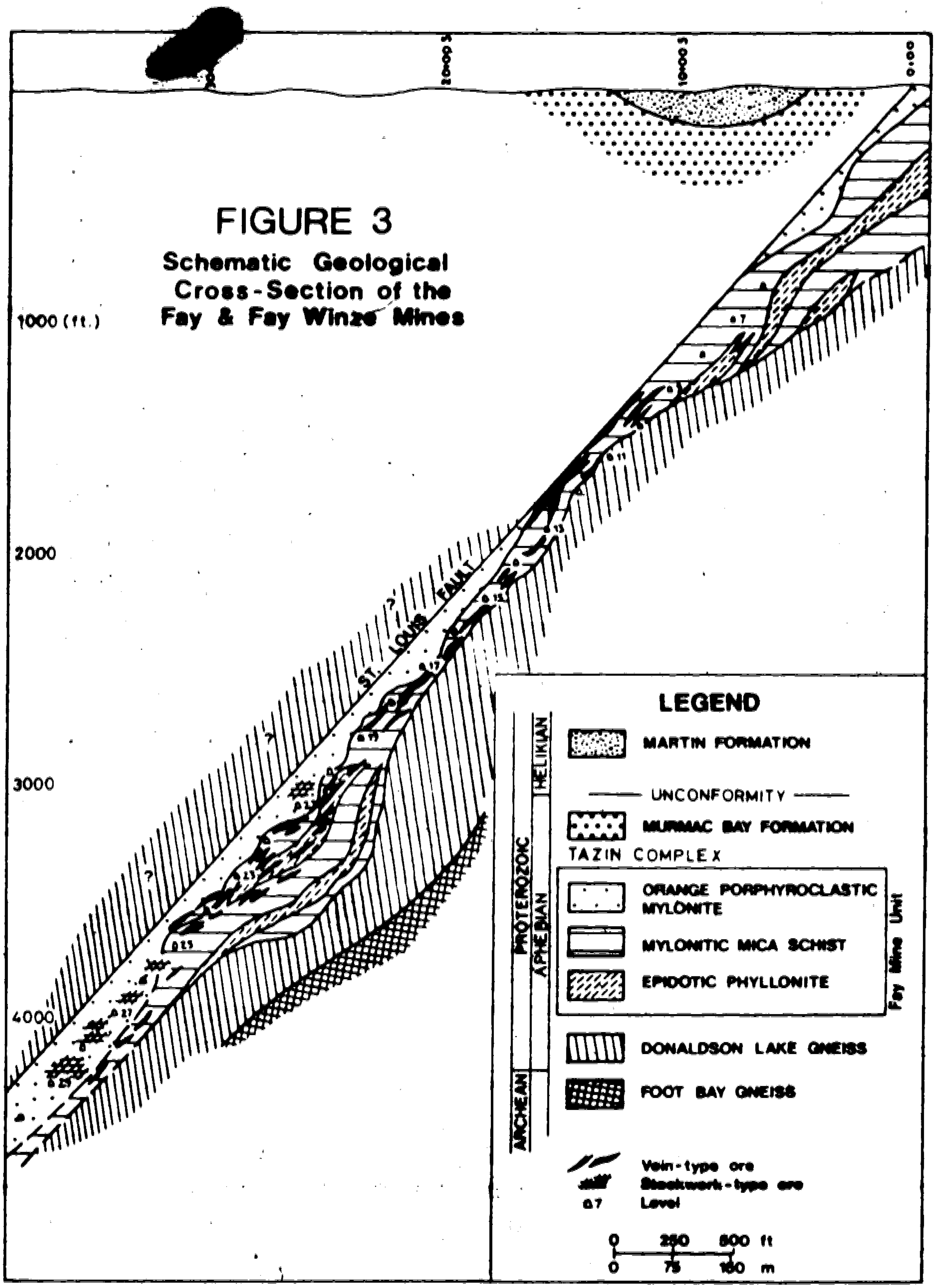


Figure 3 Schematic geological cross-section of the Fay & Fay Winze mines.

of biotite and that this alteration is associated with sphene, hematite, pyrite and traces of magnetite, apatite and zircon. This observation is confirmed elsewhere by the work of Kerrich *et al.* (1980) who report the breakdown of biotite to chlorite, epidote and sphene during mylonitization.(see Appendix 2)

The Donaldson Lake Gneiss is only weakly mineralized in the Fay Mine although several showings, including two with underground development (National Exploration and Dubyna) occur in areas mapped as Donaldson Lake Gneiss by Tremblay (1972)

Fay Mine Unit

This 'unit' hosts the majority of the uranium mineralization mined at Eldorado. It occurs along a strike length of several hundred meters, is in the order of 50m thick and is adjacent to the Saint Louis Fault. It is lense shaped in both plan and section (Figs 3 and 4). The Fay Mine Complex is underlain by the Donaldson Lake Gneiss and terminated up-section by the Saint Louis Fault which is roughly parallel to the foliation of the layered and banded units within the Fay Mine rocks. The strike length and thickness of the Fay Mine Complex varies resulting in large amplitude pinch and swell structures in both longitudinal and cross-section.

The mineralized veins within the Fay Mine Complex have two principle modes of occurrence. The rocks showing a greater degree of schistosity and foliation generally contain anastomosing veins that are fairly narrow and continuous. These veins are usually high grade and often contain visible, occasionally massive, pitchblende. The more mylonitized and brittle units generally contain 'stockwork' type ore zones due to the highly fractured nature of the host rocks. These ore zones tend to form fairly discontinuous lenses with dimensions of tens of meters. They are usually of lower grade and larger tonnage than the former type and visible mineralization is uncommon. It is this type of ore zone that comprises most of the ore in the study area and is described more fully in Chapter V.

Epidotic Argillite (Phyllonite)

This is the lowest Fay Mine Unit observed in the study area. It is typically dark green to black, phyllonitic in texture and shot through with a network of fine epidote veinlets. Occasionally these veinlets coalesce to form zones of massive epidote. The unit hosts several high grade ore zones above 25th level that are characterised by continuous

TABLE 2: Fay Mine Unit Equivalent Terminology used by other authors.

MINE TERMINOLOGY (used in this report)	TREMBLAY (1972)	SAS[illegible]NO (1972)	BECK (1969)	ROBINSON (1955)
epidotic argillite	chloritic argillite rock, chlorite -epidote rock	phyllonitic and epidotic amphibolite	chlorite-epidote rock	chlorite-epidote facies
mylonitic mica schist	hornblende schist, amphibolite	albite chlorite-muscovite paraschist and parageneiss	meta-argillite(?)	chloritic paragneiss
orange porphyroclastic mylonite	chloritized feldspathic quartzite	granitic gneiss	red-altered wall rock,	oligioclasite

veins of massive pitchblende. Below 25th level, the epidotic 'argillite', while still present, appears to be more discontinuous and does not host the high grade ore of the upper levels.

Sassano describes the unit as "mylonite-phyllonite, sometimes with strong affinities to meta-volcanics and meta-tuffites". A typical modal analysis (Tremblay, 1972) consists of clinozoisite or epidote (10 to 20%), calcite (3 to 5%), chlorite (45%), feldspar (15 to 20%) and quartz (10 to 15%). The unit is interpreted in this report as a calc-silicate mylonite (or phyllonite, to comply with Sassano) because of the spatial relationship to the orange porphyroclastic mylonite adjacent to the Saint Louis Fault and the apparent tectonically controlled shape of the 'argillite' in longitudinal section.

Mylonitic Mica Schist

The 'mylonitic mica schist' unit of the mine geology is described by Sassano (1972) as a 'chlorite, albite and muscovite schist and paragneiss, locally intensely mylonitized'. This unit hosts mineralization similar to, but not as high grade, as that in the epidote-chlorite rock described above. The unit, as observed by the writer, is usually quite siliceous, only occasionally schistose and strongly mylonitic. In thin section the feldspars are typically crushed and deformed , pervasively altered to calcite and sericite and cemented by recrystallized quartz. Higgins (1971) has defined a phase of deformation where neomineralization and recrystallization are dominant over cataclasis. This results in the production of a mylonite schist, where recrystallized porphyroblastic micas have grown as feldspars, have undergone cataclasis and comminution. The mylonitic mica schists of the Fay Mine Unit could be products of such a deformation process.

The unit is usually orange-brown to dark grey with uniform and often tightly folded foliation and is commonly porphyroclastic. Where mineralized it is usually stained bright orange by hematitic wall-rock alteration. Calcite-and quartz-filled veining and brecciation are common, as are zones of pink and white quartzo-feldspathic migmatite. The contact with the overlying orange porphyroclastic mylonite is usually gradational and often, as in the study area, obscure.

Orange Porphyroclastic Mylonite

The uppermost mine unit is called 'orange porphyroclastic mylonite' by the mine staff. It is generally very siliceous, full of small white oligioclase and microcline porphyroclasts and always adjacent to the footwall of the Saint Louis Fault. It is quite often banded, possibly reflecting relict bedding and can contain up to 30% mafics. Due to its very siliceous, brittle nature, it tends to host lens-shaped stockwork ore zones consisting of hundreds of small, cross-cutting fractures containing radioactive mineralization and calcite, quartz and chlorite gangue.

This unit typically contains zones of brecciation in the footwall of the Saint Louis Fault. The most common type of breccia consists of angular fragments of mylonite and, occasionally, breccia cemented by quartz and feldspar. Chlorite and hematite are also seen in the matrix, which often displays open-space-filling textures. This appears to be a typical high level tectonic breccia and has been generated during several phases of deformation.

A second type of breccia, appearing less frequently in the mine, consists of rounded siliceous fragments in an arkosic matrix. This unit bears a strong resemblance to the younger Martin Formation conglomerate seen on surface and underground down to third level. It has consistently presented an enigma in the interpretation of underground stratigraphy and has been assumed by most workers to be part of the overlying Helikian sediments (Sassano, 1972; Sibbald, et al, 1976). In a study of this unit, discussed in Appendix 2, the writer has concluded that it is not a conglomerate, but rather a 'crush breccia' (Moorhouse, 1959) locally derived from the rocks adjacent to the Saint Louis Fault.

Sassano (1972) has given the orange porphyroclastic mylonite status as a separate lithology situated between the 'mica schist' and the (apparent) Martin Formation conglomerate, and called it granitic gneiss. It is the opinion of the writer, based upon underground and drill core observation that this unit is not a separate lithology as much as an alteration (mylonitization) of the underlying Fay Mine Unit. This is supported by the observed similarity of the 'orange porphyroclastic mylonite' at all places along the Saint Louis Fault, apparently independent of the underlying lithology. Porphyroclastic mylonitized rocks similar to these have been observed elsewhere in the Beaverlodge area

(Christie, 1953; Blake, 1951). Blake states that the end product of mylonitization is the same in general appearance regardless of the original lithology of the rock affected.

In thin section, this unit has a mylonitic texture that is locally cataclastic and/or brecciated. Plagioclase (albite-oligioclase) porphyroclasts display deformed twinning lamellae and the larger microcline porphyroclasts show undeformed twinning and a weak but pervasive sericitic alteration. In the banded varieties the dark mafic layers are predominantly chlorite with minor biotite and commonly have flow-texture around medium to fine grained porphyroclasts of plagioclase, microcline or recrystallized quartz.

The orange porphyroclastic mylonite commonly hosts the '01' zone (Fig. 4) which is found on most levels from surface down to 32nd level. It is observed by the writer that the difference between the 'mica schist' and the 'orange porphyroclastic mylonite' is not too significant in the lower levels of the mine, and as a result, there is little difference between the '01' and the '09' zone which is traditionally further into the footwall (Fig. 4) in the more foliated units. The lensoidal stockwork-type ore bodies first observed on 26th level form a more significant part of the Fay ore body with depth.

Murmac Bay Formation

Outcrop of the Murmac Bay Formation is confined to the area south of the mine in the hanging wall of the Saint Louis Fault. On surface, this consists of quartzites, gritty quartzites and quartz pebble conglomerates, calcareous variants of these, and schists, graphitic phyllites and amphibolites. The Murmac Bay Formation is characterised by only weak deformation and metamorphism. Tremblay (1972) thinks that these units unconformably overlie the more highly metamorphosed Tazin Complex units north of the Saint Louis Fault.

The rocks seen underground in the hanging wall of the Saint Louis Fault consist of banded to massive, pink to orange gneiss termed leucocratic paragneiss or alaskite by the mine staff. The stratigraphic position of this paragneiss is not understood by the present writer, although Sassano (1972) places it within the Donaldson Lake Gneiss.

This unit is not mineralized in the vicinity of the Fay Mine. Tremblay (1972) observes that the unit is mineralized at two stratigraphic levels in the area around Murmac Bay on Beaverlodge Lake, where vein-type uranium is associated with siliceous dolomites and graphitic rocks.

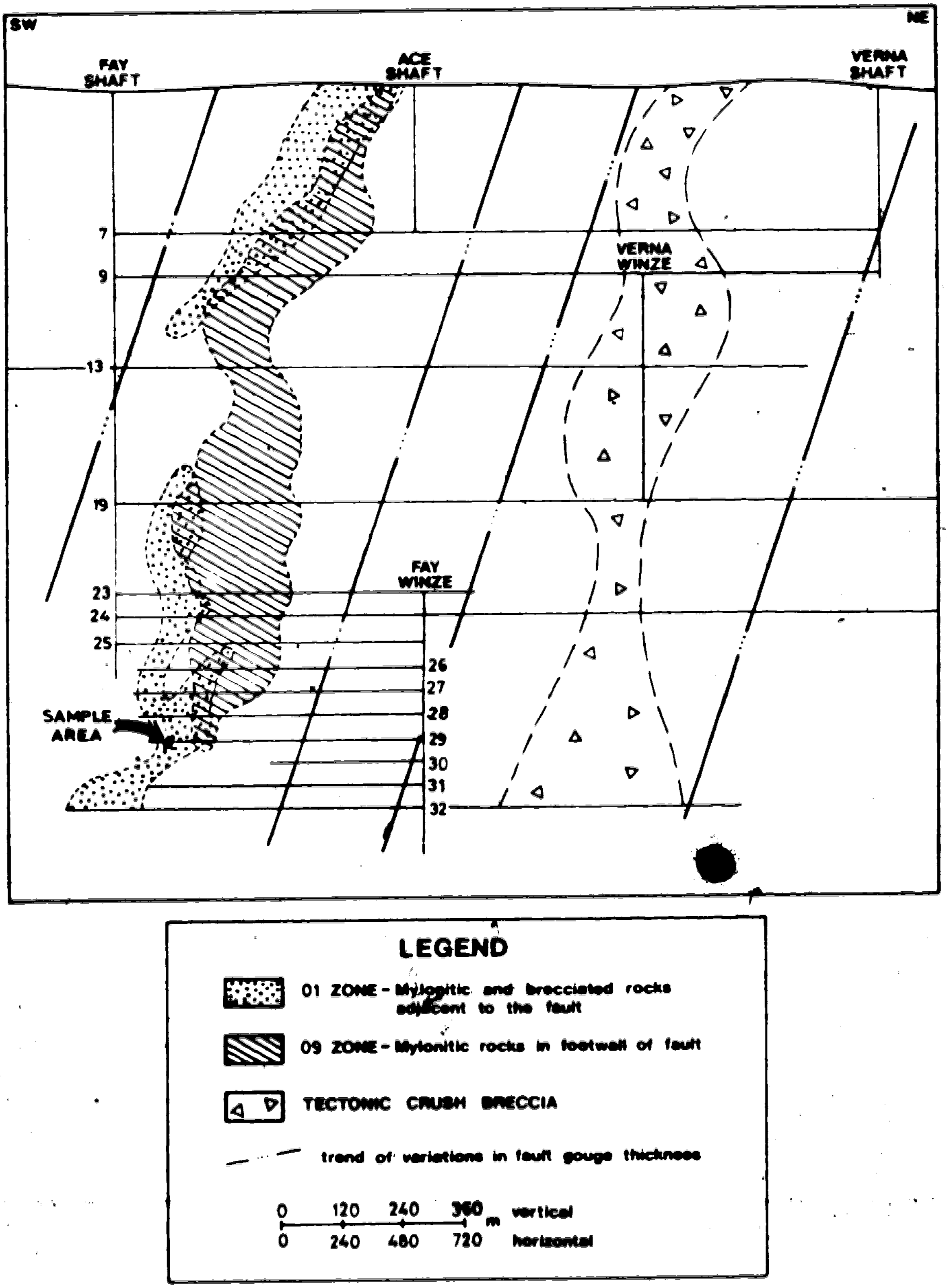


Figure 4 Longitudinal section showing the '01' and '09' ore zones and some tectonic elements of the Fay & Fay Winze mines.

Martin Formation

The Martin Formation consists of late Aphebian to Helikian red-beds and volcanics occupying several fault bordered basins in the Beaverlodge area. It is made up of shallow-water red arkoses, siltstones and conglomerates with some interbedded plateau-type basaltic flow rocks (Tremblay, 1972). The source of the red coloration is from pink feldspars and hematite cement (Sibbald and Lewry, 1980).

The base of the Martin Formation is characterized by a layer of coarse basal conglomerate locally derived from the underlying units (Tremblay, 1972) rather than by a layer of regolith which occurs at the base of the Athabascan Group to the south.

Uranium mineralization is confined to silica and calcite filled veins and breccias in a conglomerate-filled shallow basin occurring from surface down to third level, where the basin bottoms out. Higher in the section, a few kilometers to the southwest along the Saint Louis Fault, calcite and quartz veins cutting interbedded Martin Formation clastics and volcanics contain radioactive mineralization (Smith, 1952). It is suggested (Tremblay, 1972; Hoeve, 1978) that the uranium mineralization in the Martin Formation is related to the event that occurred about 1100 Ma.

A controversial aspect of the Martin Formation is its possible occurrence underground. Several workers, including Sassano (1972) and Sibbald, *et al*. (1976) have, in the opinion of the writer, mistakenly assigned a conglomerate-looking crush breccia to the Martin Formation. This is discussed more fully in Appendix 2.

Structure

Faults

The Saint Louis Fault, named after one of the discoverers of the Fay orebody, is a major structure that is part of a large scale anastamosing system that can be traced on satellite photographs for hundreds of kilometers to the east. To the west, the fault is traceable for 10 kilometers where it abuts against the northerly trending Black Bay Fault. The northwest trending ABC Fault, a few kilometers west of the mine, is considered by Tremblay (1972) to be a splay fault from the Saint Louis. These faults or fault-systems appear to be confined to the fold-linear belts (Beck, 1969) and possibly to outline the margins of stable granitic blocks.

Tremblay (1972) considers these faults to be part of an early phase of tectonism that occurred at or near the start of the Hudsonian orogeny. Zones of cataclasite and/or mylonite up to several kilometers wide have been observed adjacent to most of these early faults (Christie, 1953; Krupicka and Sassano, 1972). Patches of cataclasite also occur in areas not presently cut by major faults (Tremblay, 1972) suggesting to the writer that some of the present fault zones post-date at least one period of deformation.

Many small scale fractures, bounded by these large scale fault systems, have tension features such as open space filling (with or without brecciation) with quartz, calcite and hematite veins. Radioactive mineralization is common in these small veins which account for a large percentage of approximately 2000 surface showings in the Beaverlodge area. A period of late faulting, represented by clean, non-brecciated fractures, is reported by Tremblay (1972). These trend southeast and, because of the similarity in their attitudes, are thought to be the result of regional forces. The late stage gabbro dykes appear to be synkinematic and fill many of these fractures.

The Saint Louis Fault has been the focus of much work in the past due to its close association with the Eldorado orebodies. Tremblay (1972) suggests that left-lateral movement of 370m has occurred over the history of the fault zone and that the latest movement of the fault was normal. Beck (1969) thinks that normal movement occurred on most of the northern Saskatchewan structures once the 'intense compression' of the Hudsonian orogeny started to wane. The writer agrees with Tremblay that the latest movement was both left-lateral and normal. This is based upon underground observation of small drag folds and the ore-bodies and crush breccia zones as observed in longitudinal section (Fig. 4).

Small scale faults form lensoidal stockworks in the ore zones of the Fay Winze and appear to have a strong influence in the ore deposition. This style of faulting is in contrast to the long, sinuous type of fracture that is prevalent in the more schistose units that are most common in the upper levels of the mine. The stockwork type of fracture is believed by the writer to be related to late (post-Hudsonian) movement on the Saint Louis Fault and the brittle nature of the Fay Winze lithologies.

Folds

Folding in the Beaverlodge area does not appear to have the same significance to the ore zones as does faulting. Many folds, both isoclinal and open, are seen throughout the Tazin metamorphic rocks and these are thought to be related to deformation during the Hudsonian orogeny. The Helikian units that post-date the Hudsonian orogeny have only very gentle to non-existent folding.

The Donaldson Lake Anticline is the major structure in the mine area and consists of broad upright open folds whose axis is sub-parallel to the strike of the Saint Louis Fault. The Fay orebody is situated on the southeast limb of the anticline where it encounters the Saint Louis Fault (Fig. 5). Ptygmatic small amplitude drag folds are common in the Donaldson Lake Gneiss and the Foot Bay Gneiss, but are infrequent in the mylonitized units.

Mylonitization of the Tazin Complex

Many authors have recognized the high degree of the multistage deformation that has affected the rocks of the Beaverlodge area. Christie (1953) observed that dynamic metamorphism has been "very prominent locally" and that partly crushed rocks, mylonites, flaser gneisses and crush breccias are particularly well developed along the Saint Louis Fault. He also notes that the Tazin Complex rocks all show some microscopic evidence of crushing and that some mylonite zones are up to one kilometer wide.

Blake (1951), mapping an area to the east of the Fay Mine, described well developed mylonite zones in the vicinity of the Saint Louis Fault and suggests that "because of the overall great width of the zones of mylonitized rocks, they are best considered as representing a broad belt of continuous slippage and plastic flow rather than an individual fault or faults". Mylonite zones at one location have an aggregate width of 4.8 km. Blake places the mylonitization after the main period of metamorphism (1800 Ma) and before the late stages of intrusion (1650 Ma). He thinks that the rocks responded to stress early in the orgogeny by flowing into complex minor folds and later, at higher crustal levels, perhaps near the end of the event, channeled the stress into more definite zones of mylonite.

Tremblay (1972) says that the mylonitization and cataclasis are responsible for some of the retrograde effects noted in the Beaverlodge area. The mylonitized rocks commonly contain abundant chlorite and albite. Because of the width of some of the zones, it is difficult to describe them as faults and, instead, he assigns them to a sub-unit. Such zones are characterized by wide bands of mylonitized and brecciated rocks, by narrow mylonite zones associated with irregular areas of brecciated rocks and by seemingly unoriented patches of brecciated rocks. Tremblay places the mylonitization into two events: an early stage coeval with metamorphism and faulting but after the folding (about 1700 Ma), and a late stage from 1400 to 1500 Ma coincident with a late phase of tectonism.

Krupicka and Sassano (1972) have classified mylonitization on an ascending scale of one (stained rocks) to four (ultramylonitic rocks). The highest degree of deformation they observe in the Fay Mine rocks are in the Foot Bay Gneiss, which they rate at 3.0. The Fay Mine Unit rates at 2.0 to 2.6 and the Donaldson Lake Gneiss is lowest at 1.7. They think that the Foot Bay Gneiss, being the oldest, has undergone the highest degree of deformation and cataclasis. They also suggest that the preservation of amphiboles in some crush zones indicates a high prevailing temperature during deformation. The mylonites and cataclasites were later brecciated and developed a network of ultramylonitic shear zones. Their final conclusion is that "the time of the great crushing, kneading, shearing, and shattering of all the rocks of the Tazin Group came in the Hudsonian". A generalized account of the process of mylonitization is discussed in Appendix 1.

IV. GEOCHEMISTRY AND DEFORMATIONAL PETROLOGY OF SOME FAY WINZE WALL-ROCKS

General

This section reports the findings of a geochemical study and a petrological examination of some non-mineralized rocks of the Fay Winze. Included with the petrological description of each mineral is a discussion of specific deformational effects which have been observed by others. A general summary of the literature referred to in this chapter is included in Appendix 5. A number of authors have reported on the *textural* changes that accompany cataclasis (Tremblay, 1972; Krupicka and Sassano, 1972). It is the purpose of this chapter to describe the *mineralogical* and *geochemical* changes.

The rocks studied for this report are from diamond drill core from the 29th and 31st Levels of the Fay Winze mine and constitute an unmineralized 100m section from the Saint Louis Fault into the footwall through the Fay Mine Unit and ending in the Donaldson Lake Gneiss (Fig. 5). The rocks are described in hand specimen and thin-section and a modal analysis of thin-section mineralogy is included in Table 3. Prior to petrological examination the rocks were stained for compositions of feldspar and carbonate. In addition, the samples were routinely checked for magnetic and ultraviolet response and radioluxography was performed to check for non-visible disseminated or vein-type radioactive mineralogy.

The rocks of the Beaverlodge area have achieved an ultimate metamorphic grade of almandine amphibolite facies. Retrograde reactions related to cataclasis are a well documented feature (Higgins, 1971; Tremblay, 1972) and in the Fay Mine area have resulted in a number of mineralogical transformations. Since the sampling did not include undeformed rocks, the necessary comparisons and transformations are based upon published accounts of underformed Beaverlodge equivalents.

Hand Specimen Descriptions

The rocks in hand specimen are classified as either mylonites or cataclasites as defined in Appendix 1. In terms of the definitions of Chapter III, they are orange, porphyroclastic mylonites and mylonitic mica schists included in the Fay Mine Unit. They are dark brown, orange or pink, usually cherty and weakly to moderately foliated and banded. They often display a mylonitic 'fluxion' texture. The samples are almost all porphyroclastic with isolated, rounded feldspar porphyroclasts set in a fine-grained matrix. Some samples from zones affected by the last phase of brittle deformation have broken grains and porphyroclasts and an overall brecciated appearance.

Staining reveals that about one third of the porphyroclasts are potassium feldspar and the rest plagioclase. Most of the samples are cut by veins or veinlets of pink or white calcite, quartz, and hematite and veinlets of potassium feldspar or plagioclase. Dolomite is not seen. None of the samples are magnetic or display any fluorescence under ultraviolet light. Radioactive minerals were not observed in any of these samples.

Thin Section Descriptions

The mylonitic and cataclastic textures are more obvious in thin section than in hand specimen. Microcline porphyroblasts are well developed and usually strain free, whereas porphyroclasts of plagioclase are usually bent or broken and often comminuted down to a very fine grain size. The matrix is a fine grained, well foliated mixture of chlorite and muscovite. Mortar textures are common in masses of recrystallized quartz. Zircon porphyroclasts are rounded and isolated in a matrix that usually shows a well-developed, fine-grained fluxion texture. Pyrite euhedra are seen in some samples and are often broken and distorted. In terms of the definitions used by Krupicka and Sassano (1972) and summarized in Appendix 1, the samples of Fay Winze rocks show deformational textures between 2 (cataclasites) and 3 (mylonites) and, occasionally, 4 (ultramylonite). According to the definitions of Higgins (1971) (Appendix 1) they are classified as mylonitic schists and gneisses, mylonites and, occasionally, ultramylonites. The samples display only a slight increase in degree of deformation approaching the Saint Louis Fault.

Mineralogy and its relationship to deformation

The major mineralogy of the samples is generally quite simple and consists of quartz, plagioclase, potassium feldspar and chlorite and, usually, muscovite and calcite (see Table 3). The minor mineralogy is somewhat more complex and consists of sphene, anatase, epidote, apatite, hematite, zircons (?) and opaque minerals. The minor mineral phases rarely constitute more than five percent of the rock.

TABLE 3: Estimated mineral compositions of some Fay Winze rocks, in percentages.

SAMPLE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Quartz	15	40	45	30	15	20	30	35	40	40	40	40	50	70	85	25
Plagioclase	20	-	-	15	30	5	20	5	40	-	30	-	10	-	10	35
Microcline	40	15	10	15	20	25	20	25		35		40	5	-		15
Sericite	2	-	-	-	-	20	20	15	10	10	10	2	5	-	tr	-
Chlorite	10	20	30	-	15	20	10	10	10	10	10	10	5	5	2	10
Calcite	2	-	5	25	20	-	-	-	-	-	2	-	10	10	2	10
Sphene	-	<5	5	<5	5	-	<2	<2	tr	-	-	-	2	10	-	2
Hematite	2-5	<2	5	5	2	-	<2	-	2	5	2	2	-	2-5	-	2
Epidote	2	-	-	-	<2	-	-	-	-	-	-	2	15	-	-	-
Zircon(?)	tr	-	-	5	-	-	-	-	<2	-	tr	-	2	-	-	-
Opaques	-	15	-	-	-	10	-	5	-	-	-	-	-	-	<2	-

Quartz

Quartz is present in all of the sections in amounts ranging from 15 to 85 percent. It is ubiquitous as a recrystallized matrix, where it is interstitial to the larger porphyrclastic grains. It also occasionaly forms large (up to 5mm) recrystallized masses with feldspar. Small 'drops' of quartz often occur as myrmekitic intergrowths in plagioclase. Quartz and quartz-feldspar veinlets are common in most sections and euhedral 'comb' quartz occurs at the margins of some calcite veins.

Quartz is considered by most workers to be an easily recrystallized constituent of mylonite zones (Higgins, 1971; Bell and Etheridge, 1973) and is therefore expected to show considerable remobilization and textural transformation during cataclasis. The recrystallized 'mortar texture' is described by Bell and Etheridge (1973) as a typical feature of cataclasis.

Porphyroclasts of quartz and feldspar are fairly common and could possibly be relicts of the original quartzo-feldspathic gneiss that is predominant in the relatively undeformed areas north of the Saint Louis Fault (Tremblay, 1972). These also form a significant proportion of the fragments of the cataclastic 'crush breccia' seen at many locations in the mine and discussed in Appendix 2. Conybeare and Campbell (1951) describe porphyroclasts from the Saint Louis Fault mylonite that are composed of quartz and feldspar partially altered to microcline. The presence of fine-grained hematite indicates that at least one phase of quartz remobilization occurred after the breakdown of the mafic minerals (biotite) and release of iron (Tremblay, 1972) into the system. The euhedral "comb quartz" in calcite veins suggests a period of late tensional readjustment, as described by Sinha Roy (1977) with quartz and then calcite filling in the porosity.

Feldspar

Plagioclase occurs as porphyroclastic grains that range in size from several millimeters to less than ten micrometers. These usually display bent and broken twin lamallae, serrated grain boundaries and moderate but pervasive alteration to, what appears to be, sericite and calcite. The plagiclase composition of these samples is albite-oligioclase (AnO-30) as was determined by electron microprobe analysis of plagioclase in the wall rocks of mineralized veins (see Chapter V) and past reference by other workers in the area (Conybeare and Campbell, 1951; Robinson, 1955;

Tremblay, 1972). Plagioclase generally displays the highest degree of deformational strain among the minerals observed in these sections.

Plagioclase observed in this study tends to have undergone mechanical breakdown (comminution) with related high degrees of strain, rather than recrystallization. Metasomatic alteration of plagioclase porphyroclasts to calcite and sericite tends to occur most readily among the finer grains or else along fractures in the larger ones. Areas of very fine-grained plagioclase are usually clouded with alteration products. Many workers, however, have described the chemical breakdown (generally albitization) of plagioclase in mylonite zones and the resulting loss of calcium from the system (Ashley and Chendall, 1976; Conybeare and Campbell, 1951). The present writer believes that the alteration of plagioclase in these rocks has possibly contributed to the formation of calcite, which is observed in all sections examined. Sodium may have been lost from the system, as suggested by Conybeare and Campbell,(1951), and Wintsch (1981) although it is proposed here that at least some of the sodium remained to form the pure albite that was observed in electron microprobe analysis of some of the gangue minerals in the ore veins described in Chapter V.

Potassium feldspar is present as large, unstrained and unzoned porphyroblasts that occasionally reach several millimeters in diameter. It also occurs as fine, untwinned matrix material and as small twinned euhedra with quartz and calcite in veinlets less than one millimeter wide. The matrix material does not display the fluxion texture observed in the muscovite and chlorite. Weak sericitic alteration has affected most of the potassium feldspar porphyroblasts. The behavior of potassium during cataclasis has been well-documented by a number of writers. Burwash and Culbert (1976) feel that it is introduced (via metasomatism) at an early stage of deformation. Wintsch (1975) proposes a mechanism for the conversion of muscovite to potassium feldspar using a phenonomon known as "abrasion pH" which, when applied to muscovite during cataclasis, results in an increase in pH due to surface exchange reactions between the newly exposed "001" faces and the surrounding solutions. This new solution chemistry is in the stability field of potassium feldspar and, so long as deformation proceeds, microcline porphyroblasts will be produced at the expense of muscovite.

Kerrich *et al.* (1980) observed the loss of sodium from feldspars during the formation of orthoclase in a shear zone. Excess sodium is probably lost from the system (Conybeare and Campbell, 1951; Wintsch, 1975) possibly through diffusive transport in a fluid medium (Wintsch, 1981). Ashley and Chendall (1976), however, report a net increase in the Na_2O content of the sheared vs unsheared rocks.

Micas

Muscovite is present as fine-grained interstitial matrix with a well-developed fluxion texture and, less commonly, as elongate, strained masses with strong undulatory extinction that resemble porphyroclasts. Fine intergrowth of muscovite and chlorite are seen in most sections. Sericite occurs as an alteration product in plagioclase and potassium feldspar.

Micaceous minerals are a common constituent of most mylonite zones, a fact consistent with the mechanical processes that result in a strong two-dimensionality and a high degree of flattening (Higgins, 1971; Sinha Roy, 1977). Muscovite is the only mica observed in the Fay Winze samples. Biotite is included in this discussion however, as it is thought to be important in its absence as a supplier of titanium and iron to the system. Biotite is "fairly abundant" in the unmylonitized equivalents of the Fay Winze samples (Tremblay, 1972).

Ashley and Chendall (1976) observe that primary muscovite tends to recrystallize during mylonitization and that secondary muscovite results from the cataclastic breakdown of both biotite and plagioclase. This is supported by Kerrich *et al.* (1980) who also see muscovite as one of the alteration products of biotite. Wintsch (1975, 1980) on the other hand, maintains that primary muscovite can alter to produce feldspar and that this reaction may be responsible for the feldspathization commonly observed in mylonite zones.

Biotite is thought to have been present in the unmylonitized equivalents of these samples and to have been altered during deformation (Tremblay, 1972). This is considered significant as products of this alteration are important to the ore genesis as described in Chapter V.

The alteration or destruction of biotite appears to be a common phenomenon in mylonite zones. Ashley and Chendall (1976) describe primary biotite breaking down to a secondary more highly oxidized variety deficient in titanium and iron. This is supported by Wintsch (1981) who suggests that 'syntectonic oxidization' of the ferrous iron in biotite during cataclasis ultimately results in the decrease in the Mg/Fe ratio accompanying deformation. He also observes the partial replacement of biotite by muscovite.

Kerrich *et al.* (1980) propose a progressive breakdown of biotite that initially involves the formation of Fe-muscovite, ilmenite and low Ti-biotite (similar to that proposed by Ashley and Chendall) and, eventually, chlorite, sphene and TiO_2 (rutile or anatase) with or without muscovite. According to their observations, the total consumption of biotite coincides with the appearance of "significant" epidote. This is inconsistent with the mineralogy of this study, although epidote does form a substantial part of the epidote-chloriite rock (Epidotic Argillite, Chapter III) that is associated with high grade footwall ore in the Fay Mine and some parts of the Fay Winze.

Chlorite

Chlorite occurs in all the sections in amounts from 5 to 30 percent, generally as an interstitial mineral with muscovite and quartz. Occasional porphyroclastic masses are seen that may represent chlorite replacement of an original grain. The chlorite is typically pale green to colorless and very weakly pleochroic. Anomalous blue interference colors are always seen. Chlorite often occurs in veinlets, either by itself or with quartz, calcite, titanium phases or unidentified opaque minerals. Chlorite replacement of square euhedral opaques (pyrite?) is seen in one sample. Rare pleochroic haloes surround high relief grains (uranoanatase or zircon?) in some chlorite areas.

Chlorite is, with muscovite, the most abundant and widespread mineral occurring in the samples used in this study. The composition of chlorite from the Fay Mine are is usually given as penninite (Conybeare and Campbell, 1951; Sassano, 1972). Robinson (1955) reports prochlorite and clinochlore from the Beaverlodge area and Scott (1979) observed clinochlore and ripidolite as gangue minerals in some Fay Winze ore samples. A diabantite composition (Fig. 8) was determined from microprobe analyses of ore-zone chlorite reported in Chapter V.

Tremblay (1972) observes that, "chloritization represents retrogressive metamorphism due to cataclastic deformation" and describes the increasing chloritization that is coincident with the disappearance of biotite in the Donaldson Lake and Foot Bay gneisses when they become mylonitized in the Saint Louis Fault zone. The process of cataclastic chloritization elsewhere is described by Ashley and Chendall (1976) who suggest the production of chlorite and sphene and, possibly, muscovite and clinozoisite from the breakdown of biotite. Kerrich *et al.* (1980) recognize chlorite as one of the final products of the 'deformation induced breakdown' of biotite, where it coexits with ilmenite and, possibly, epidote.

Calcite

Calcite occurs as anhedral masses scattered throughout the matrix of many samples and, more commonly, as veins up to several centimeters wide that cut-across foliation and often display signs of open-space filling. The calcite is usually clear although some is pink due to finely disseminated hematite, particularly in the ore zones. It appears to be a very late forming mineral and rarely shows any signs of strain. The samples closer to the Saint Louis Fault appear to have more calcite then those further into the footwall, although this may not be significant due to the few samples examined. Calcite is the only carbonate observed in these sections.

Calcite is considered to be an easily recrystallized constituent of mylonite zones (Higgins, 1971), behaving in much the same manner as silica. Strained 'primary' calcite is not seen in the sections examined for this study. Conybeare and Campbell (1951) described the calcite from the Saint Louis Fault zone as either very late solution or recrystallized. In the literature reviewed, calcite is a rare to non-existent constituent of fault zones. Kerrich *et al.* (1980) suggest that calcite with epidote replaces biotite at the highest states of deformation. These zones, however, appear to have only minor production of OH^- and CO_3-bearing secondary minerals, indicating only minor introduction of volatiles along the shear zones. It is the opinion of the writer that the Saint Louis Fault shear zone acted as a conduit for the migration of more significant quantities of volatile components.

These results suggest that calcite in mylonite zones is due to the recrystallization of pre-existing calcite and is not a product of the alteration of any primary minerals. In the Fay Mine area, however, calcite is at best a minor constituent in the unmylonitized quartzo-feldspathic gneisses. The source of the calcite, which is thought to be significant in the genesis of the ore, remains a mystery. Tremblay (1972) believes that the calcite is derived from hydrothermal carbonitization.

Sphene

Sphene occurs in most sections as small high relief grains with yellow to orange-brown pleochroism and high interference colors. These are usually scattered infrequently throughout the rock although they do occasionally concentrate into bands, where the sphene is associated with chlorite, hematite and possibly zircon and anatase. When viewed under medium power (x125) with the condenser lens and crossed-nicols they appear as distinctive, clove brown 'clouded' masses due to the strong internal reflections. In reflected light under crossed-nicols they display distinctive brilliant white internal reflections and, in plane-polarized light, medium to light grey color and medium reflectance. They are usually elongate sub-hedral to anhedral masses less than 100 micrometers in size. Occasional euhedral rhombic sections are observed. It is possible that much of what is being called sphene, particularly the anhedral masses, could in fact be anatase, which was seen during microprobe analyses of vein material reported in Chapter V.

The titanium phases that occur in the rock samples from the Fay Winze consist of sphene and possibly, anatase. These usually occur in minor quantities, are associated with chlorite and tend to be more abundant closer to the Saint Louis Fault. Titanium phases in mylonite zones are described by Ashley and Chendall(1976) and Kerrich *et al.* (1980). These studies suggest that the titanium originates from biotite and is released to the system as the biotite becomes altered due to deformation. Sphene with or without anatase or rutile is the usual phase that is formed. The formation of sphene involves the consumption of calcium, which could, perhaps, account for the calcium produced by the albitization of plagioclase. Biotite does not usually contain more than 0.50 percent CaO (Deer *et al.*, 1966). The release and migration of titanium is thought to play an important role in the formation of the ore.

Epidote (var. Pistacite) is present in small quantities only and is more common with increasing distance from the Saint Louis Fault. In one section where it comprises 15 percent, it occurs as pale green columnar masses. Its occurrence and petrogenesis is described by Ashley and Chendall (1976) and Kerrich *et al.* (1980) who feel that it is a final product of biotite alteration. The source of the calcium necessary for this alteration is not given. Deer *et al.* (1966) state that the paragenesis of epidote can be due to the retrograde readjustments associated with dynamic metamorphism, particularly of basic igneous rocks. Its formation is favored by low temperature and shearing stress. The lack of epidote in the samples used in this study is not understood, but it could be related to a lack of calcium in the original rocks.

Hematite is the most common opaque mineral thin section. Hematite occurrences vary from coarse blaades of specularite up to one centimenter in length to fine hexagonal plates that are less than ten microns across. These are finely disseminated throughout most of the mineral phases particularly the quartz and calcite. In one section, fine blades of hematite occur with chlorite in cubic to orthorhombic skeletal crystal outlines.

Host Rock Geochemistry

This study was performed for two principal reasons. The first was to check for any overall systematic variations in elemental concentrations with respect to distance from the fault (assuming a decrease in the intensity of cataclasis). The second was to examine the overall bulk concentrations of several elements in these rocks. Samples were taken from diamond drill core and were not obviously mineralized, although calcite and hematite veining, usually indicators of uranium mineralization, were seen in some. Prior to analysis all samples were microscopically examined in handspecimen and checked for radioactivity. The samples were analysed by fully quantitative X-ray fluorescence spectrometry by Midland Earth Science Associates, Nottingham, England. Uranium was determined by delayed neutron activation by Nuclear Activation services Limited, Hamilton, Ontario. All of the samples were analysed for six major elements (Si, Al, Fe, Ti, Na, K) and eight trace elements (Co, Cu, Ni, Pb, S, V, Se, U).

The results of these analyses are shown in Table 4. When compared to analyses published in Tremblay (1972) and also shown in the table, the average values of the six major elements correspond more closely to analyses of argillites and slates than they do to Donaldson Lake or Foot Bay gneiss. The trace element concentrations, with the exception of vanadium and uranium, are all at or below the crustal averages shown in Mason (1966). Trace element analysis of unmineralized Beaverlodge rocks are not published, however Beck (1969) reports trace element geochemistry of composite ore

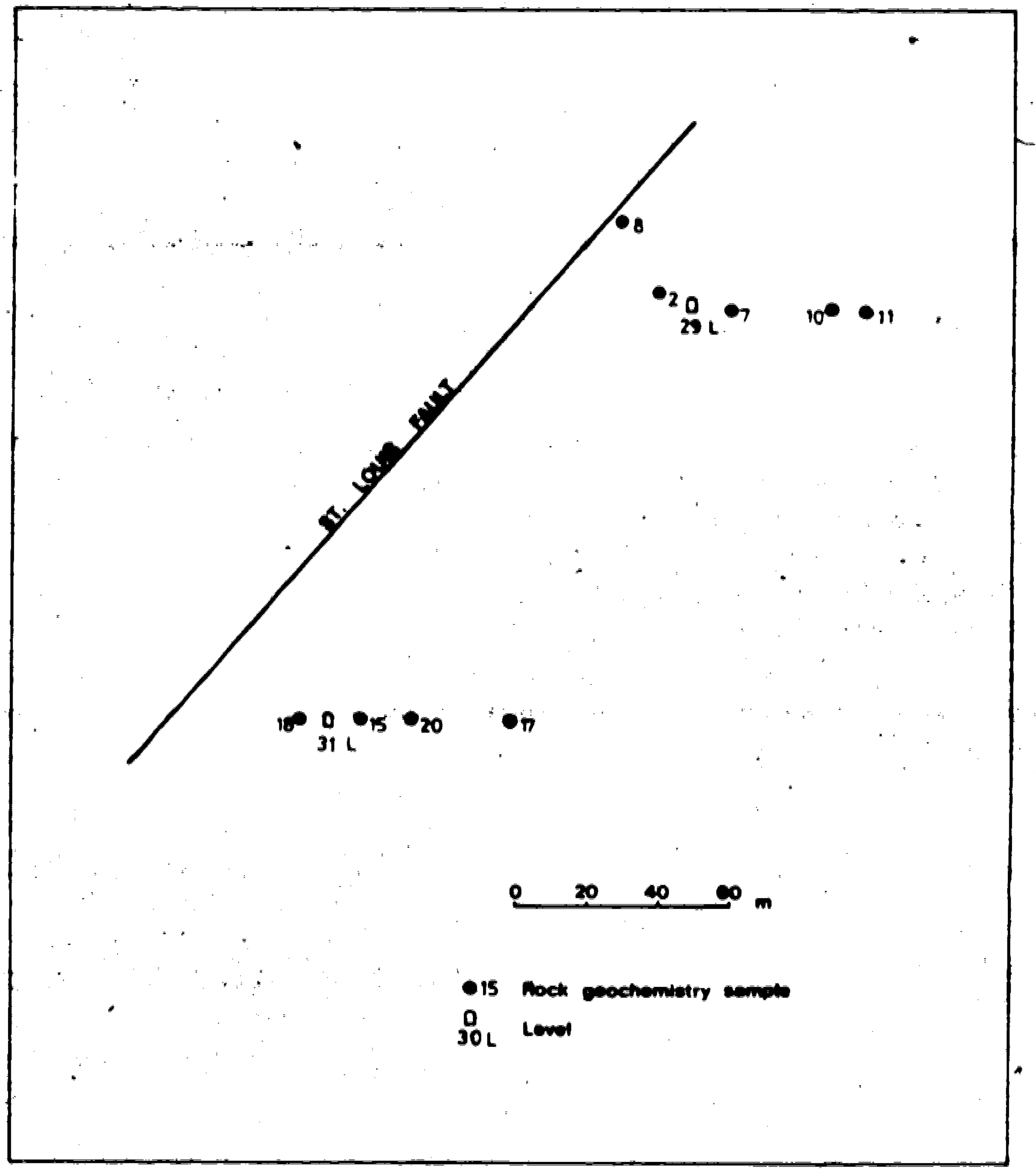


Figure 5 Schematic cross-section showing the location of rock geochemical samples from the Fay Winze mine.

TABLE 4: Geochemistry of some rocks from the Fay Winze in weight percent and parts per million. See Appendix 3 for sample descriptions.

SAMPLE NUMBER	2	6	7	10	11	15	16	17	18	Avg.	A**	B	C	D
① SiO_2	59.23	61.01	61.91	59.91	49.69	58.51	53.39	54.37	52.88	56.77	52.50	59.14	65.91	73.86
Al_2O_3	11.03	16.45	14.79	14.67	9.75	15.78	12.54	14.24	12.35	13.51	13.28	13.97	15.86	13.12
TiO_2	0.70	0.62	0.75	0.74	1.51	0.93	0.73	1.20	0.50	0.85	1.41	1.12	0.53	0.26
⑤ FeO	8.98	4.82	9.36	8.37	9.29	8.55	6.07	7.97	5.65	7.67	11.39	9.39	4.11	2.09
Na_2O	3.08	2.93	2.22	1.93	3.75	2.30	3.21	6.95	5.31	3.52	3.88	2.82	3.07	2.75
K_2O	0.52	2.71	2.15	2.62	1.19	2.61	1.82	1.08	1.81	1.83	0.73	1.45	4.43	4.48
2 Co	43	22	32	29	36	29	32	19	21	29				
Cu	36	16	46	90	26	38	41	75	27	44				
Ni	49	38	58	56	37	76	19	16	23	41				
Pb	24	13	4	31	22	6	16	23	17	17				
V	146	97	124	253	340	164	137	236	281	198				
** ③ U	16.0	8.0	6.5	17.0	13.5	2.1	95.7	13.2	46.1	24.2 ④				
S	BDL *	BDL	BDL	1355	BDL	162	377	23	1061	NA ***				
Se	1	1	BDL	BDL	1	BDL	1	BDL	BDL	NA				

* below detection limit (see 'Notes')
** see 'Notes for Table 4'
*** not applicable

Notes for Table 4

1. Weight percent, determined by quantitative x-ray fluorescence spectrometry, Midland Earth Science Associates.*
2. Parts per million, determined by quantitative x-ray fluorescence spectrometry, Midland Earth Science Associates.*
3. Parts per million, determined by delayed neutron activation analysis, Nuclear Activation Services Limited.
4. Average, excluding the high of 95.7 ppm, is 15.4 ppm U.
5. Iron reported as total Fe in XRF analysis.

Analyses reported in Tremblay, 1972:

A. Hornblende schist and gneiss, Ace shaft west of Ace Lake, Beaverlodge, Saskatchewan.

B. Argillite and slate, Southwest of Nesbitt Labine shaft, Beaverlodge, Saskatchewan.

C. Foot Bay gneiss, Beaverlodge area, Saskatchewan.

D. Donaldson Lake gneiss, Beaverlodge area, Saskatchewan.

*XRF analyses performed on a Phillips PW 1400 automated spectrometer equiped with a Rhodium X-ray tube.

Trace element detection limits (ppm)

Co	2.5
Cu	0.8
Ni	1.7
Pb	1.5
V	1.9
U	0.1
S	3.5
Se	1.0

samples from the Ace-Fay mines (probably down to about 10th Level). These results indicate that, as expected, the trace element content of the ore samples is considerably higher than that of the wall-rocks, particularly in Pb and V. Substantial increases are also shown in Ni and Cu whereas Co only shows slight increase in the mineralized versus non-mineralized samples.

A comparison of element concentration with distance from the Saint Louis Fault fails to indicate any consistent or systematic variation. What is displayed however, is a sympathetic trend in the variations of Fe, Ti and V. As these are the major components of some ore zone hematite analysed in Chapter V, it is possible that the similar behavior of these three elements reflects changes in hematite content of the rocks. Another feature noted is the absence of any increase in the silica content approching the fault. Traditional belief maintains that the increasing brittleness immediately adjacent the fault zone is due to silicification of the rocks. It is apparent that such a process has not affected these rocks. One possible explanation for increased brittleness is by textural modification and 'work-hardening' due to cataclasis, as described by Higgins (1971).

In general, these results indicate that the scale of the sampling was too small to indicate any geochemical change due to mylonitization. More useful information is derived from dealing with the results as an average and treating them as a bulk sample of the Fay Winze rocks. The most significant fact to emerge from this is that the uranium content is about eight times higher than crustal averages shown in Mason (1966). This is interesting because specific uranium minerals were not observed in any of these rocks, although occasional pleochroic haloes were seen surrounding isolated grains of uranoanatase or zircon in chlorite and epidote. It is likely that a lot of uranium is held in these accessory minerals. However, these are uncommon and probably would not contribute very much uranium to the analysis. Another possibility, described in detail in Chapter VI, uses the adsorption capacities of layer silicates (mainly chlorite and biotite) to retain uranium. This phenomenon is used in Chapter V to explain the high uranium contents observed in some petrographically "clean areas" of chlorite in the ore veins.

Summary and Discussion

The Fay Winze host rocks all display both textural and *mineralogical* evidence of cataclasis and mylonitization. The mineralogy, shown in Table 3, consists of quartz, plagioclase (oligioclase–albite), microcline, muscovite, chlorite and calcite with minor amounts of sphene, anatase, zircon(?), hematite, epidote and apatite. This mineral assemblage, is believed to have formed from hydrothermal alteration coincident with strong deformation along a shear zone. Several elements, including Fe, Ti, V and U are probably remobilized during such alterations and possibly migrate into highly fractured, porous zones to be deposited as the mineral phases discussed in the following chapter. The high uranium values returned from the geochemical study indicate that some of the uranium may have been adsorbed in to the plate edges and cleavage fractures of layer silicates such as chlorite and muscovite.

V. MINERALOGY, CHEMICAL ANALYSIS, GEOCHRONOLOGY AND PETROGENESIS OF URANIFEROUS ORES

This section describes in detail the petrology and chemical composition of most of the vein minerals from the 29th Level ore zone and the uranium-lead geochronology of one of the uranium minerals. Two gangue minerals, bertrandite $Be_4Si_2O_7(OH)_2$ and roscoelite $KV_2(AlSi_3O_{10})(OH)_2$ are described for the first time from northern Saskatchewan.

Sample Selection, Preparation and Analysis Techniques

The samples used in this study were collected from a large working slope in the "01" zone of the 29th level, Fay Winze (Fig. 6). During the sampling, access was restricted to the western end of the orebody. The sampling represents a cross-section through a lensoidal stockwork-veined ore zone with an overall grade of about 0.20 percent U_3O_8. Since most of the uranium mineralization occurs in hairline chloritic veinlets and is not visible in hand specimen, samples were selected radiometrically and represent the highest detectable grade at each sample location.

Hand specimens were cut perpendicular to the trend of the veinlets and radioluxography was used to select the most radioactive areas for polished thin section preparation. Several thin sections were also made of non-radioactive areas and all reject slices were stained for feldspar and carbonate determination. Mineralogy and parageneses were determined using reflected and transmitted light microscopy and qualitative energy-dispersive electron microprobe analysis.

Areas suitable for detailed chemical analysis were determined at this time and quantitative energy-dispersive analyses were done on selected clean mineral phases. Some problems were encountered during this analysis due to the extremely fine-grained nature of many of the clean phases, which necessitated the use of a static 'point' beam for much of the work. The analyses of some minerals (ie. chlorite and mica) using a static electron beam can result in the migration of volatile components (H_2O, F, K, etc.) away from the point of beam impact. In order to minimize the amount of variability due to the loss of the volatile fraction from these minerals, the results of these analyses are expressed in terms of 'dry oxides'. Minor potassium dispersion was noted in one qualitative microcline examination.

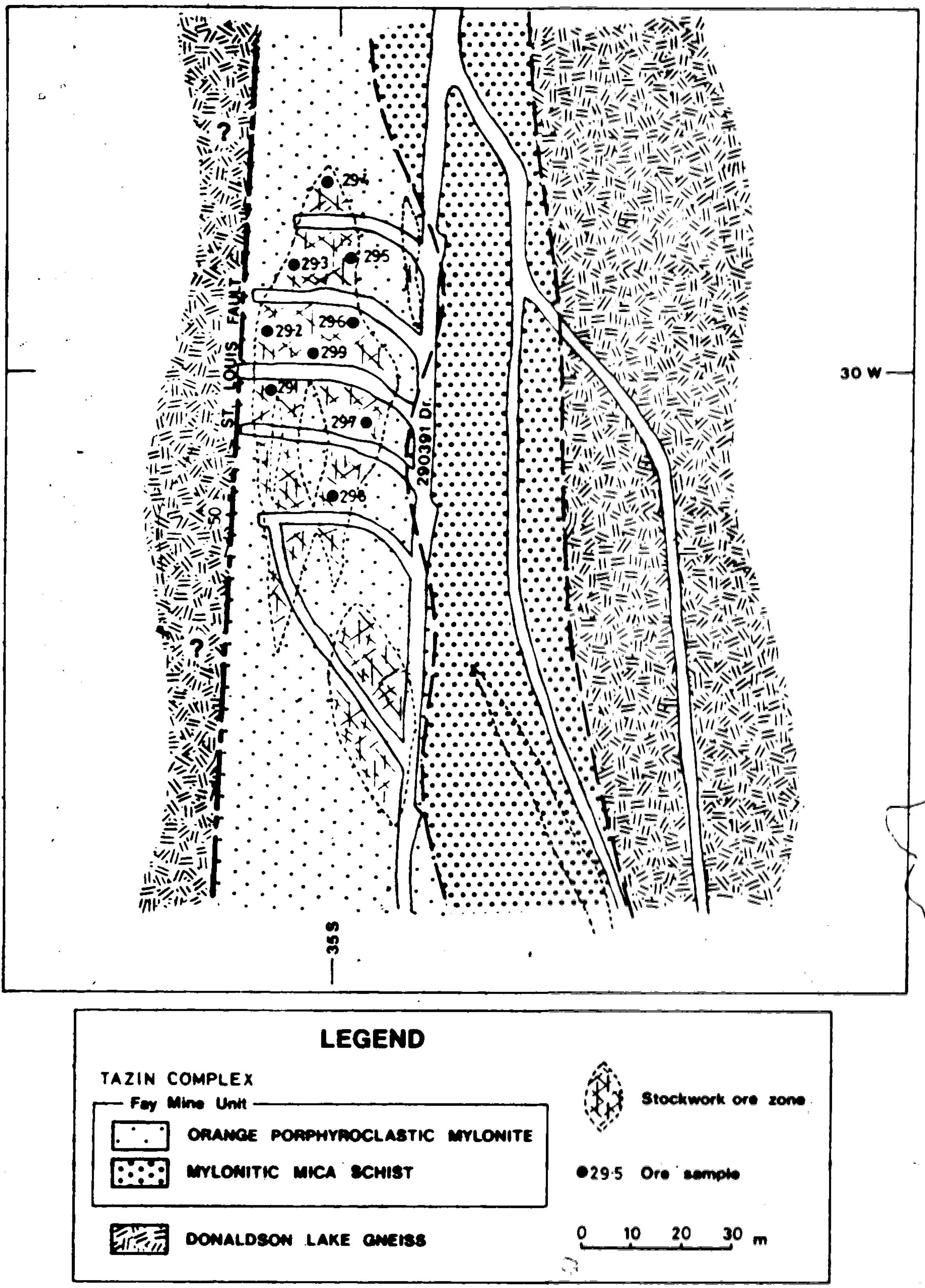


Figure 6 Geology and location of ore samples, Fay Winze mine, 29th Level.

Data reduction was performed using a standard microprobe data-reduction program (EDATA2, Smith and Gold, 1979). The instrument was calibrated before and after each quantitative analysis session using willmite calibration standards to check for drift in operating conditions. In addition, analytical standards were run for each element to be analysed in the unknowns.

Elemental concentration profiles (Fig. 7) were run across two veinlets and back scattered electron and X-ray scans were attempted on a few areas to help sort out some fine-grained mineralogy. This latter exercise, unforunately, was abandoned due to equipment problems.

One problem noted in the energy-dispersive microprobe analysis of these samples is the absence of lead from any of the uranium minerals. As uranium is constantly decaying into radiogenic lead, one would expect at least trace amounts to be present and even if the lead minerals had exsolved into separate phases (ie. galena) and were avoided during the microprobe analysis, it is unlikely that it would all be gone from the uranium mineral.

Uranium-lead isotope analysis returned lead concentrations of 200 p.p.m. to 1.2 percent. Assuming that some of this occurs as exsolved galena, the remaining is not reported in the microprobe analysis probably because of a strong overlap between of the uranium 'm' lines and the lead 'm' line. Since the intensity of the uranium line is much greater than that of the expected lead line, the lead concentration is almost completely obscured. It is possible that wavelength dispersive analysis, with its greater resolution, could solve this problem.

Qualitative atomic absorption spectophotometry was used to confirm the presence of beryllium in a vein sample thought to contain bertrandite ($Be_4Si_2O_7(OH)_2$).

Hand Specimen Descriptions

The ore samples, in hand specimen, are all characteristically dark brick red. The uranium minerialization, as revealed by radioluxography, occurs in dark chloritic veins and veinlets that usually have associated quartz-plagioclase and/or pink hematite stained calcite. Uranium phases are generally too fine-grained to be observed in hand specimen, with the exception of coffinite which appears as a vitreous and amorphous black mineral. Specular hematite and galena are occasionally observed in hand specimen.

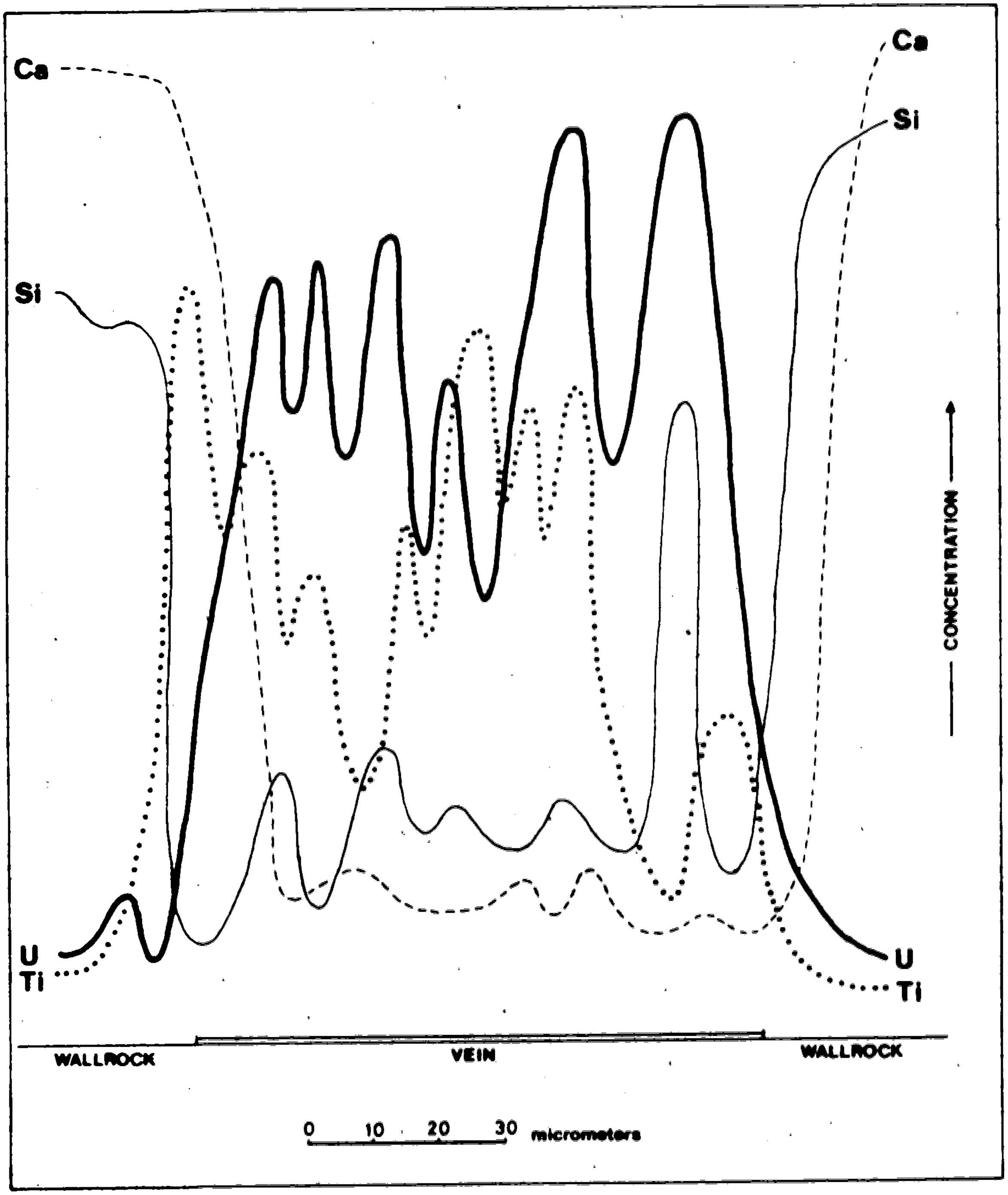


Figure 7 Variations in uranium, titanium, silicon and calcium across a mineralized veinlet.

The wall rocks are always porphyroclastic and often banded. They are occasionally strongly carbonatized by calcite deposition. Feldspar staining indicates that some of the small veinlets cutting the wall rocks are, in part, composed of potassium feldspar and that many of the larger prophyroclasts are microcline. Potassium feldspar,however, is rarely observed with mineralization. A few of the samples are moderately magnetic, probably due to vanadiferous hematite (Scott, 1979) as described below. None of the samples contain any minerals that fluoresce in either long or short wave ultraviolet light.

Petrology and Chemical Analysis of the Ore Minerals

In thin section, the vein minerals typically occur in opaque 50 to 350 micrometer wide veinlets that cut wall rocks composed of a porphyroclastic medium-to fine-grained quartz-feldspar mosiac. These wall rocks rarely display any sort of fluxion texture and usually have strained and altered feldspar porphyroclasts. They are often carbonitized and hematite stained up to several millimeters from the veinlets. Both albite, microcline and, rarely, plagioclase are seen in the wall rocks. Opaque minerals observed in the wall rocks are usually specular hematite and are commonly associated with chlorite. Opaque minerals do not constitute more then ten percent of the wall rocks.

The mineralized veinlets are often branching and are usually continuous across the section. Minerals observed in the veinlets consist of quartz, albite,a brannerite-like phase, coffinite, chlorite, hematite, anatase, bertrandite (beryllium silicate) and galena. Rare constituents include epidote, sphalerite, chalcopyrite and roscoelite (vanadium muscovite). Although usually quite narrow, the veins frequently show signs of open space filling such as coxcomb quartz and fragments of wall rocks. This observation is consistent with the brittle and siliceous nature of the ore zone.

The ore minerals in the study area have been sepaarated into two phases on the basis of petrographic description and both qualitative and quantitative microprobe analysis. The first to be described is coffinite, a mineral that has a relatively uniform composition and is always Ti-free. The second mineral shows wide variability in composition, although it always contains U, Ti, Si, Ca and Fe, and for reasons described below has been termed 'brannerite-like'. Pitchblende is not found in any of the 29th Level ore samples.

Coffinite $(U,Ca)(SiO_4)$

Coffinite is uncommon in the ore zone and is observed in only one ore sample in this study. It is the only uranium mineral visible in hand specimen where it is black, adamanitine to vitreous, and amorphous with a hardness of about 6. In reflected light it is dark grey, has low reflectivity and isotropic and opaque in transmitted light. It occurs as very small (less than 100 micrometer) euhedra with square or diamond-shaped outlines. It is interstital to albite and is associated with clear euhedral quartz and bladed hematite and often contains inclusions of euhedral galena. Late-stage introduction of orange, hematized silica, which has partly altered and corroded the albite and euhedral quartz, has not affected the coffinite. In the vein paragenesis the coffinite follows albite, euhedral quartz and euhedral galena and precedes the bright orange quartz.

The physical properties of this coffinite are consistent with photographs and descriptions published by Bayushkin and Dikov (1974) and Steacy and Kaiman (1978) who describe coffinite from sandstone-hosted uranium deposits as black and adamantine with a conchoidal fracture. Rimsaite(1977) reports semi-transparent brown coffinite filling vugs at Rabbit Lake, Saskatchewan.

Quantitative electron microprobe analyses of coffinite are shown in Table 5. The relatively large size of the mineral grains and the lack of intermixing permitted clean analyses and no rejections due to contaminants. The results are shown as dry oxides although initial results indicate a water content of about four percent. Uranium and silica are the two major constituents, averaging 83.4 and 78.6 dry oxide weight percent. Iron is the only other oxide present in amounts greater than one weight percent. There are a number of minor constituents, the most interesting of which are the rare earth elements cerium and neodymium. Cerium and other rare earths are reported in Fay ore samples (Beck, 1969) although this is the first reported occurrence of neodymium.

The structural formula for coffinite is based on the model ABO_4, (Ramdhor, 1969) where A consists of U and Ca and B consists of Si and Al. The minor constituents are all placed in the A-site. The two analyses indicate a variable composition, however, the best calculated structural formula is $A_{1.1}B_{.9}O_4$. Steacy and Kaiman (1978) report that coffinite can contain varying amounts of $(OH)^-$ in substitution of SiO_4 which suggests that the above structural formula could be modified by taking into account the water that was removed from these results prior to the structural formula calculation.

TABLE 5: Electron microprobe analyses of coffinite expressed as dry oxide weight percent and as structural formulae based on a 4 oxygen anhydrous unit cell.

See Appendix 3 for sample descriptions.

SAMPLE NUMBER	25	26	Avg.
Na_2O	0.81	0.96	0.89
MgO	0.26	0.32	0.29
Al_2O_3	0.54	0.56	0.95
SiO_2	17.01	6.27	11.64
CaO	0.27	1.54	0.91
TiO_2	0.0	0.0	--
MnO	0.17	0.33	0.25
FeO	1.16	1.07	1.12
UO_2	78.60	88.26	83.43
* Ce_2O_3	0.46	0.23	0.35
* Nd_2O_3	0.43	0.20	0.32
	(95.67)	(95.73)	(95.70)

	25	26
Si	0.94	0.44
Al	0.04	0.05
Total	0.98	0.49
U	0.96	1.21
Na	0.09	0.13
Mg	0.02	0.03
Ca	0.02	0.12
Mn	0.01	0.02
Fe	0.05	0.06
Ce	0.01	0.01
Nd	0.01	0.01
Total	1.17	1.59

All analyses recalculated to 100 percent with the original totals shown in parentheses. The differences between these and 100% were assumed to be H_2O for the purposes of calculating corrections.

* these results are qualitative only as there are severe, uncorrected overlap problems between the rare earth elements when in low concentrations (Smith and Reed, 1981).

Representative Energy Dispersive spectrum of Coffinite

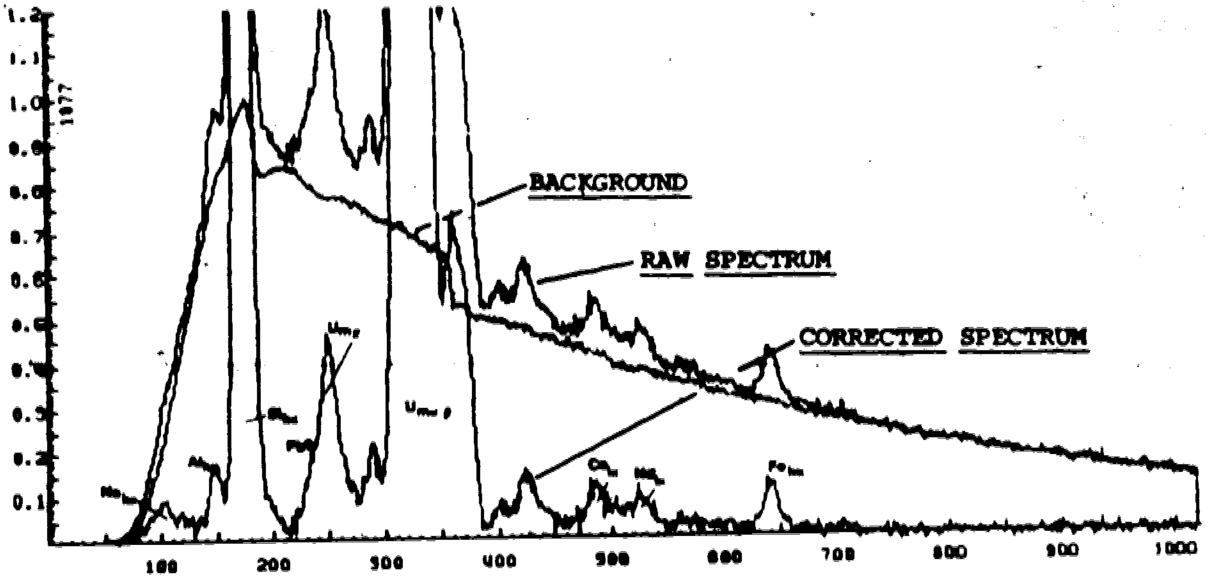
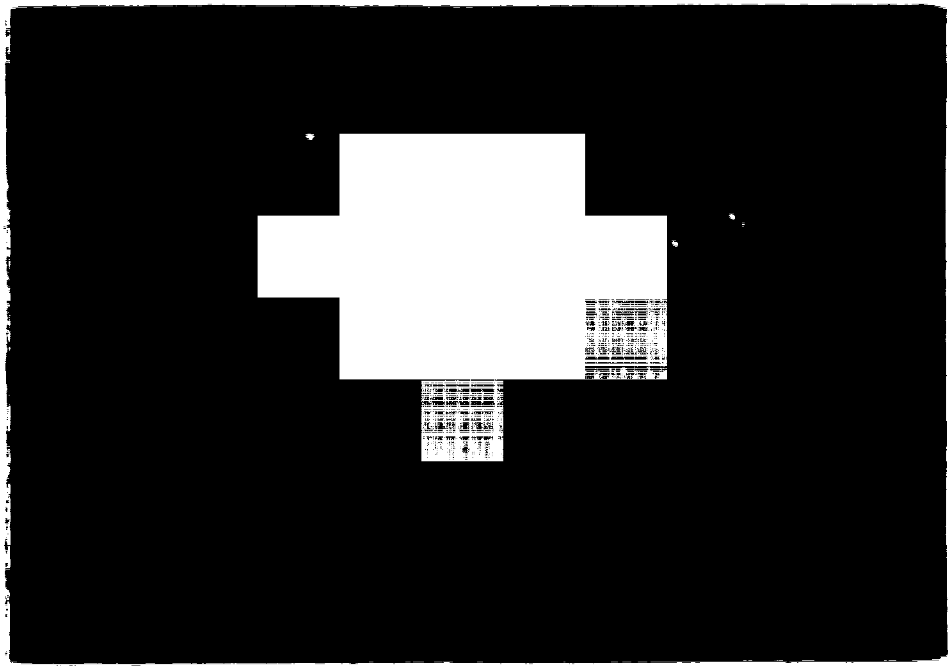
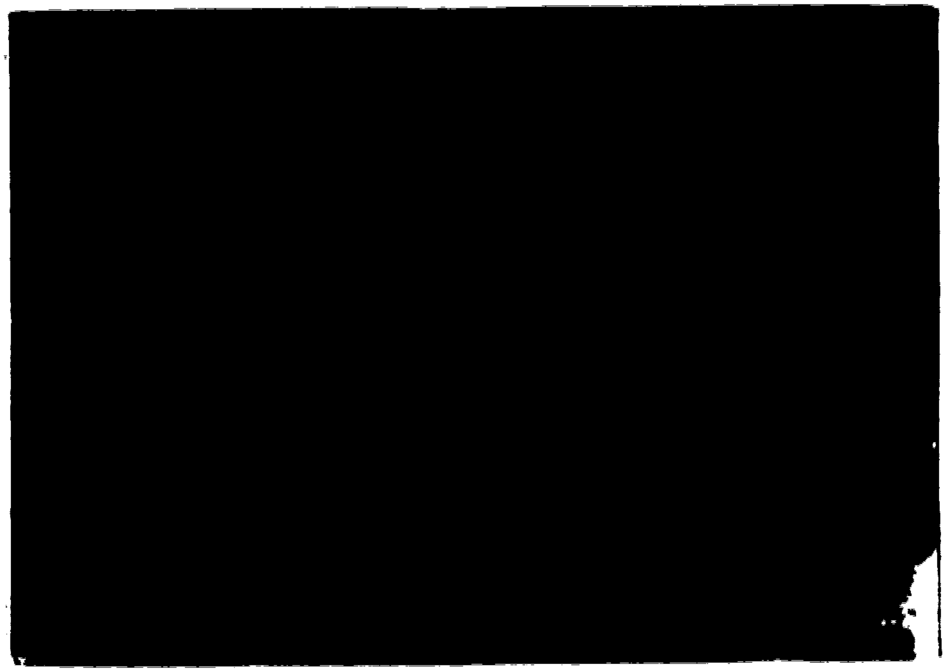


Plate 2 Coffinite (medium grey and massive) containing grains of exsolved galena (white) and cut by a thin veinlet of hematized quartz (orange). This area is similar to that reported in Table 5.
(oil immersion, PP reflected light)

Plate 3 Coffinite (black) surrounded by hematized quartz (orange). Coffinite often forms euhedral crystals as are seen in this photomicrograph.
(oil immersion, XN reflected light)



100 μm



100 μm

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Occurrences and formation of coffinite have been studied by a number of workers. Bayushkin and Dikov (1974) interpreted previously published paragenetic associations to conclude that coffinite forms under "metasomatic hydrothermal" reducing conditions in a high sodium, strongly alkaline environment. This coffinite is metastable and finally breaks down into "oxide-silicate uranium ores". This environment is consistent with the high albite content of the vein and the high pH deformation induced muscovite alterations described by Wintsch (1975) and summarised in Chapter IV.

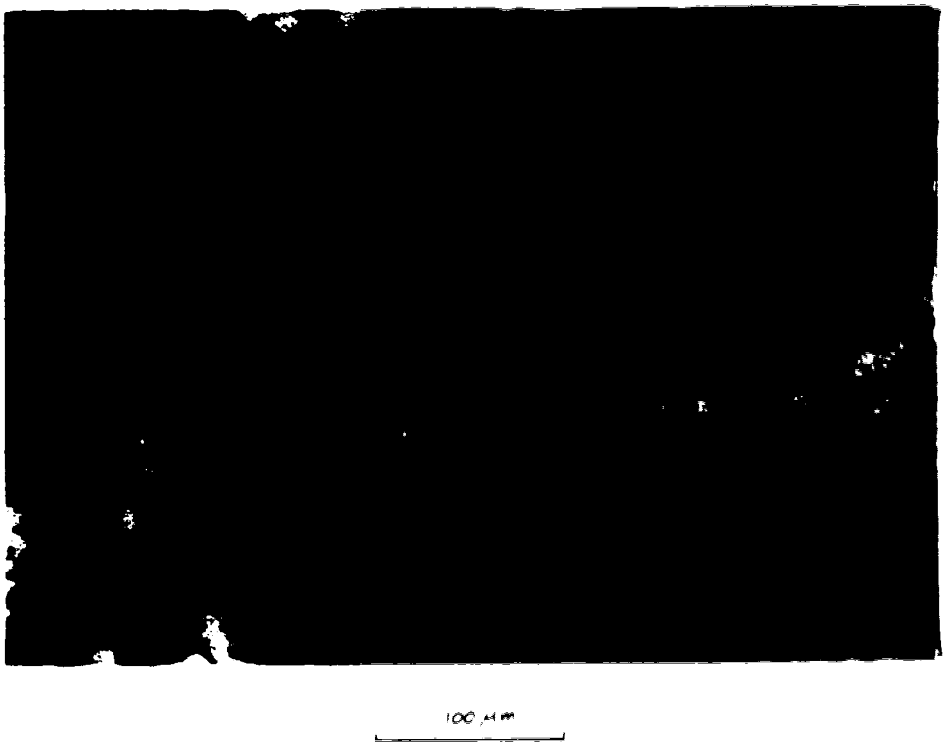
Coffinite is a common mineral in uranium deposits. It is frequently reported from the sandstone-hosted variety (Steacy and Kaiman, 1978) as well as from a number of uranium deposits in northern Saskatchewan. Hoeve (1978) reports coffinite occurrences at the Key Lake, West Bear, Collins Bay and Cluff Lake deposits. Rimsaite (1977) describes lead-deficient secondary coffinite from the uranium mine at Rabitt Lake, Saskatchewan.

A brannerite-like mineral

The most common occurrence of uranium observed in this study has similar chemical and physical properties to published accounts of brannerite although the calculated structural formulae do not conform to previously established models. For these reasons the mineral is identified as brannerite-like. It is not visible in hand specimen and in thin section occurs as an opaque to semi-transparent mineral that is found, often in calcite or chlorite, as masses of discrete needle or diamond-shaped euhedra, usually less than 100 micrometers long. It is also associated with anatase in thin veinlets where it forms irregular amorphous masses. The possibility of intergrowths with other uranium phases in these thin veinlets cannot be overlooked. However, there is a compositional consistency between the isolated,discrete 'brannerite' and that from veinlets, suggesting that, if they are intermixed phases, their compositions do not widely differ. In transmitted light the transparent varieties are brown to red-brown have high relief and apparently high birefringence although it is usually obscured by strong internal reflections. In reflected light, both the opaque and semi-transparent phases are medium grey and have medium reflectance in plane polarized light and show distinctive clove brown internal reflections under crossed-nicols. Occasional mottled grey varieties and phases showing blue-white internal reflections are observed. Some locations have white to

Plate 4 Acicular and diamond shaped euhedral crystals of 'brannerite' occuring as inclusions in quartz.
(oil immersion, PP transmitted light)

Plate 5 As Pl.4, showing the medium grey reflactance of some of the 'brannerite'.
(oil immersion, PP reflected light)



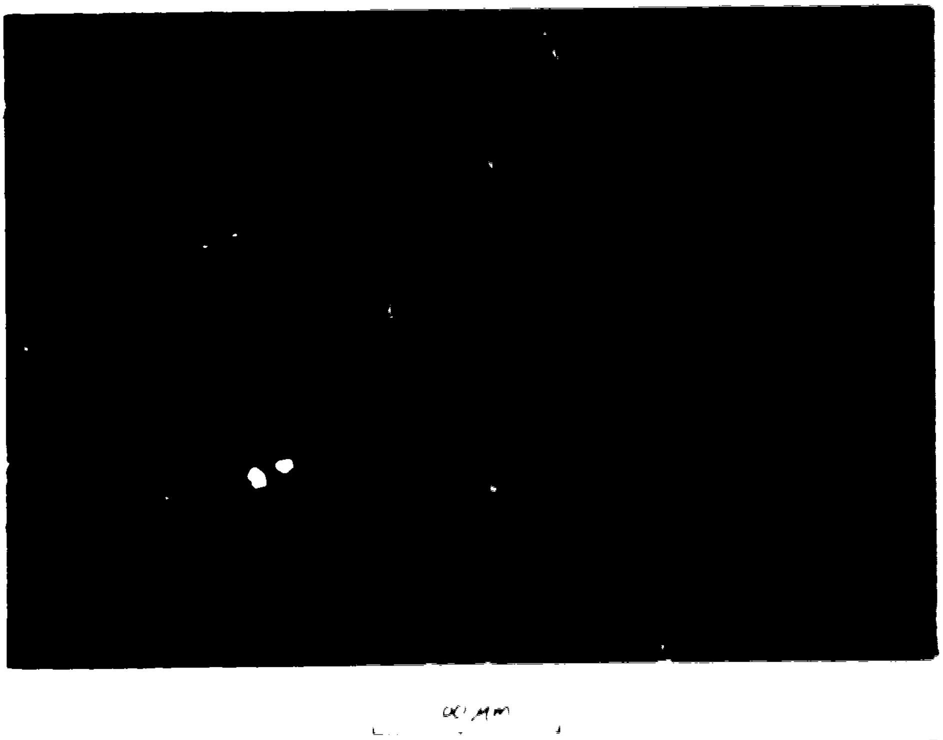


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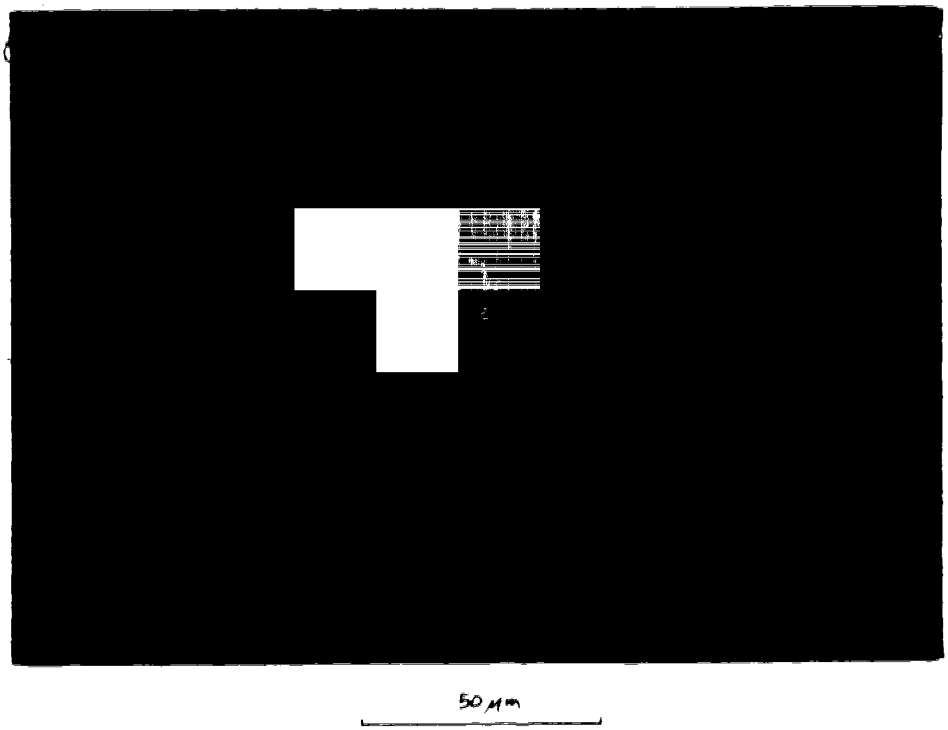
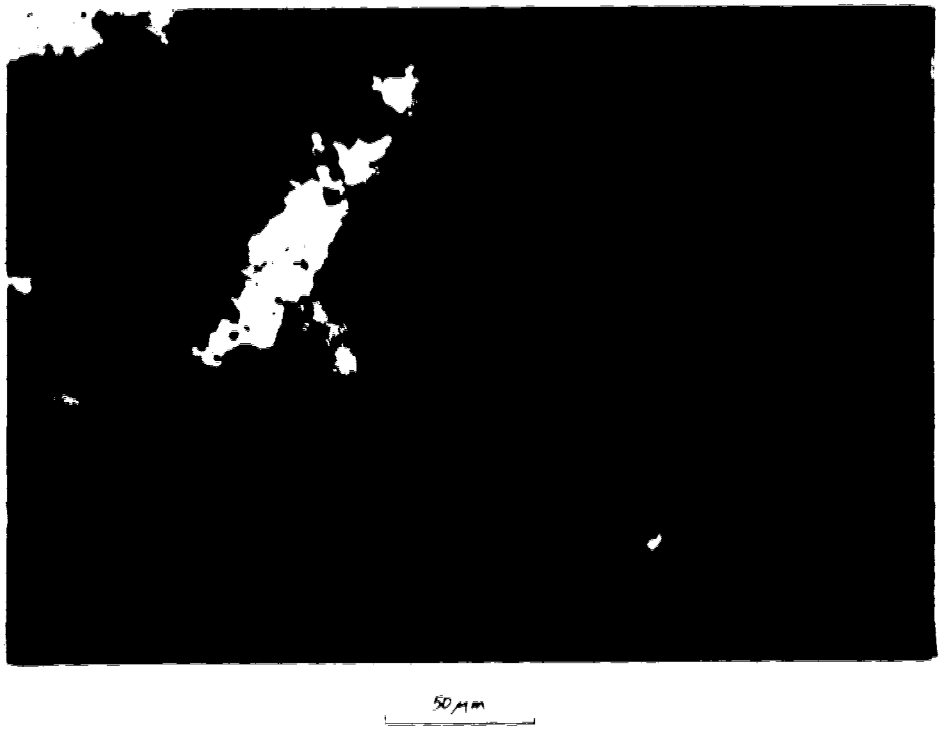
Plate 6 'Brannerite' (medium grey-brown) quartz and hematized quartz. This is typical of most of the 'brannerite' seen in the ore samples.
(oil immersion, PP reflected light)

Plate 7 Bertrandite occurring with galena (opaque) and albite (grey). There is no detectable compositional variation across this grain. Zoning such as this is a rare feature.
(in air, XN transmitted light)





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yellow-brown internal reflections and are semi-transparent and medium brown in transmitted light. Ramdhor (1969) reports that strong yellow-brown internal reflections may occur in brannerite due to the presence of titanium minerals.

Published descriptions of brannerite suggest varied physical properties, probably related to the equally varied chemistry. Ramdhor observes that brannerite has blue grey, blue-white or dark brown internal reflections and almost always contains small laths of exsolved anatase.' Steacy and Kaiman (1978) describe macroscopic brannerite crystals as prismatic and generally wedge-shaped, resembling sphene. Brannerite at Witswatersrand, South Africa, is described forming microscopic felted nests of columnar or needle-shaped crystals (Schidlowski, 1966). Photographs of this brannerite have a strong resemblance to the networks of needles in chlorite and calcite from 29th Level. Koeppel (1967) includes photographs of 'brannerite' intergrown with pitchblende and hematite from the 24th level of the Fay Mine which are also very similar in appearance to the brannerite-like mineral from the study area.

The quantitative electron microprobe analyses of several brannerite-like minerals are shown in Table 6. A total of eleven separate analyses were made but contamination by chlorite and/or hematite resulted in the rejection of seven. The results are reported as weight percent of dry oxides to compensate for the loss of water during analysis. Initial results indicate a probable water content of ten to fifteen percent. Uranium oxide is reported as tetravalent uranium (UO_2) and varies from 30.0 to 60.7 percent. The other significant oxides, occurring in amounts greater than one weight percent in the average of the analyses are, in descending order, TiO_2, SiO_2, CaO, FeO and Al_2O_3. Published analyses of brannerite, for comparitive purposes, are shown in Table 7.

The structural formula of the brannerite-like mineral is expressed in terms of the Ramdhor (1969) model AB_2O_6 where A is U and Ca and B is Ti, Fe and Si. The minor elements, which do not usually constitute a significant proportion of the total, are placed in the B site to conform with Frenzel *et al.* (1975). None of the analyses satisfy the structural model and the average structural formula is $A_{1.05}B_{2.46}O_6$. This discrepancy suggests that the mineral is not the brannerite defined by Ramdhor. However, converting the structural formula to that of Theis (1976) results in a average of $A_{2.80}B_{6.15}O_{16}$ instead of the ideal of $A_3B_5O_{16}$.

TABLE 6: Electron microprobe analyses of a brannerite-like mineral, expressed dry oxide weight percent and as structural formulae based on a 6 oxygen anhydrous unit cell. See Appendix 3 for sample descriptions.

SAMPLE NUMBER	21	22	23	24	Avg.
Na_2O	0.45	0.62	0.54	0.52	0.53
MgO	0.76	2.05	0.29	0.53	0.91
Al_2O_3	1.12	2.04	1.05	0.95	1.29
SiO_2	6.66	10.78	10.53	14.40	10.59
K_2O	0.30	0.50	1.04	0.38	0.56
CaO	12.31	9.34	6.21	8.22	9.02
TiO_2	38.51	35.59	15.23	42.04	32.84
V_2O_5	0.31	1.69	0.96	0.0	0.74
MnO	0.45	0.67	0.13	0.23	0.37
FeO	3.70	6.63	3.30	3.87	4.38
UO_2	35.33	30.00	60.74	28.87	38.71
	(88.85)	(85.31)	(89.88)	(84.58)	(87.22)

	21	22	23	24
U	0.44	0.34	0.95	0.32
Ca	0.73	0.52	0.47	0.44
Total	1.17	0.86	1.42	0.76
Ti	1.61	1.40	0.80	1.58
Fe	0.17	0.29	0.19	0.16
Si	0.37	0.56	0.74	0.72
Na	0.05	0.06	0.07	0.05
Mg	0.06	0.16	0.03	0.04
Al	0.07	0.13	0.09	0.08
K	0.02	0.03	0.09	0.02
V	0.01	0.06	0.04	--
Mn	0.02	0.03	0.01	0.01
Total	2.38	2.72	2.06	2.64

Average Structural Formula: $A_{1.05}B_{2.45}O_6$

All analyses are recalculated to 100 percent with original totals shown in parentheses. The differences between these totals and 100% were assumed to be H_2O for the purposes of calculating corrections. The small amounts of K_2O indicated may be due to imperfect correction for the severe overlap of the U peaks.

Representative Energy Dispersive spectrum of Brannerite

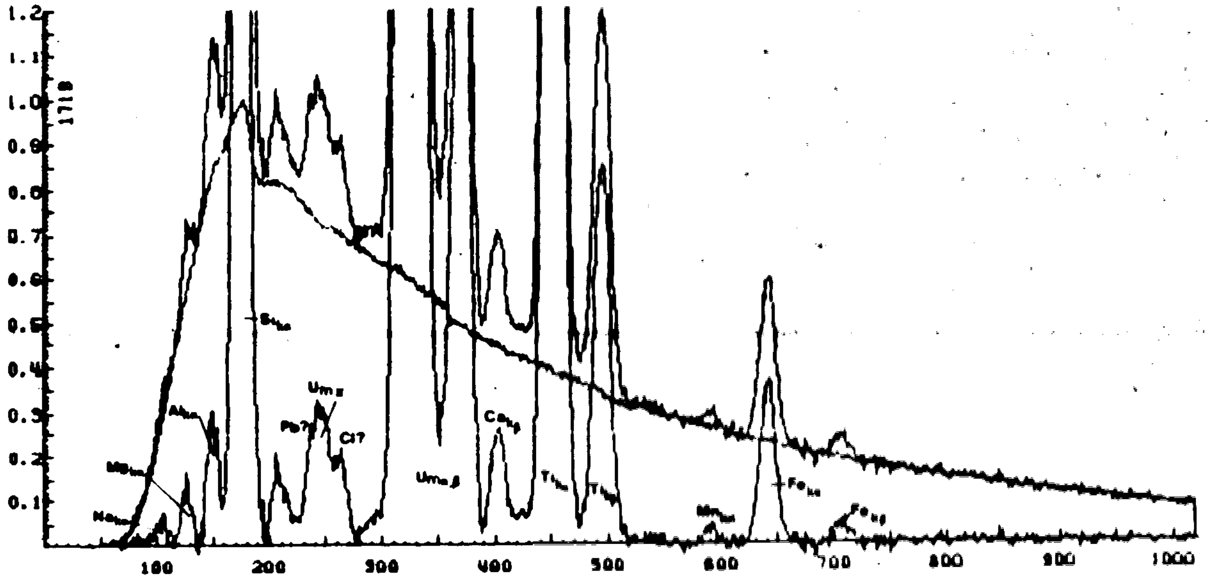


TABLE 7: Published analyses of brannerite and coffinite, in oxide weight percent.

	A	B	C	D	E	F	G	H	I	J	K
Na_2O											
MgO								0.2			
Al_2O_3		1.1	4.5		3.9	6.8	10.1	1.7	0.6	0.9	4.9
SiO_2		3.0	7.0	18.2	5.2	7.4	8.5	16.7	5.1	4.9	11.2
K_2O											
CaO	2.7	2.5	1.7				2.0	1.3	5.0	5.5	3.5
TiO_2	35.0	38.0	28.3						35.6	35.3	27.6
V_2O_5					2.8	18.9	3.2		1.7	1.0	0.8
MnO											
FeO	1.7	2.6	1.8		1.2	1.6	4.4		2.3	3.9	7.6
UO_2	61.7	54.1	57.3	81.8	68.3	46.4	58.6	75.8	44.2	39.7	40.0
As_2O_5					4.4	1.4	1.2				
P_2O_5						2.7					
PbO									3.8	1.6	2.8

A–C	Brannerite	(Frenzal, *et al.*, 1975)
D–G	Coffinite	(Stieff, *et al.*, 1956)
H	Coffinite	(Rimsaite, 1977)
I–K	Brannerite	(Scott, 1979)

These results indicate that more detailed determinitive mineralogy would be required to fully characterize this mineral. Unfortunately, the extremely fine grain size and the intimate intermixing of other mineral phases would hamper extraction of clean samples and the usually metamict nature of the crystal lattice would negate the effectiveness of x-ray diffraction analyses. X-ray scanning could help sort out the finely intermixed phases.

Brannerite is a mineral found at many uranium deposits and it appears to occur in most geological environments. The most common localities are in the modified-placer Archean conglomerate deposits such as at Blind River, Ontario (Theis, 1976) and the Witwatersrand Reefs, South Africa (Feather and Snegg, 1978). Ramdhor (1969) thinks that the Blind River-type brannerite is detrital while others (Ferris and Ruud, 1971) believe that it is derived from the alteration of detrital Fe-Ti grains in the presence of uraniferous solutions. These findings may be significant to the genesis of the brannerite-like minerals examined in this study and discussed in detail in a later section. Brannerite is not commonly observed in the uranium deposists of northern Saskatchewan, although it has been described in the Fay Mine (Koeppel, 1967) and the Foster Lake showings (Steacy and Kaiman, 1978).

Muscovite (*Roscoelite* $KV_2(AlSi_3O_{10})(OH)_2$)

Roscoelite *is* a vanadium mica that is found in one sample of 29th Level ore. It has a distinctive yellow-brown to clove-brown pleochroism and occurs in masses up to 50 micrometers wide intergrown with chlorite and calcite. Muscovite was not observed in association with roscoelite. The mineral was examined by quantitative energy-dispersive microprobe analysis and the chemical composition and structural formula are reported in Table 8.

The chemical composition is consistent with those in Deer, *et al.* (1966) who state that roscoelite can contain up to 17 percent V_2O_3, replacing Al_2O_3 in the octahedral sites. The structural formula is based on their model $X_2Y_{4-6}Z_8O_{20}(OH)_4$, where X is the inter-layer cation site (K,Na,Ca), Y is the octahedral site (Al,V,Fe,Ti,Mg,Mn) and Z is the tetrahedral site (Si,Al). The results, shown on Table 8, produce a best structural formula of $X_{1.97}Y_{3.58}Z_{7.88}O_{20}(OH)_4$.

This is the first reported occurrence of roscoelitie in Northern Saskatchewan and, possibly, the first in Canada. It is reported from the United States where it was

TABLE 8: Electron microprobe analyses of roscoelite expressed as dry weight percent and structural formulae based on a 22 oxygen anhydrous unit cell equivalent to $O_{20}(OH)_4$. See Appendix 3 for sample descriptions.

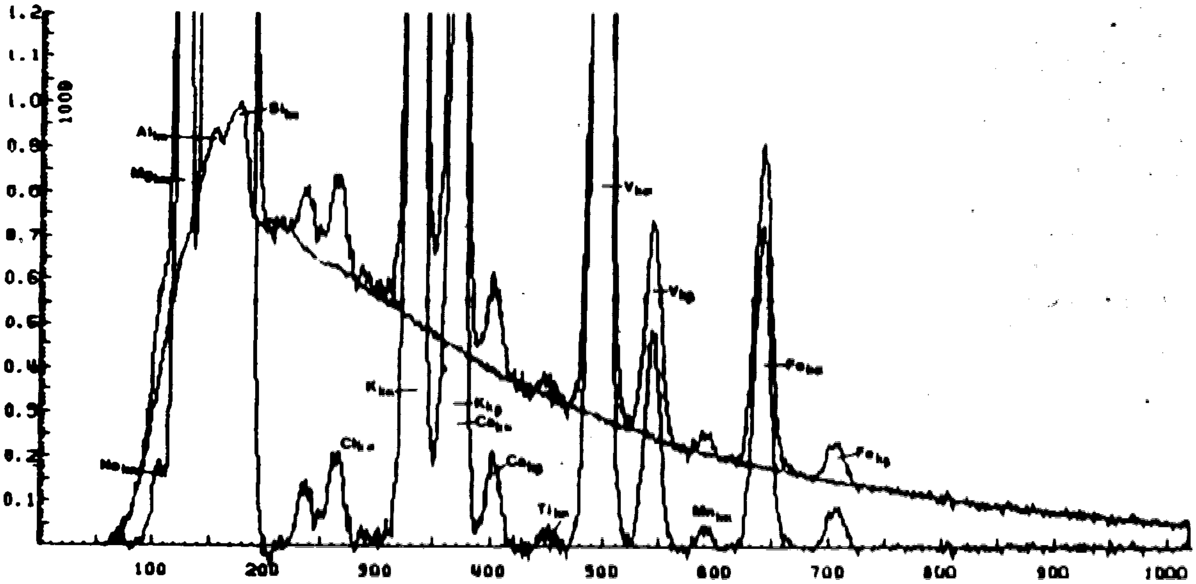
	27	28	29
Na_2O	6.3	1.1	0.5
MgO	4.7	6.9	6.9
Al_2O_3	15.4	12.0	11.0
SiO_2	55.5	45.1	43.1
K_2O	3.8	7.1	7.0
CaO	0.6	3.6	4.2
TiO_2	—	0.1	0.1
V_2O_5	10.1	19.2	21.6
MnO	0.2	0.2	0.2
FeO	3.3	4.7	4.9
	(89.14)	(89.56)	(93.77)

	27	28	29
Na	1.53	0.28	0.13
K	0.62	1.19	1.02
Ca	0.08	0.51	0.33
Total	2.23	1.98	1.48
Mg	0.89	1.35	1.36
Ti	—	0.01	0.01
V	0.85	1.67	1.89
Mn	0.02	0.02	0.02
Fe	0.35	0.52	0.55
Al^{VI}	1.31	--	2.94
Total	3.42	3.57	6.77
Al^{IV}	0.98	1.86	2.26
Si	7.02	5.94	5.74
Total	8.00	7.80	8.00

Average Structural Formula: $X_{1.80}Y_{4.59}Z_{7.93}O_{20}(OH)_4$

All analyses recalculated to 100 percent with original totals shown in parentheses. The differences between these totals and 100% were assumed to be H_2O for the purposes of calculating corrections.

Representative Energy Dispersive spectrum of Roscoelite



determined by X-ray studies and chemical analyses in sandstone-hosted uranium-vanadium deposits at Placerville, Colorado (Foster, 1959). At Moumana, Gabon it is associated with uraninite, coffinite and vanadium minerals in a 'reduced' ore zone in Helikian aged (1750 Ma) sandstone, pelite and conglomerate (Cesbron and Bariand, 1975).

Bertrandite $Be_4Si_2O_7(OH)_2$

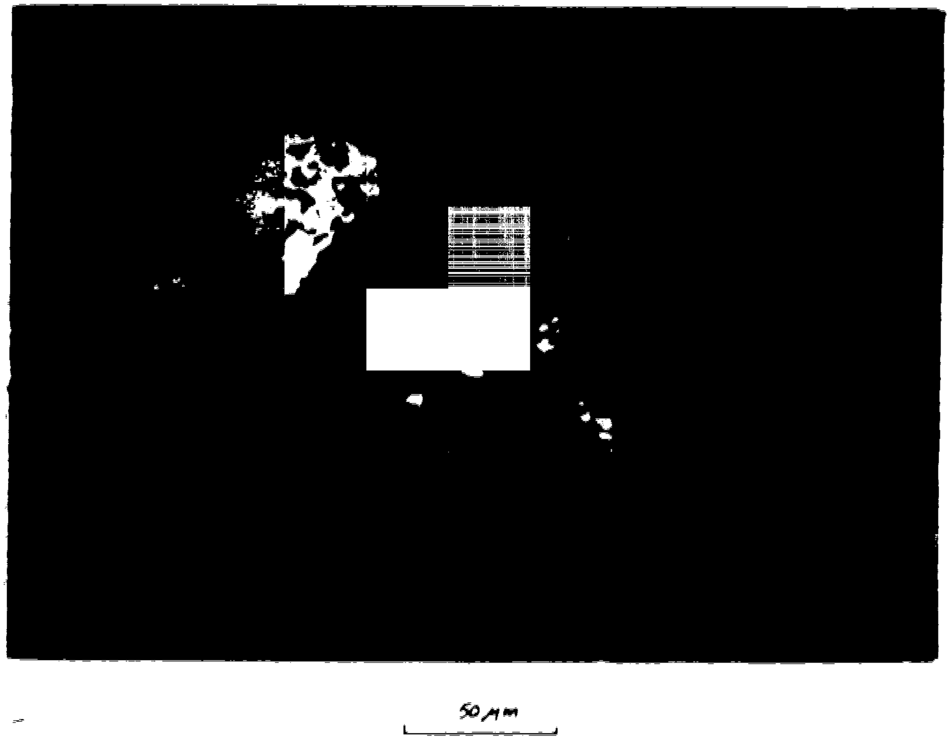
Bertrandite was first observed associated with lead mineralization in a pitchblende vein from 26th Level, Fay Winze and has since been observed in many of the 29th Level samples used in this study. On 29th Level it is typically associated with specular hematite, albite, 'brannerite' and chlorite. It usually occurs as slightly elongated prismatic crystals with high relief and a typically 'pitted' surface appearance. The crystals are colorless with a moderate to high birefrigence, have three good cleavages and often form characteristic 'knee-twins'. Zoning and fluid inclusions are seen in the 26th Level bertrandites but not on 29th Level. A dark blue cathodoluminescence accompanied by an energy dispersive spectrum showing only silica is characteristic of this mineral under the microprobe beam. Grains separated from the 26th Level sample were insufficient for X-ray diffraction analysis. A qualitative sample of this ore, however, returned significant amounts of beryllium in geochemical analysis. Bertrandite appears to form early in the petrogenetic sequence and is little altered by later events, although partial replacement and corrosion by fluids rich in TiO_2 and Fe_2O_3 is seen in one sample.

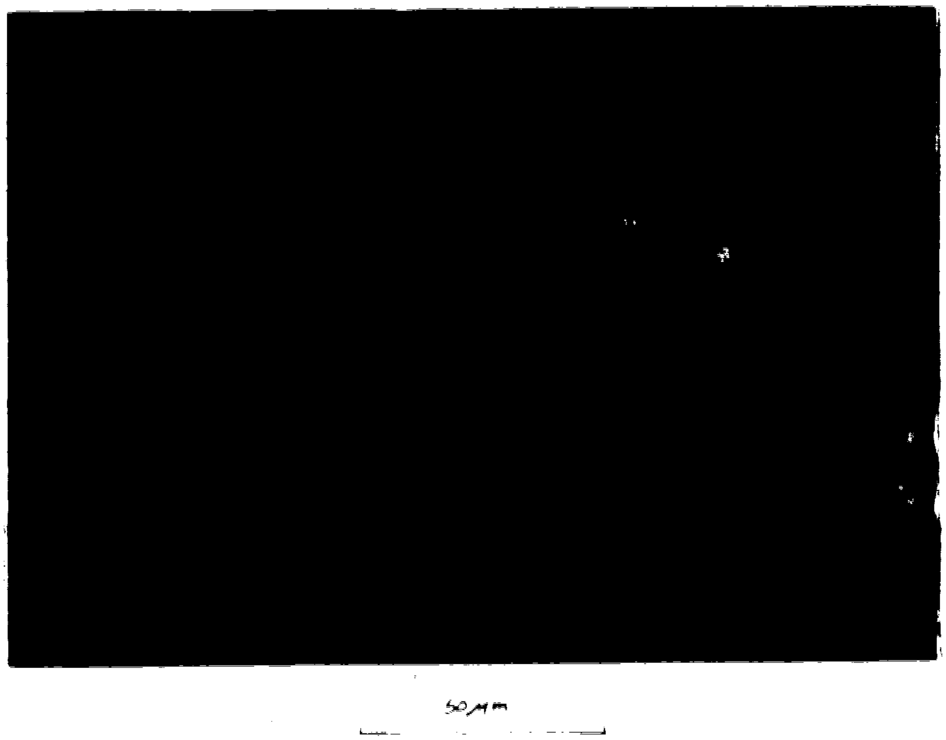
Quantitative energy dispersive microprobe analyses of two samples from 29th Level and wavelength dispersive analyses of several from 26th Level have returned silicon values of 20.8 percent, which is slightly lower than the ideal of 23.6 percent. Substituting Be and $(OH)^-$ into the formula in stoichiometric amounts relative to Si results in totals of around 95 percent. If one H_2O molecule is included in the formula, resulting in $Be_4Si_2O_7(OH)_2 \cdot H_2O$, the totals are very close to 100 percent, (S. Launspach, pers. comm.). This formula is not reported in the literature and may not be structurally feasible. Other elements detected in the energy dispersive analysis were Mg, Al, Ca, Fe and U, all in amounts less than one percent. These are probably due to observed microfracture fillings and inclusions and are not thought to be part of the lattice.

This is the first reported occurrence of bertrandite from northern Saskatchewan, although composite samples of Ace-Fay mineralization reported by Beck (1969) returned

Plate 8 Bertrandite (yellow, white, dark grey) occurring with 'brannerite' (dark brown, opaque) and calcite (light blue). The inclusions within these grains are thought to have contributed the impurities discussed in the text. This is typical of the bertrandite observed in the ore-zone. (in air, XN transmitted light)

Plate 9 Specular hematite containing titanium and vanadium (blue-white) surrounded by the 'brannerite' (medium brown) and hematized quartz (orange) with minor anatase (white). (oil immersion, PP reflected light)





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10 ppm Be. Other Canadian occurrences of bertrandite are confined to pegmatites. The only reported occurrence of bertrandite associated with uranium is at Spor Mountain, Utah in Paleozoic tuffs (Williams, 1963). The presence of beryllium in other mineral phases from the Fay Winze samples was not investigated. The texture and occurrence of the mineralization prohibits the separation of clean phases for regular chemical analysis and the light atomic weight of beryllium prohibits its detection by electron microprobe analysis.

Chlorite (Diabantite)

The chlorites analysed in this study are all associated with uranium mineralization. They are weakly pleochroic and medium to dark green with low birefringence and anomalous blue and brown interference colors. They occur as vein fillings and masses and are usually intergrown with all of the mineral phases present in the ore zone, which resulted in the rejection of several analyses due to suspected contamination.

The results of the remaining chlorite analyses are shown with the calculated structural formula in Table 9. Minor elements in the chlorites include Na, K, Ca, Ti, V and Mn, which are all assumed to reside in the octahedral lattice sites with Mg, Fe and Al. The values of the minor elements are mostly higher than those reported in Deer, *et al.* (1966) although the major oxide concentrations are all similar. Sodium and potassium are probably not part of the chlorite lattice and may relect the presence of contaminants. However, as they are reported in the chlorite analyses and structural formulae of Deer *et al.* (1966) they are left in these results and are treated in a similar manner in the calculation of the structural formulae.

The structural formula for chlorite is based on the model $Y_{12}Z_8O_{20}(OH)_{16}$ from Deer, *et al.* (1966) where Y is the octahedral site (Mg, Al), Fe, K, Ca, C, Mn) and X is the tetrahedral site (Si and Al. The best analysis returned from the 29th Level analysis results in a calculated structural formula of $Y_{12.00}Z_{8.00}O_{20}(OH)_{16}$.

The sample results are plotted on a chlorite nomenclature diagram (Fig. 8) to aid comparisons with previous studies from the Beaverlodge area. These are, based on optical properties, usually reported as penninite (Tremblay, 1972; Sassano, 1972) although ripidolite and clinochlore have also been determined by energy-dispersive microprobe analysis (Scott, 1979). The 29th Level chlorites reported here plot in the

TABLE 9: Electron microprobe analyses of chlorite expressed as dry oxide weight percent and as a 28 oxygen anhydrous unit cell equivalent to $O_{20}(OH)_{16}$. See Appendix 3 for sample descriptions.

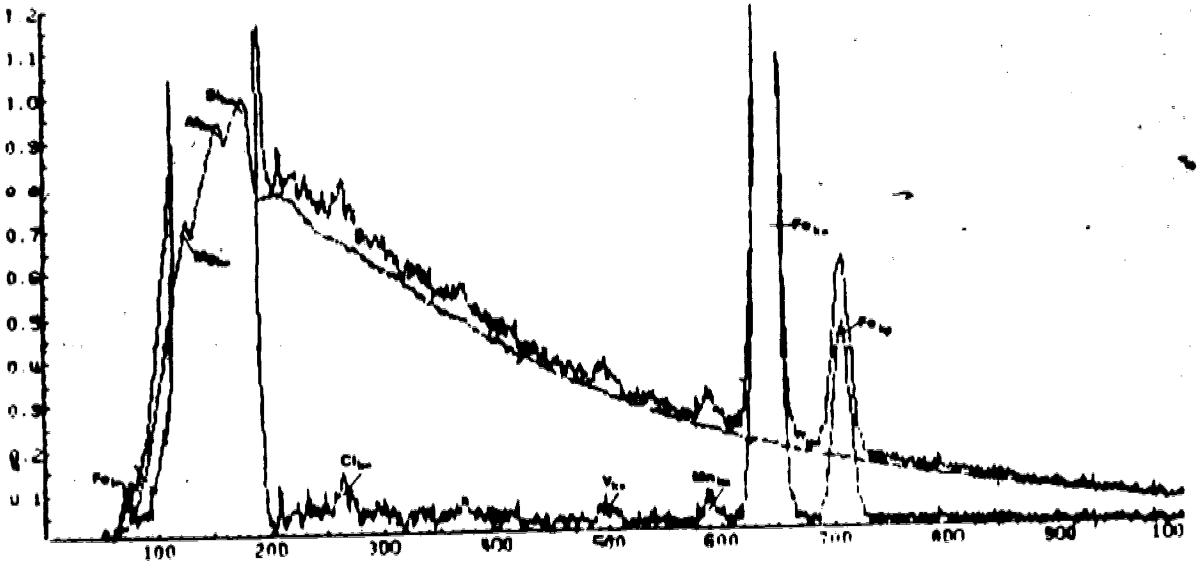
SAMPLE NUMBER	30	31	32	33	34	35
Na_2O	0.12	0.12	0.0	0.22	0.0	0.0
MgO	22.31	18.24	24.63	23.84	29.32	27.98
Al_2O_3	17.86	21.15	20.11	17.09	15.99	15.77
SiO_2	40.05	36.92	34.26	35.87	35.98	36.72
K_2O	0.11	0.11	0.11	0.0	0.09	0.09
CaO	0.20	0.63	0.16	1.29	1.58	1.40
TiO_2	0.18	0.17	0.0	0.0	0.0	0.0
V_2O_5	0.41	0.32	0.29	0.24	0.33	0.41
MnO	0.25	0.35	0.35	0.67	0.53	0.52
FeO	18.50	21.98	20.08	20.78	16.19	17.38
	(85.74)	(82.29)	(83.42)	(80.80)	(81.43)	(82.35)

	30	31	32	33	34	35
Si	6.92	6.51	6.05	6.38	6.29	6.34
Al^{IV}	1.08	1.49	1.95	1.62	1.71	1.66
Total	8.00	8.00	8.00	8.00	8.00	8.00
Al^{VI}	2.56	2.91	2.23	1.96	1.58	1.64
Fe	2.67	3.24	2.97	3.09	2.37	2.58
Mg	5.75	4.80	6.48	6.32	7.64	7.38
Na	.04	.04	--	.07	--	--
K	.03	.03	.02	—	.02	.02
Ca	.04	.12	.03	.24	.30	.26
Ti	.02	.02	—	—	--	--
V	.05	.04	.03	.03	.04	.04
Mn	.04	.05	.05	.10	.08	.08
Total	11.20	11.25	11.81	11.81	12.03	12.00

Average Structural Formula: $Y_{11.68}Z_{8.00}O_{20}(OH)_{16}$

All analyses recalculated to 100 percent with the original totals shown in parentheses. The differences between these totals and 100% were assumed to be H_2O for the purposes of calculating corrections.

Representative Energy Dispersive spectrum of Chlorite



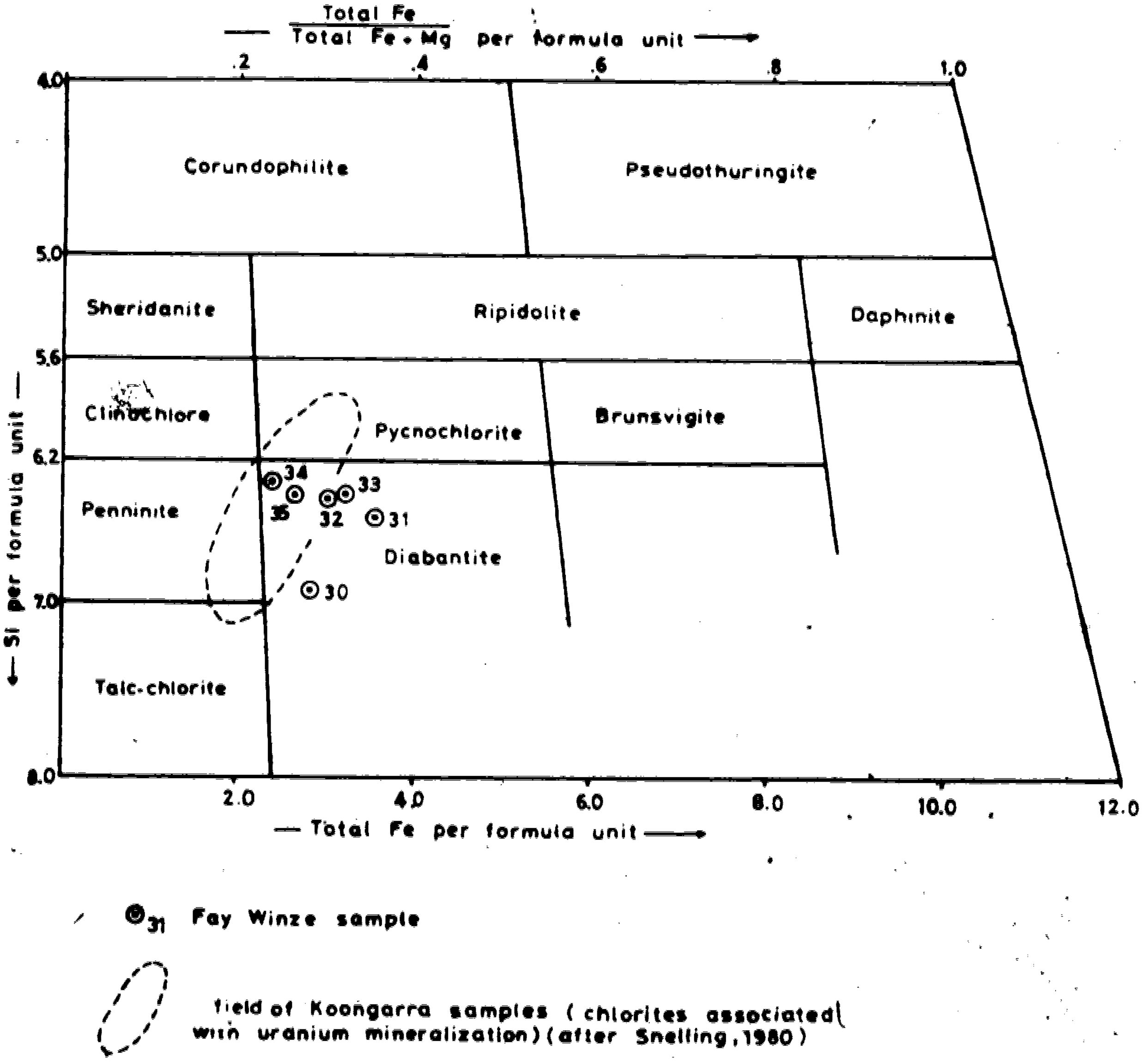


Figure 8 Composition of ore zone chlorite from the Fay Winze mine and a comparison with chlorite from the Koongarra uranium deposit, Australia.

diabantite field, indicating a slightly higher Fe content than penninite and clinochlore and more Si than ripidolite. A comparison with uranium-associated chlorite from the Koongarra deposit, northern Australia (Snelling, 1980) is shown on Fig. 8. There is a strong similarity in composition, suggesting that there were similar chemical environments, particularly with respect to Fe, in the ore zones at the time of chlorite formation.

Interesting elements seen in the microprobe studies of the chlorites are vanadium and uranium. The vanadium is assumed to be substituting for Al in the octahedral lattice sites. Vanadium chlorites are not reported in the literature although a chlorite equivalent of the vanadium mica (roscoelite) could be expected. Uranium is present in several analyses although follow-up examination did not detect any obvious uranium minerals. This uranium is thought to be adsorbed onto plate edges and cleavage fractures as described by Gavshin (1972) and Dostal, *et al.* (1978) and not part of the chlorite lattice. It has therefore been deleted from the analytical results to avoid interference in the calculation of the structural formulae. Initial results with greater than one weight percent U_3O_8 were not used.

Hematite

Quanitative energy dispersive microprobe analysis was performed on two areas of bladed specular hematite, one associated with calcite, bertrandite and pale green chlorite and the other with chlorite only. The results and calculation of structural formulae are shown in Table 10. The best structural formula from these analyses is $(Fe,Ti,V)_{1.95}O_3$.

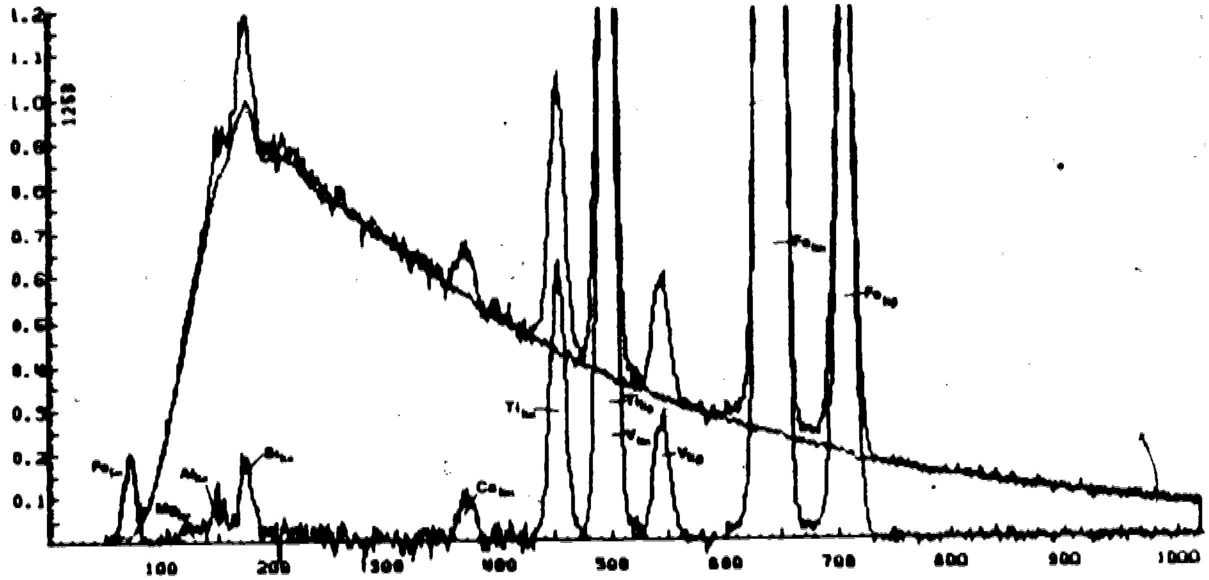
Vanadiferous hematite has been reported elsewhere in the Fay Mine (Scott, pers. comm.). This hematite is always primary and usually occurs as radiating clusters displaying typical reflectance and anisotropism. A later phase of hematite, containing no vanadium or titanium, occurs as fine-grained dusting causing red coloration in wall rocks and early vein minerals. This hematization is most intense within 50 to 100 micrometers of the veinlets although hematite staining is common in wall rocks throughout the ore zone.

TABLE 10: Electron microprobe analyses of hematite from 29th Level expressed as weight percent and structural formulae based on a 3 oxygen unit cell. See Appendix 3 for sample descriptions.

SAMPLE NUMBER	36	37
Fe_2O_3	88.10	90.73
TiO_2	2.58	3.40
V_2O_5	10.77	2.44
Total	(101.45)	(96.57)

	36	37
Fe	1.62	1.84
Ti	0.05	0.07
V	0.17	0.04

Representative Energy Dispersive spectrum of V-Ti Hematite



Feldspar

The feldspars seen in the ore veins are determined by qualitative microprobe analysis to be albite (An=0). They are usually euhedral, often twinned and frequently display bright orange internal reflections from fine inclusions of hematite. Albite in one sample is corroded with partial replacement by anatase and by chlorite. Albite also occurs, along with plagioclase and microcline, in the wall rocks surrounding the veinlets. Porphyroblasts in the wall rocks are usually partly sericitized, unstrained microcline.

Sulfides

The sulfides observed in these veins are galena and, rarely, chalcopyrite and sphalerite. The latter two both occur in separate areas of bladed specular hematite. Both were detected by qualitative microprobe analysis although neither was observed under the microscope.

Galena is the only lead mineral seen in this study although clausthalite is common elsewhere in the mine. The galena typically occurs as a small exsolved blebs within the brannerite and coffinite and, in one sample, as thin veinlets cutting a quartz-feldspar vein. Small 10 micrometer euhedral crystals of galena are occasionally seen within chlorite and calcite. It is also disseminated through hematized albite and occurs surrounded by rims of specular hematite.

U-Pb Geochronology

A U-Pb geochronological study was performed on some of the 29th Level samples described previously in this chapter. The purpose was to determine what phase of mineralization (Koeppel, 1967) is represented by this ore zone. The samples were all strongly discordant and failed to plot in a linear fashion. Little useful information is obtainable from this study.

The samples were 'mined' from radioactive areas in the hand specimens (chosen using radioluxography) that were the same or close to areas chosen for petrological examination. Prior to sample preparation for mass spectrometric analysis, the composition of the samples was checked using energy dispersive microprobe analysis. All of the samples appeared to be of similar composition to the brannerite-like phase discussed in the previous section.

The samples underwent routine preparation for isotope dilution analysis on a solid source mass spectrometer. Weighed amounts of sample were dissolved in concentrated ultrapure HNO_3, in teflon beakers. After evaporation and dissolution in distilled H_2O, the samples were separated into measured aliquots. Known amounts of ^{208}Pb and ^{235}U spike were added to aliquots for the measurement of U and Pb concentrations. The amount of spike to be added was estimated by assuming an age of 1750 Ma for the mineralization, which proved to be an overestimation in most cases, resulting in too much spike being added. One sample (40) was used for the determination of ^{232}Th content and was spiked accordingly.

The Pb isotope ratio and isotope dilution aliquots were passed through chloride anion-exchange columns to remove the Pb and the U for isotope dilution was removed by passing the aliquots through nitrate anion-exchange columns. The samples were loaded onto rhenium filaments, dried under heat lamps and outgassed at red heat in air.

The samples were run on a 12-inch, 90° sector, single focusing solid source mass spectrometer with facilities for peak switching at pre-set magnet currents. After stabilization, the Pb isotopic compositions were determined on ten separate 'runs' for each sample. Unstable runs were rejected prior to data reduction. Pb isotope ratio and U isotope composition runs were treated in the same manner.

The results of the isotope analysis are shown in Table 11 and plotted on a concordia diagram (Fig. 9). The samples are strongly discordant and fail to plot in a linear fashion, producing what is referred to as a 'scatterchron' (H. Baadsgaard, pers. comm.). It is unlikely that much, if any, usable information can be derived from such a plot. The type of discordance and the factors producing the scatter of points is discussed below.

The type of discordance displayed on Fig. 9 and the distribution of the apparent ages in relation to the various ratios (Table 11) indicates either a loss of radiogenic Pb or a gain in U during the history of these samples. (Koeppel, 1967). Loss of Pb is the probable reason since it is not stable in the lattice of the uranium mineral and is generally highly mobile. Any of the events discussed in the section on genetic models could provide an adequate mechanism for this remobilization. Koeppel (1967) postulates a major period of lead loss at about 1100 Ma for Fay Mine samples.

TABLE 11: Isotopic compositions of Pb and U and apparent ages of Brannerites from 29th Level, Fay Winze Mine.

	ISOTOPIC COMPOSITIONS (ppm)				APPARENT AGES (Ma)		
SAMPLE NUMBER	U^{235}	U^{238}	Pb^{207}	Pb^{206}	$^{206}/_{238}$	$^{207}/_{235}$	$^{207}/_{206}$
38	115.65	16149.33	10.97	197.21	90.3	103.8	430
39	1036.09	144679.19	545.30	8512.63	423.9	475.6	730
40	521.89	72876.24	1046.22	11946.91	1118.1	1204.8	1360
41	39.78	5555.21	13.64	192.74	253.3	333.7	940
42	330.84	46197.94	303.48	3969.80	610.2	724.6	1100
43	152.59	21308.23	160.70	2197.39	725.6	798.5	1010

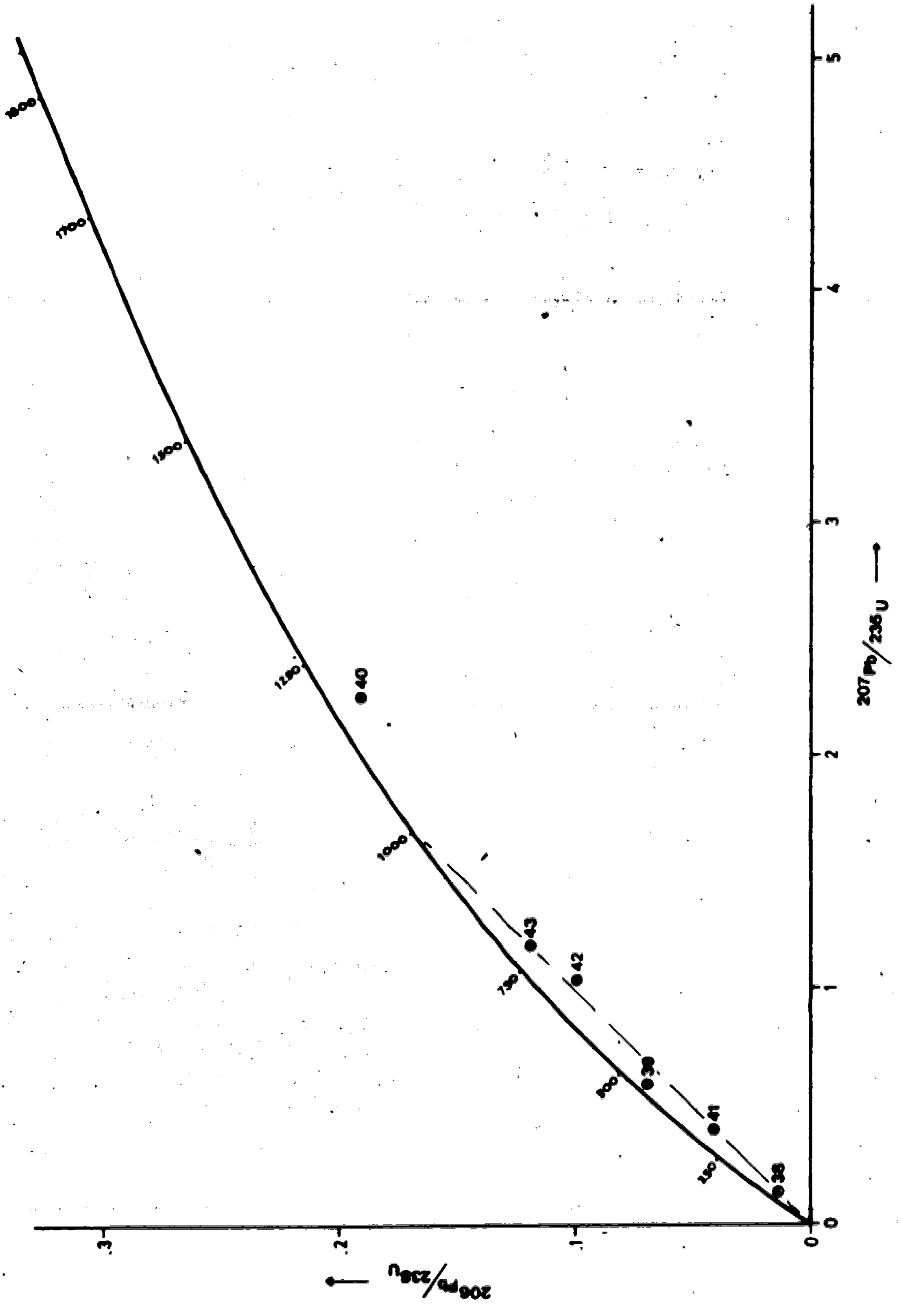


Figure 9 Uranium-lead geochronology of the 'brannerite' from the Fay Winze mine.

The reason for the scatter of points is probably due to different ages of mineralization in the same sample and/or the strong possiblility of minute amounts of remobilized 'old' lead occurring in some of the samples. Koeppel (1967) observed different ages of mineralization in samples as small as 2 mm across. As it was not possible to control the sampling for this study to that degree, this is a real possiblility. Petrographic examination of the ore samples located a few grains euhedral galena surrounded by 'brannerite'. This galena is considered to be remobilized from an earlier phase of mineralization and if it was included in with these samples, it would cause a scattering of points. The fine-grained nature (30 to 60 micrometers) of this lead mineralization prevented its being observed and avoided during the sampling.

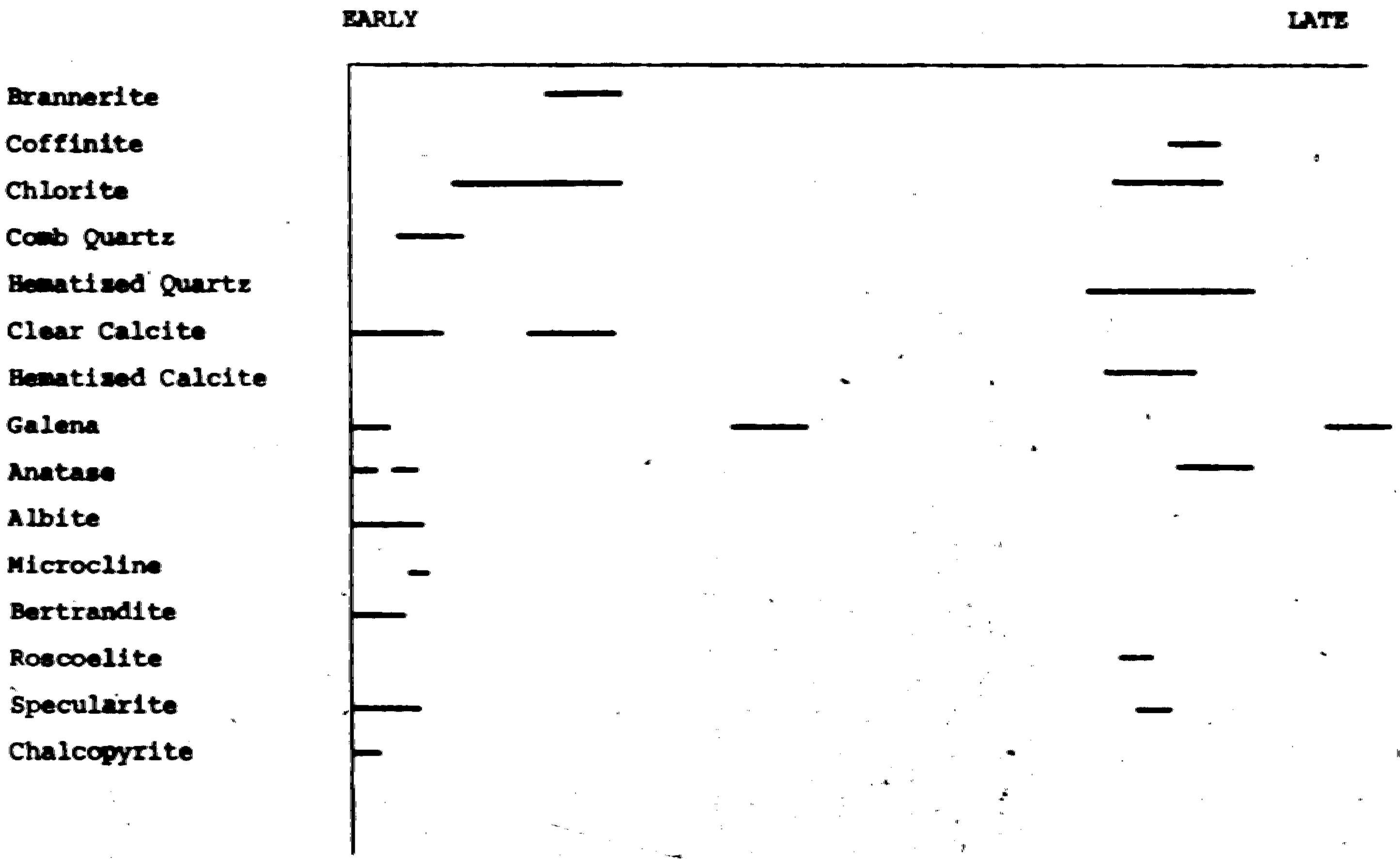
The amount of total lead (206+207) determinded by the geochronolgical study varies from 200 ppm to 1.3 percent, which is much higher than that determined during microprobe analysis of individual grains. This discrepancy can only be due to the contamination of the geochronological samples by remobilized lead. The solution to this problem would be to analyse microscopically controlled samples. This method of sampling was attempted in this study but it was not possible to obtain adequate amounts from the polished thin sections used for microprobe analysis and the method of sampling described above had to be used.

Although the scatter of the sample points on the concordia diagram negates any useful interpretation, it is interesting to note that if sample 40 is ignored, the remaining five samples plot on a reasonably straight discordia that intersects the concordia at about 1000 Ma, which would set an initial age for this mineralization that coincides closely with Koeppel's (1967) first phase of remobilization (1100±50 Ma) of the 'old' Eldorado ore (1780±20 Ma). The presence of euhedral galena of probable radiogenic origin that apparently pre-dates the brannerite mineralization is further evidence to indicate an age for this mineralization that is younger than 1780±20 Ma.

Paragenesis

The paragenetic sequence observed in the sections described above is summarized in Table 12. The mineralization process has been roughly divided into two phases. The first phase involves the crystallization of bertrandite, albite, euhedral quartz, 'brannerite', calcite, chlorite, specular hematite, galena and chalcopyrite. The second

TABLE 12: Mineral Paragenesis observed in ore veins, 29th Level, Fay Winze



phase, possibly related to the alteration of brannerite, saw the deposition of chlorite, roscoelite, coffinite and anatase, the intense hematite staining of some of the calcite and silicate phases and the hematization of the wall rocks. Any pyrite that may have existed has been completely replaced by chlorite and hematite.

Summary and Discussion

The results of the chemical analysis reported in this chapter indicate that the ore zone minerals are probably hydrated uraniferous phases containing Fe, Ti, Si and Ca (the brannerite-like mineral) and Si with minor amounts of Ce and Nd (coffinite). The chlorite occurring with the uranium minerals plots in the diabantite field of a chlorite nomenclature diagram, indicating that these chlorites are slightly more iron-rich than the usual chlorites reported from the Fay mine. Other gangue minerals are albite, hematite (containing substantial amounts of V and Ti), bertrandite, roscoelite and quartz. Trace amounts of galena, chalcopyrite and sphalerite complete the list. The paragenesis suggests that the earliest solutions included Fe, V, Na and Be, followed by solutions depositing the brannerite-like mineral and chlorite and, finally, siliceous, iron-rich solutions that caused the alteration of many of the earlier formed minerals and the deposition of coffinite. the geochronology, although inconclusive, suggests that the brannerite-like mineral was possibly formed between 1300 and 900 Ma.

The findings of this section are essentially consistent with findings in the upper levels of the Fay mine. Exceptions are the lack of pitchblende, which is a major constituent elsewhere and pyrite which is commonly found in most other ore zones. Although beryllium had been detected in geochemical studies of the upper level ore, specific beryllium phases such as bertrandite had not been identified in the Fay mine prior to this study.

VI. ORE GENESIS, SUMMARY AND CONCLUSIONS

A Genetic Model

Models for the genesis of the Fay orebody have varied from purely hydrothermal to purely supergene during the 30 year study period. The model proposed here is a combination of those of Tremblay (1972) and Morton and Beck (1978) with modifications to account for specific features observed in this study. A summary of the model is given below, followed by a more detailed analysis of the mechanisms involved.

Uranium in the Tazin rocks, it is thought, was initially present in dark pelites that were probably carbonaceous. Metamorphism of these pelites up to amphibolite facies during the Hudsonian orogeny resulted in the adsorption of uranium on to cleavage fractures and plate edges of ferromagnesian minerals. The subsequent cataclasis and resulting retrograde metamorphism caused the remobilization of this uranium, along with a number of other elements, and the formation of chlorite-associated deposits in zones of fracture porosity.

Mechanisms important to this model involve the accumulation of uranium during metamorphism and the release of uranium and formation of uraniferous minerals during subsequent alterations associated with cataclasis.

Concentration of Uranium during Prograde Metamorphism

Uranium in prograde metamorphic rocks was studied by Dostal and Capedri (1978). They observed that high concentrations of uranium collected along fractures, cleavage planes and margins of many ferromagnesium minerals and conclude:

> "Rough estimates indicate that 60 to 70 percent of the uranium in metasedimentary rocks of amphibolite grade is located along the cleavage planes and fractures of biotite and, to a lesser degree, garnet, with the rest mostly in accessories."

The relationship of mafic layer silicates and uranium mineralization was also examined by Gavshin (1972). The results of his study suggest that uranium can be held in chlorite (up to one percent) and biotite (up to three percent) and he concludes that "the role of layer alumino silicates in the uranium accumulating process is equally as important as that of uranium minerals".

The main ferromagnesian mineral in non-mylonitized rocks in the Fay Mine area is biotite (Tremblay, 1972) and it is probably responsible for most of the prograde uranium accumulation. Detailed analysis of the biotite for uranium content is not reported in the literature and was not performed as part of this study since biotite has been altered to chlorite in all of the rocks examined.

The Release, Transportation and Precipitation of Uranium During Cataclasis

The alterations accompanying cataclasis that are important with respect to uranium are the breakdown of the previously described ferromagnesian minerals, biotite and amphibole. The complete destruction of these minerals will release uranium and titanium into the system. The breakdown of amphibole will also contribute calcium.

These alterations are thought to be related to the fluids within the shear zone, as there would otherwise not be enough water to form minerals such as chlorite from minerals of 'higher' metamorphic grade.' This water probably also transports Na, CO_2 and SiO_2. The formation of uranyl-carbonate complexes in an alkaline environment is described by McMillan (1978) and the alkaline environment associated with cataclasis is described by Wintsch (1975). It is believed that the uranium released by cataclastic alteration of biotite and amphibole could be transported in mylonite zones.

The transport of the other elements in the 'brannerite' composition is not understood. If not transportable, then it is possible that they were in the mylonitized ore zone prior to the introduction of the uraniferous solutions. In this model, the residual products of ferromagnesian alteration, possibly weakly uraniferous themselves, acted as 'precipitators' of uranium in solution and the increasing concentration of uranium onto these minerals eventually produced the mineral called 'brannerite' in this study. The adsorption capacity of titanogels for dilute uranium solutions has been discussed by Ferris and Ruud (1971).

The gangue minerals observed with this phase of mineralization include albite, calcite, quartz, bertrandite and specular hematite. Most of these are thought to have formed by a mechanism similar to that of the 'brannerite' where many of the elements are supplied by the cataclastic breakdown of minerals. The eventual mineral compositions were formed by interaction with the fluids circulating through the shear zone that were probably rich in CO_2, SiO_2 and Na. The fixation of beryllium onto micaceous metamorphic minerals and its transport by sodium-rich solutions is described by Hormann (1978).

Coffinite and hematized quartz are deposited during the second phase of mineralization. The coffinite is considered to be due to the alteration of brannerite, possibly by a modified version of the reaction observed by Rimsaite (1977). She describes the alteration of pitchblende liberating uranium to react with silica to form coffinite at Rabbit Lake, Saskatchewan. A similar reaction in the Fay Winze would result in the release of Ti, which could account for the anatase that is associated with the coffinite.

The standard mechanism for any later remobilizations in the Beaverlodge area involves the Grenville (or later) orgeny (Koeppel, 1968) which is thought to have had thermal, and possibly metasomatic effects on the rocks of northern Saskatchewan. Another mechanism to explain periodic remobilizations in steeply dipping uranium ore bodies has been proposed by Tillsley (1981) who suggests that radiogenic heat increase is related to the degree of heat conduction and the depth of cover and may build up enough to cause the redistribution of minerals. He summarizes:

> "The periodic redistribution of uranium within these ore zones, as suggested by the spread of radiogenic age determinations, may reflect changing cover thickness due to sedimentation and erosion rather than assumed regional metamorphic or intrusive events for which there is often little evidence."

Summary and Discussion

A possible scenario for the development of the ore zone examined in this report is shown in Table 13. The uranium in this deposit probably originated from Aphebian uraniferious pelites whose source was an Archean granitic highland, possibly containing known uraniferous rocks such as the Viking Lake granite discussed in Chapter II. Prograde metamorphism during the Hudsonian orogeny concentrated some of the uranium on to mafic layer silicates distributed throughout the rock as well as into chemical traps, possibly consisting of zones enriched in mafic minerals. Hydrothermal alterations, as a result of cataclasis associated with the major fault zones, caused the destruction of the original mafic layer silicates and the second remobilization of uranium. At this stage there are two possibilities for the formation of the Fay Winze ore zones. The first is that the remobilized uranium migrated over sizable distances to concentrate in the structural traps represented by the stockwork ore zones. The second, and possibily more acceptable, is that the cataclasis resulted in the local remobilization and adsorption

TABLE 13: Sequence of events in the Beaverlodge Area (after Tremblay, 1972 and Snelling, 1980).

ERA	Ma	EVENT
Aphebian	2000	Original deposition of sediments including uraniferous pelites.
	1850	Metamorphism of sediments during Hudsonian Orogeny. Uranium is held in ferromagnesium minerals representing the initial concentration towards an ore body. Emplacement of granites with possible remobilization (or introduction) of uranium.
Helikian	1750	Formation of shear zones and mylonites after the peak of the Hudsonian Orogeny coincident with the onset of retrograde metamorphism and the release of uranium from the prograde (ferromagnesian) minerals and deposition into channel ways and fractures in chemically favorable meta-pelites.
	1650	Deposition of Martin Formation red-bed clastics and coarse fanglomerates. Coincident emplacement of flow basalts in a miogeosynclinal basin.
	1350 to 1000	Final period of mylonitization and readjustment of stresses result in extensive local fracture porosity. Deformation induced release of Ti, Fe and U in the presence of oxidizing solutions results in the deposition brannerite in stockwork fractures. Na, K and Be are also remobilized at this time. The final stage of this period saw the formation of coffinite, possibly at the expense of brannerite. This latest remobilization could be due to effects of the Grenvillian Orogeny or to radiometric heating and reactivation of fluids within the deposit.

of uranium on to chlorites in the more ductile zones represented by the wall-rocks described in Chapter IV. Coincident to or slightly following this was the local remobilization and deposition into fractures in the more brittle 'work-hardened' rocks in the areas of most intense cataclasis adjacent to the fault. This second possibility is attractive because it would account for the high uranium concentrations in the wall-rocks and does not require remobilizations over large distances.

A final period of uranium remobilization, represented by the coffinite-phase of mineralization, occurred after the deposition of the brannerite-like phase. This remobilization could be due to several possible mechanisms, including the radiogenic heating of the deposit due to poor heat conduction away from the ore zone.

The greatest difficulty with this model is explaining the lack of similar uranium deposits in all the other areas of extensive mylonitization in the Beaverlodge area. This can be partly countered by the fact that most of the uranium deposits and many hundreds of showings do occur in strongly sheared and mylonitized rocks. These are all however, smaller than the Fay-Fay Winze ore body and there must be some other factors here that resulted in this particular deposit. It is suggested that perhaps the initial sedimentation occurred in an environment suitable for the concentration of uranium and formation of a syngenetic deposit. This could have been due to the presence of carbonaceous matter in a reducing environment (Morton, 1980) or the adsorption of uranium on to clay minerals (Tillsley, 1981) or a combination of the two. It is also possible that uranium may have travelled over a considerable distance to be deposited at this location, possibly due to certain chemical or physical conditions such as a strongly reducing environment, or low pressure due to fracture porosity.

This model, however, does provide a good thesis for the formation of the stockwork-type Fay Winze ore zones and, it is thought, helps to explain the relationship between cataclasis and ore deposition. Further work that could be done in this area would be to examine in detail the chemical compositions of layer silicates from mylonitized and non-mylonitized areas and to provide a more detailed description of the degrees of cataclasis present in the rocks.

Conclusions

The units of the Tazin Complex consist of primarily Aphebian sediments that were metamorphosed during the Hudsonian orogeny. Subsequent cataclasis along major shear zones resulted in the remobilization of uranium and other elements that were associated with prograde metamorphism minerals. Particularly brittle zones of mylonite and cataclasite acted as structural traps and accumulated uranium to form the deposits being mined today. The uranium minerals consist of a brannerite-like phase high in Fe, Ti, Si and Ca and coffinite containing trace amounts of the rare earth elements cerium and neodymium. Other trace elements associated with the ore zone include vanadium and beryllium.

The geochemical effects of the deformation are not obvious within 100 meters of the Saint Louis Fault. Except for uranium and vanadium, all of the trace element concentrations examined are at or below crustal averages. Uranium-lead isotope analysis, while inconclusive, suggests that the brannerite-like phase of mineralization may have formed around 1300 to 1000 Ma.

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Appendix I - Summary of Works Regarding Cataclasis

Higgins (1971) in a comprehensive summary of cataclastic rocks, divided them into the following categories. The first two are primarily destructive, involving the communition and crushing of the rocks and the final two are constructive and involve the growth of new minerals (neo-mineralization) or new, larger crystals (recrystallization) at the expense of the original constituents. The process of forming a blastomylonite is interesting in that it involves the simultaneous destruction (cataclasis) and reconstruction (neomineralization) of the rock.

1. Cataclasis dominant, no fluxion (flow) structure
   - a. microbreccia - megascopic, structureless
   - b. cataclasite - aphanitic, structureless
2. Cataclasis dominant, with fluxion structure
   - a. protomylonite - megascopic, typically lenticular fragments
   - b. mylonite - has a microscopic fluxion structure
   - c. ultramylonite - aphanitic, resembling a chert, felsic volcanic or quartzite
3. Neomineralization - recrystallization dominant over cataclasis
   - a. mylonite gneiss (mylonite schist) - a rock between a protomylonite and a crystalline schist as a result of cataclastic and crystalloblastic processes
   - b. blastomylonite - a rock between a very fine grained mylonite and a crystalline schist as a result of cataclastic and crystalloblastic processes (ie. breakdown (cataclasis) occurs simultaneously with reconstruction (crystalloblastis))
   - c. protoclastic rocks - cataclasis of an igneous body due to late intrusive movements.
4. Retrograde cataclastic rocks - products of retrograde metamorphism concurrent with cataclasis and common near major fault zones.

Higgins also gives a number of criteria for the recognition of cataclastic rocks.

1. Textural contrast with non-cataclastic rocks
2. Differential weathering compared to non-cataclastic rocks
3. Gradational contacts with non-deformed rocks (to help differentiate from meta-volcanic rocks)

4. Presence of porphyroclasts or visible fluxion structure
5. Zones of (economic) mineralization and alteration
6. Presence of mica masses (producing a slight 'augen' appearance)
7. Association with fault zones.

He concludes that the only true way of determining cataclasis is to observe the textures in thin section.

In terms of the definitions of Higgins (1971) the rocks of the mine can be classified as follows:

a. Foot Bay Gneiss = blastomylonite or mylonite gneiss
b. Donaldson Lake Gneiss = blastomylonite or mylonite gneiss
c. leucocratic gneiss = ultramylonite
d. epidotic argillite = ultramylonite to mylonite schist
e. mica schist = mylonite schist to myloniite
f. orange porphyroclastic mylonite = ultramylonite to mylonite (mylonite schist)

The present study bases its definitions upon those of Higgins, as they appear to be the most comprehensive and serve best to describe the rocks seen in the Fay Winze. Three other classification schemes are included for comparison.

Krupicka and Sassano (1972) divided the mylonitic process into four stages, which included the following textural criteria:

1. strained – pre-deformational textures discernible
2. cataclastic rocks – most pre-deformational grain shapes destroyed; tendancy to porphyroclastic texture.
3. mylonitic rocks – complete destruction of pre-deformational texture and development of fluxion structure, scattered, rounded porphyroclasts
4. ultramylonitic rocks – crushing of all minerals to a very fine-grained powder; common development of glassy 'pseudotachylitic' textures.

They define the rocks of the Fay Mine Complex at about 2.5 (cataclastic to mylonitic). The observation of the present study, based on the above criteria, would define the rocks of the Fay Mine Complex at 3, as it is seen that original grain shapes and textures are non-existent in these rocks. The rocks of the Foot Bay and Donaldson Lake gneisses do not enter into the above classifiation as there is no place for crystalloblastic processes.

Bell and Etheridge (1973) have attempted to redefine 'mylonite' in terms of ductile deformation recovery and recrystallization only. They contend that brittle deformation is not necessary and should not be automatically assumed when dealing with mylonitic rocks. They conclude that mylonites can form from three processes;

a. predominantly ductile deformation, recovery and recrystallization

b. brittle crushing of grains into smaller fragments, powder and/or glass

c. neomineralization as a result of the change in conditions and movement of material during (a and b)

They define mylonite as:

> "A mylonite is a foliated rock, commonly lineated and containing megacrysts, which occur in narrow planar zones of intense deformation. It is often finer grained than the surrounding rocks into which it grades."

The development of mylonitic structures is divided into five stages by Sinha Ro (1977), starting with initial cataclasis and recrystallization through shearing, recovery and recrystallization, flattening and, finally, a last stage of recovery and recrystallization. It is not necessary, he feels, for all of these stages to be operable during a mylonitization event and the degree to which these come into play depends upon the intensities of deformation, the degree of strain heterogeneity and the rate of strain. He concludes

> "ductile flattening, primarily responsible for mylonitic foliation/banding may be preceded by brittle shear strain, and also in some cases be followed by it. The former is associated with prograde metamorphism, the latter with
>
> retrograde."

Appendix II - Crush Breccia - A Tectonic unit that resembles Martin Formation Conglomerate

An unusual breccia, described by most observers as Martin Formation conglomerate is seen underground at Eldorado. It occurs at several locations adjacent to and in the footwall of the Saint Louis Fault. The largest body located is a continuous unit from surface, where it outcrops beneath Verna Lake to 32nd Level, where it was encountered during lateral development to the east of the Fay Winze. The unit generally occurs as a skin of uniform thickness (about 30m) and varying strike length (50 to 350m) which result in broad scale pinch and swell structures when viewed in longitudinal section. Most of the samples used in this study come from this exposure, although others were taken from previously collected specimens from the upper levels of the Fay Mine.

Several factors prompted a study of the breccia, the primary one being the incongruity of a thin 'skin' of apparently unaltered conglomerate persisting for more than 2 kilometers down-dip on a major fault that has produced extensive mylonite zones elsewhere. Another puzzling feature is the apparent extent and uniformity of a lithology which is characterised on surface by its ruggedness and local extent (Tremblay, 1972). The crush breccia does resemble cataclasites seen on both surface and underground. It was observed, while the author was working underground, that these rock types display a wide variability in their appearance and composition.

A problem that has arisen from this unit being considered a part of the Martin Formation is its use by several authors (Lewry and Sibbald, 1978; Langford, 1979) to support near surface or supergene genetic models for the Fay ore bodies. Sassano (1972) describes this as the Martin Formation and includes it in his underground stratigraphic section.

It is the opinion of the writer, for reasons described below, that this unit is of cataclastic origin and should be termed a 'crush breccia' (Moorehouse, 1959) or a 'proto-mylonite' (Higgins, 1971).

Mineralogy

The mineralogy of the crush breccia samples examined is fairly uniform and consists of quartz and feldspar with lesser amounts of chlorite, sericite and calcite and trace amounts of muscovite, zircon and sphene (Table 14). The latter two occur as rounded porphyroclasts. Biotite is uncommon and appears to be restricted to the larger formation. Quartz typically occurs as recrystallized matrix and porphyroblastic masses. It is commonly seen in myrmekitic intergrowth with feldspar, a texture common to cataclastic rocks (Spry, 1969).

Plagioclase occurs as bent, broken and disrupted relict grains which are comminuted to very fine grain sizes. Microcline is found as corroded and altered (sericitized) relict grains and as small twinned euhedra in veinlets of chlorite and calcite. Occasional rounded grains of microcline are seen.

Chlorite is the predominant mafic mineral present in the crush breccias and is thought to be derived from the destruction of biotite. There is, however, a lack of titanium phases (sphene, rutile) that would also result from this alteration. Chlorite is generally interstitial although it occasionally forms veinlets within some of the fragments. Strained relict chlorite grains are seen at rare intervals. The chlorite is pale green, pleochroic and displays anomalous blue interference colors under crossed nicols.

Sericite occurs with calcite as an interstitial matrix mineral and as an alteration product within microcline crystals. It is pervasive and found throughout the rock. Occasional strained relict muscovite grains are also seen. Opaque minerals (probably pyrite and hematite) constitute about five percent of the rock and occur as broken, often corroded grains, usually associated with chlorite.

Textures

Fragments in these crush breccias range in size from less than 1mm to tens of centimeters and are set in an aphanitic to coarse sand-sized matrix. The packing of these fragments varies from tight and clast-supported, with less than five percent matrix to open and matrix supported. Fragments are typically although not always surrounded by carbonate, chlorite and sericite.

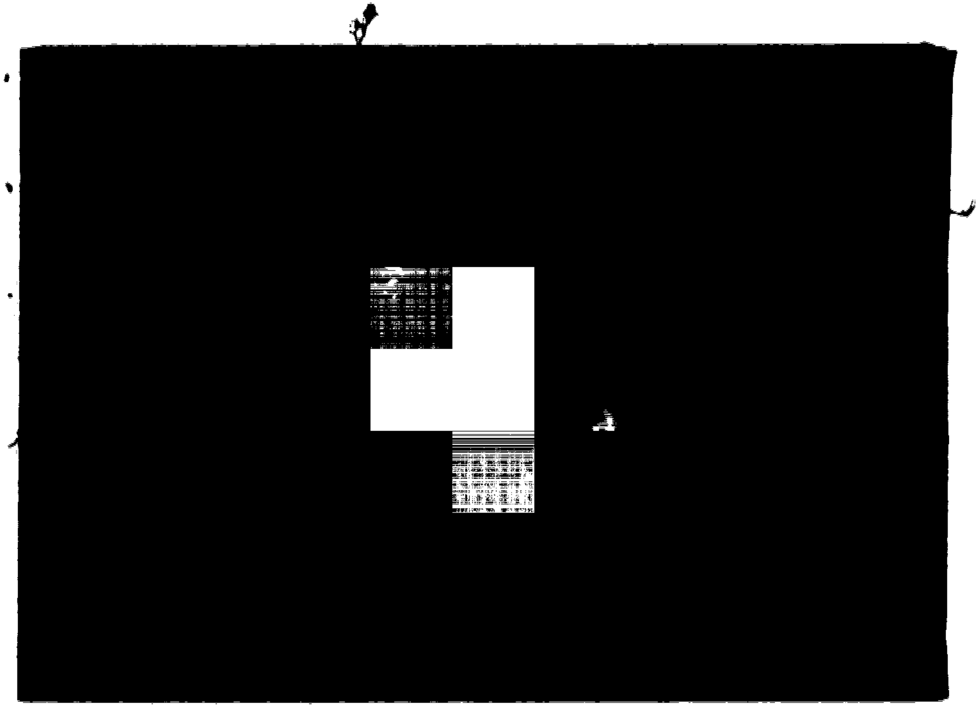
Occasional, but locally abundant hematized bands cut the matrix and bear a strong resemblance to bedding planes. These are in fact (0.5 to 2mm), parallel shear zones

TABLE 14: Estimated mineral composition of crush breccia matrix, in percentages.

	10a	28a	32b	32c	13a	77
Quartz	20-30	20-30	35-45	50	35-45	30
Plagioclase	30	25	10	15	20	15-20
Microcline	5-10	?	5-10	15	15	tr?
Sericite	<1	<2	5	20	10	10
Chlorite	5	20	5	5-10	5-10	5
Hematite	tr	tr			tr	
Calcite	<5	<2	5-10	5		15
Muscovite				2		
Zircon	tr		tr	tr		<2
Opaques	5-10	tr	5-10	5	tr	<5
Fragments	70	70		80	70	80
Matrix	30	30		20	30	20

Plate 10 Tectonic breccia near the plane of the St.Louis Fault. This breccia is filled with euhedral quartz, pink calcite, dark chlorite, and feldspathic 'chert'. The large fragment at top center is composed of an earlier breccia, indicating the multiphase nature of these units.

Plate 11 Crush breccia displaying the diversity of fragment size, composition, and rounding. Pressure shadows, although not seen in this example, are frequently observed around the larger fragments. Plates 11 and 12 are typical of the crush breccia seen on 32nd level of the Fay Winze. The matrix is a fine grained crush of the larger fragments.



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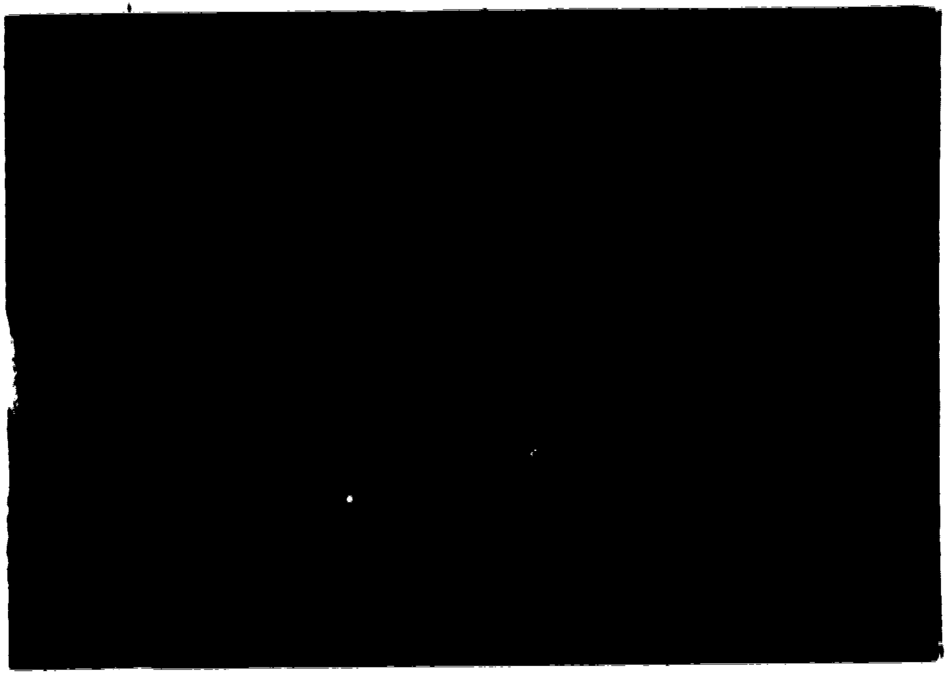

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containing hematized quartz, feldspar and chlorite. These veinlets are considered to be the result of late movement within the breccia body.

These rocks do not show evidence of mylonitic neocrystallization (Higgins, 1971) but appear to represent an earlier cataclastic stage with bent and deformed feldspars, strained and recrystallized quartz and a general rounding of constituents. There is little development of fluxion texture and pressure shadows are only occasionally observed. Fragments show, at best, very weak alignment.

Modal analysis of the fragments indicates approximately five percent (2 to 15%) white quartz, 65% (60 to 80%) alaskitic 'granite' and granitic gneiss and less than 10% of other types (mostly dark mica schist). The silica and 'granite' fragments tend to be rounded whereas the dark schist fragments tend to be elongate. The size sorting and rounding are extremely variable.

Contacts with the surrounding rocks of the Tazin Complex are poorly documented at the upper levels, where the unit was interpreted by mine geologists as occurring within a lateral drag fold indicating right-hand movement along the Saint Louis Fault. At the lower levels the contacts are sheared and usually contain about 5 to 10cm of chloritic gouge. Major faults also cut through the unit resulting in several areas of poor ground stability. These faults parallel the contacts and intersect the Saint Louis Fault at a shallow angle.

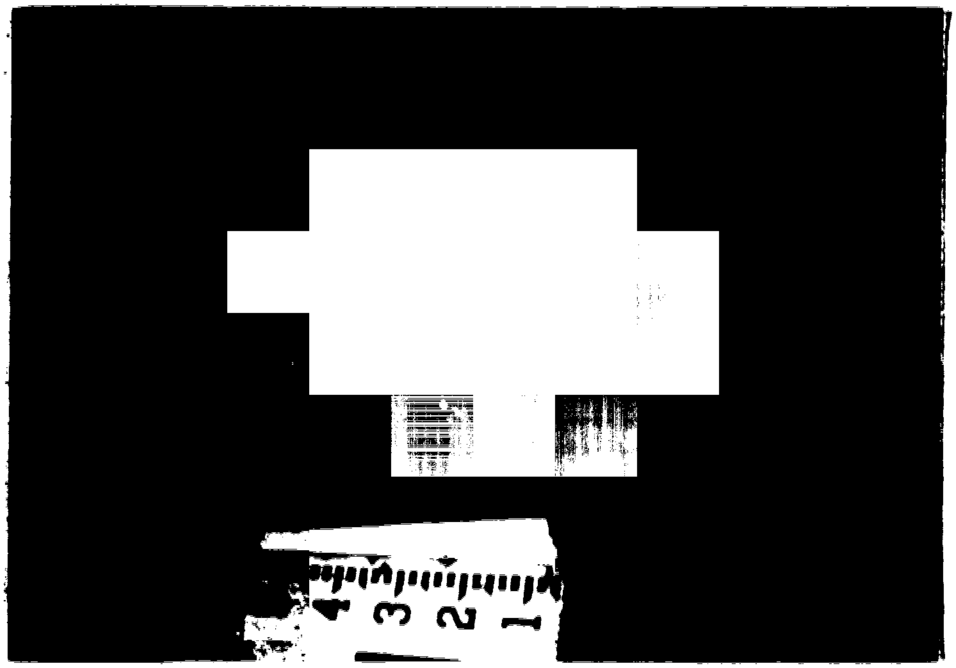
Interpretation

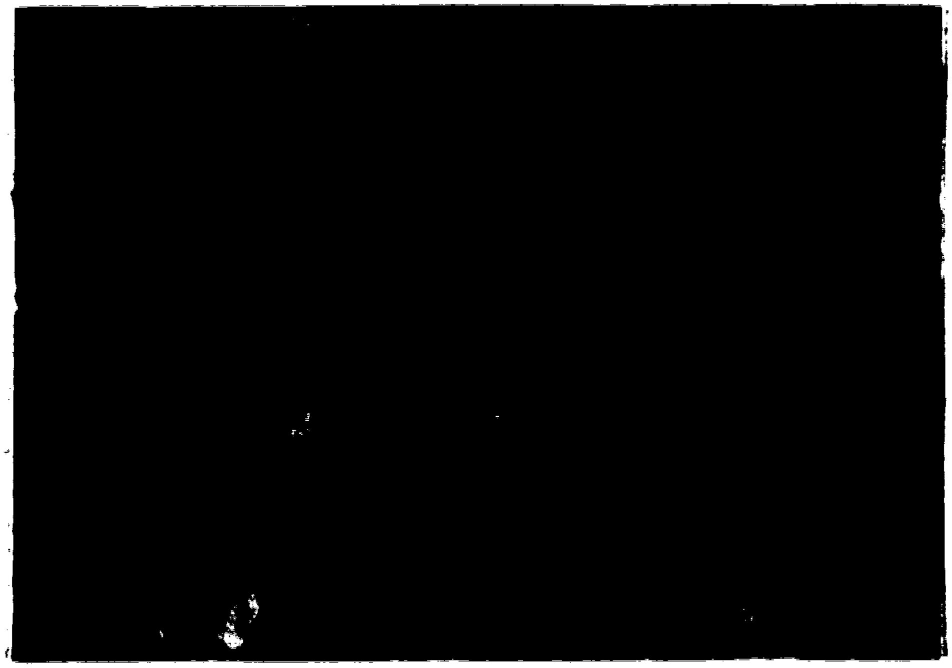
Evidence supporting a tectonic as opposed to clastic origin for these rocks consists of textural and geometric observations. Common textures in the exposure on 32nd Level consist of the juxtaposition of well-rounded and very angular fragments, very large and very small fragments and pressure shadows associated with some of the large fragments. In thin section, bent and disrupted feldspars and myrmekitic quartz-feldspar intergrowths are both typical of cataclasis (Spry, 1969).

The geometric evidence includes the location, attitude and extent of this unit. As mentioned above, it is difficult to conceive of an apparently fresh and unaltered conglomerate having been dragged 2km down a major fault that has caused extensive deformation and cataclasis of the footwall rocks adjacent to the conglomerate. It is also difficult to rationalize a 2km continuous exposure for a lithology apparently derived from

Plate 12 Three phases of crush breccia. Across the top there is a zone of strongly alligned fragments surrounded by less than ten percent matrix; across the middle there is a band of finely comminuted rock containing about sixty percent matrix; at the bottom the breccia contains non-alligned, rounded fragments surrounded by about twenty percent matrix. It is interesting that some of the latter fragments are sheared at the contact with the middle unit whereas others protrude into it.

Plate 13 A thin section of some of the fine grained matrix typical of the crush breccia. Across the center is an ultra fine-grained chloritic crush which in hand-specimen has a similar appearance to sedimentary bedding. The main mineralogy consists of recrystallized quartz, feldspar, muscovite, chlorite and calcite.





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a high-energy source and one observed on surface to form very local basins (Tremblay, 1972).

This conglomerate-like rock is interpreted as a tectonically derived 'crush breccia' (Christie, 1953; Moorehouse, 1959; Spry, 1969) produced by several periods of fault movement resulting in a progressive rounding of the more resistant lithologies and comminution of the others. Cataclasis has progressed to the point of mafic (biotite) alteration to chlorite, a feature noted in the Beaverlodge mylonite zones on surface (Tremblay, 1972). Since the predominant large fragment composition is alaskitic 'granite', it is expected (and observed) that the matrix consists mostly of finely comminuted equivalents of these (quartz and feldspar).

Accessory minerals, which are generally interstitial to the quartz and feldspar, include calcite, sericite and chlorite. These are probably the alteration products of very finely ground original minerals. This alteration could have been promoted by fluid transport along the porous brecciated zone.

Reynolds (1954) has proposed a mechanism of fluidisation resulting from tectonic heating and fluid overpressure causing fluids to ascend through the brecciated 'conduit'. In her paper she describes fluidised breccias similar to those of this study. At one location she observes:

> "The most suprising thing about this breccia is the rounding of some of the quartzite blocks. So striking is this rounding that they have been regarded as water-worn boulders, derived from a loose surface formation which had fallen down a fissure or pipe."

This mechanism of fluidisation could also be used to explain the apparently injected zones of finely comminuted material that are frequently observed in this unit.

Other 'crush breccia' units are seen elsewhere in the mine, always in the immediate footwall of the Saint Louis Fault and associated with strongly mylonitized rocks. Many of these units have gradational contacts with the surrounding mylonites. They are occasionally associated with low grade '01' zone type orebodies. The main 'crush breccia' unit, exposed on 32nd Level, has at least a spatial relationship with the '44'ore zone in the upper levels of the mine although mineralization is not observed at the lower levels. The unit is rarely described in surface mapping, possibly due to its resemblance to conglomerate. Christie (1953) described crush breccia from the Beaverlodge area:

"In many of these rocks the augen and lens-like forms of the less crushed materials are less well developed, and the rock is composed of rounded, elliptical, and irregularly-shaped rock fragments set in a fine grained crushed groundmass. These rocks have been termed crush breccias. The crush breccias are in places, difficult to distinguish from the Athabasca (Martin) conglomerate, particularly where both are composed entirely of fragments of granite-gneiss and in areas where the Athabasca Series itself has suffered some crushing."

Appendix III - Sample Descriptions

Samples used in the tables

19 A fine grained leucocratic rock with a cataclastic to mylonitic texture. Quartz occurs as fine to medium grained layered mosiacs; plagioclase as small grains and aggregates, usually strained but unaltered; chlorite occurs in thin veinlets parallel to the foliation and pyrite as isolated, broken masses, often associated with chlorite. Much of the recrystallized quartz is dusted with hematite. Traces of TiO_2 occur as small deep-red to opaque grains and masses. Calcite occurs in cross-cutting veinlets.

14 A fine grained cataclastic rock with recrystallized quartz and chlorite cut by calcite veinlets and approximately 10 percent TiO_2 occurring as pale brown high relief masses throughout. Hematite occurs as thin, irregular cross-cutting veinlets.

11 Epidotic mylonitic rock with strong fluxion texture. A groundmass of hematized, recrystallized quartz, strained and hematized feldspar (partly altered to epidote) and clear calcite is cut first by a 5mm vein of hematite and quartz and, later, by a clean veinlet of euhedral quartz and clacite. In the groundmass, hematite crystals are often associated with zones of fibrous epidote. Minor chlorite and muscovite occur in the groundmass.

10 A strongly foliated porphyroclastic mylonite containing recrystallized quartz with muscovite and chlorite surrounding sericitized microcline porphyroclasts. Hematite and, rare, epidote occur in a thin veinlet in prismatic skeletal crystal outlines.(replacing ilmenite?)

3 A chloritic mylonite containing highly altered (sericitized) plagioclase and microcline porphyroclasts surrounded by chlorite, muscovite and recrystallized quartz. A few euhedral, high relief titanium oxides are present. Euhedral quartz occurs in a

TABLE 15: Correlation of sample numbers used on tables.

Thesis number	Original sample number
1	29-84-7
2	29-84-37
3	29-84-60
4	29-84-65
5	29-84-88
6	29-84-100
7	29-103-3
8	29-84-130
9	29-84-120
10	29-103-70
11	29-103-90
12	29-103-31
13	29-103-53
14	29-103-105
15	31-11-20
16	29-138-172
17	31-11-156
18	31-12-74
19	29-103-129
20	31-11-74
21	U-6
22	U-8
23	U-9
24	U-11
25	U-12
26	U-13
27	U-11a
28	U-11b
29	U-11c
30	C-1
31	C-1b
32	C-3
33	C-7-2b
34	C-9-1
35	C-9-1b
36	H-9-1c
37	H-7-2c
38	U-Pb-29-1
39	U-Pb-29-2
40	U-Pb-29-4-1
41	U-Pb-29-6-1
42	U-Pb-29-7-1
43	U-Pb-29-8-1

cross-cutting calcite veinlet.

12 Porphyroclastic mylonite containing feldspar and muscovite porphyroclasts surrounded by the usual muscovite, chlorite and recrystallized quartz matrix. Most of the feldspars are strongly sericitized. Hematite with associated chlorite replaces a cubic mineral (pyrite?).

7 Very fine-grained porphyroclastic mylonite in which the porphyro-clasts constitute 40 percent of the rock. Chlorite and muscovite produce a strong fluion texture surrounding the feldspar clasts which are strongly altered to sericite and minor epidote. Calcite occurs in a vein with euhedral quartz. Rare resistant grains with high relief (zircon?) produce pleochroic halos in chlorite.

9 Porphyroclastic and mylonitic muscovite schist. There is a strong fluxion texture in the recrystallized quartz-chlorite-muscovite matrix that surrounds porphyroclasts of recrystallized feldspar and quartz and strained feldspar. Masses of chlorite, possibly replacing porphyroclasts, are occasionally seen surrounded by 'flow' texture muscovite. Plagioclase shows some strain and, except for serated margins, little alteration. Myrmekitic quartz intergrowths are frequent in the plagioclase. Traces of hematite and titanium oxide (anatase?), usually associated with chlorite, are also seen throughout section.

44 A fine-grained quartz-feldspar cataclasite with strong hematite staining and no foliation. This sample is taken from the margin of an ore zone. Plagioclase has broken twin lamallae and forms medium to large porphyroclasts and microcline porphyroblasts have serrated edges. Quartz usually forms a recrystallized matrix although it does occur with plagioclase as strained porphyroclasts. Masses of leucoxene with occasional sub-hedral grains of sphene are abundant in veinlets which are visible in hand specimen. Calcite

occurs throughout the matrix and in veins – this rock is strongly carbonatized. The sample is cut by an ultramylonite or kakirite band that contains the titanium phase, calcite, feldspar and chlorite.

1 A banded quartz-feldspar cataclasite. Quartz is well recrystallized and strained. Plagioclase is strained and dusted with hematite preferentially along twin planes, microcline is altered to sericite and associated with minor epidote. Feldspar rich bands are predominantly plagioclase with bent, strained twin lamellae. Hematite occurs with leucoxene, chlorite and quartz as replacements in square skeletal crystal outlines (after pyrite or ilmenite). A pleochroic halo occurs around a brannerite (?) grain in a chlorite vein. The chlorite vein cuts a quartz-calcite vein that contains microcline euhedra.

2 A quartz-chlorite mylonite containing occasional strained plagioclase porphyroclasts and quartz-feldspar porphyroclasts. There is a pervasive dusting of hematite that tends to obscure the mineralogy. This section contains considerable opaque mineralogy which, in polished section, is identified as masses of leucoxene or anatase; ilmenite which is partly replaced by leucoxene/anatase; pyrite cubes and hematite occurring as fine blades or masses with leucoxene/anatase in skeletal, replaced ilmenite. This sample is cut by a band of ultramylonite or kakirite.

3 A dark chloritic medium- to fine-grained mylonite. Plagioclase shows some sericite alteration. This section has 10 percent anhedral masses of opaque minerals. Small scale folding (crenulation) is common. Chlorite is abundant in the groundmass and in cross-cutting veinlets. Hematite is the most common opaque and is often associated with chlorite.

4 Quartz-feldspar cataclasite with minor fluxion texture. Quartz occurs as recrystallized matrix, as euhedral crystals in calcite veins and as myrmekitic intergrowths in plagioclase. The feldspar is

mostly plagioclase occurring as porphyroclasts with moderate sericite alteration and corroded edges. Chlorite is a minor constituent and is associated with quartz, hematite and anatase. Calcite is abundant in veins and throughout the groundmass of the rock.

6 A sheared porphyroclastic mylonite with dark, chloritic bands containing small plagioclase porphyroclasts interspersed with light chlorite-muscovite bands. Small offsets in the order of hundreds of micrometers are observed in these bands and shearing is frequently seen within individual porphyroclasts. Polygonal sub-grain growth is occasionally observed in recrystallized quartz.

8 A micaceous mylonite with strong fluxion texture. Typical recrystallized quartz with muscovite in groundmass and as porphyroclasts. Feldspar porphyroclasts are highly strained and occasionally flattened and are usually smaller than 0.5 millimeters across. Microcline occurs in minor amounts along fine hairline fracture.

16 A clear chloritic vein with abundant pyrite and chalcopyrite from within a section of orange mylonite. Chalcopyrite is anhedral and occurs by itself where it surrounds clear quartz euhedra and with euhedral pyrite. Chlorite and calcite are common with the sulfides in this vein. The transparent part of the vein consists of albite, generally altered to sericite, microcline, recrystallized quartz, chlorite, calcite, hematite and a titanium phase that is probably anatase.

15 Fine-grained to aphanitic quartz-plagioclase-muscovite schist or mylonitic schist. Slightly streaky and mottled pink and white appearance.

20 Streaky banded mylonitic plagioclase-muscovite-chlorite schist with some relict original banding and resistant felsic lenses. One or two percent calcite-hematite veining.

17	Massive red plagioclase-chlorite cataclasite with a fine-grained granitic to gneissic texture with weak foliation. Minor calcite veining and hematized feldspar fragments.
18	Dark fine-grained porphyroclastic mylonite or cataclasite with about 30 percent mafic minerals (chlorite) and 5 percent calcite veining. Description of the ore samples
29-1	This consists of calcite, recrystallized quartz and chlorite in thin veinlets with brannerite, anatase and hematite, all the phases are dusted with hematite.
29-2-1	This sample contains thin needles of transparent brown brannerite in areas of calcite and chlorite. Thin veinlets (100 to 200 micrometers) contain brannerite and anatase at the margins and euhedral twinned albite crystals at the centre. Euhedral crystals of galena (less than 5mm) occur in chlorite.
29-2-2	Brannerite, galena and hematite occur in veinlets up to 350 micrometers wide and brannerite needles occur in chlorite and calcite.
29-3	This sample has a large, cherty quartz vein cutting a cataclastic fluxion texture matrix with up to 50 percent microcline porphyroblasts. The vein contains euhedral 'comb-quartz' and lath-like fine-grained trachytic feldspar in the centre. There is no radioactive mineralization in this sample.
29-4	Radioactive mineralization occurs in two, mostly opaque areas that are stained red-brown and contain abundant wallrock fragments. The veins cut porphyroclastic mylonite wall rocks. Vein mineralogy consists of 50 percent flambouyant hematite with bright orange quartz and feldspar. Small euhedral bertrandite crystals and albite crystals occur in these veins. Galena occurs as irregular blebs in hematite and as exsolved subhedra in brannerite.
29-6-1	Mineralization occurs in an open network of thin 50 to 150 micrometer veinlets cutting a cataclastic albite-rich matrix. The

	veins contain bladed to massive hematite, brannerite, galena, anatase, chlorite and minor coffinite. X-ray scanning indicates that the veins contain more uranium and titanium at the centre and more calcium and silica at the margins. The feldspars are generally stained orange with fine-grained hematite.
29-7-1	Thin orange veinlets containing brannerite cut a strongly carbonatized, albite rich matrix. Brannerite occurs as acicular inclusions in calcite and contains exsolved galena.
29-7-2	Irregular re-stained veinlets with green chlorite, acicular brannerite crystals and pink and clear calcite. Recrystallized quartz and weakly sericitized plagioclase occur in the wall rocks. The brannerite needles commonly show crossed twinning.
29-8-2	The principal radioactive mineral is coffinite which is opaque, grey and isotropic and often surrounds euhedral grains of galena, euhedral quartz and albite. The margins of this vein have comb-quartz and small laths of microcline. The wall rocks are mylonitic, banded and pink stained. Anatase does not occur in the vein but is seen in small veinlets that parallel the main vein.
29-9-1	This sample contains abundant green chlorite and flambouyant specularite intergrown with anatase. Euhedral bertandite and albite crystals appear to be partly replaced by bright orange quartz and chlorite. Chlorite zones contain small euhedral galena crystals. Acicular needles of brannerite occur in calcite and chlorite

Appendix IV - Microprobe Procedures

All of the electron microprobe analyses were performed on an ARL-EMX microprobe using an Ortec Si(Li) solid state X-ray detector and energy dispersive analysis circuitry. Operating voltages were 15.0 keV with a probe current of approximately 0.028 microamperes. Where possible, the beam was rastered over the analysis area to prevent sample damage and loss of volatiles. If a static 'point' beam, (with a diameter of about 3 micrometers) was used, the probe location was changed at atleast 50 second intervals during the standard 400 second counting period.

The instrument was calibrated using well-documented analytical standards for each element to be analysed prior to each analysis session. Variations in a standard willemite (Zn_2SiO_4) spectrum were measured before and after each session to check the drift of machine operating conditions. Sample locations were chosen petrographically prior to analysis and re-examined afterwards, especially in cases of suspected contamination.

Data reduction was performed using the EDATA2 program developed by Smith and Gold (1979). Special program functions were specified to remove minor contaminants, display the results in a desired format and produce structural formulae. Non energy-dispersive probe-detectable elements such as hydrogen, oxygen and, in the case bertrandite, beryllium, were added in stoichiometrically correct amounts. All of the results were given in terms of 'dry oxides' recalculated to 100 percent to minimize the variability introduced by water loss under the beam.

Appendix V - The Geochemical and Mineralogical Effects of Deformation

This appendix is the summary of the literature researched to help interpret the Fay Winze mineralogy in terms of cataclastic events. Most writers agree that cataclasis results in the mobilization of a number of elements such that changes in the rocks involve overall changes the geochemistry as well as in mineralogy. Some feel that these systems are open and, presumably, flooded with metasomatic solutions from a distant source whereas others feel that most of these changes occur due to short range diffusive transport in fluids possibly generated by the deformation. More detailed accounts of these findings are included in the analysis of the Fay Winze mineralogy which is found following this summary.

The earliest studies reviewed were done by Anderson (1934) who reported on 'pseudo cataclastic' replacement textures in igneous rocks and felt that the system was open to the introduction and migration of fluids. He concludes:

> "It is apparent therefore, that conditions favore both the ready interchange of substances within the rock and the introduction of material from an outside source. These conditions were provided by a freely-circulating fluid media".

Conybeare and Campbell(1951) studied the mineral associations and petrology of mylonites from the Saint Louis Fault. They speculate that "soda" is enriched along the zones of most intense shearing and speculate that perhaps the sodium released from crushed minerals will migrate along these zones. Blake (1955) in discussing the mylonites and cataclasites in his map area immediately east of the Beaverlodge area observed that:

> "...extensive alteration of the mafic minerals and feldspars to chlorite, sericite, epidote and carbonate is a feature that is characteristic of all mylonitized rocks in the map area."

Tremblay (1972) who mapped the Beaverlodge area, including the Fay Mine, says that biotite is the main mafic constituent of the Foot Bay and Donaldson Lake gneisses north of the Saint Louis Fault and that these units generally become chloritized as you approach the fault, a feature he believes is mainly due to cataclasis.

Burwash and Krupicka (1969, 1970) in a regional study of the Precambrian basement beneath Alberta, have interpreted extensive changes in mineralogy related to deformation. With increasing deformation they record a decrease in plagioclase, biotite and hornblende and an increase in microcline, epidote, chlorite, and muscovite, thus indicating that the reworking not only resulted in deformation and metamorphism but in changes in the bulk composition of the rocks. Burwash and Culbert (1976) reported on the geochemical trends and patterns in the Precambrian basement rocks of Western Canada. They performed multivariate analysis techniques using 42 variables measured in rocks ranging from non-constrained through mylonitized to recrystallized. Their results suggest that changes in whole rock geochemistry accompany each stage of deformation.

Ashley and Chendaall (1976) worked with mylonitized igneous rocks and observed that the most notable chemical changes were a slight decrease in the FeO/Fe_2O_3 ratio, TiO_2, K_2O, Rb, Rb/Sr ratio, Cu, Zn and a slight increase in Na_2O and SiO_2. They suggest that these changes require small additions and subtractions of components by a fluid phase during mylonitization.

Sinha Roy (1977) reported on the chemical processes during the mylonitization of igneous rocks from the Himalayas and Norway and, although the major element oxides showed fairly distinct trends of variation, the trends from each area were dissimilar and contradictory. He does conclude, however, that "mylonitization is not an isochemical process and that chemical factors are possibly as important as mechanical ones".

Wintsch (1975, 1980) describes mineralogical changes that can occur due to the small scale changes in local solution chemistry that accompany mylonitization. These changes involve an increase in pH as a result of a phenomenon known as "abrasion pH" as the rock becomes crushed during cataclasis. He states that the "ionic transport presumably occurs by a relatively rapid diffusional mechanism in the fluid phase". In a study of deformed rocks in the Willimantic Fault in Connecticut, he observes a net decrease of SiO_2, Na_2O, CaO and MgO in the finer-grained, more mylonitic fractions whereas K_2O, FeO, TiO_2, MnO and H_2O shows no appreciable change. These latter elements are possibly retained in the secondary biotite that ultimately forms at the expense of garnet. The distribution of a number of minor minerals in the shear zone suggest a highly variable fluid composition on the scale of centimeters. Wintsch concludes that the geochemical trends observed across the shear zone are too large to be accounted for by primary compositional differences. In a review of the work of others, Wintsch reports a general increase in K_2O, TiO_2, H_2O, Fe^{3+} and total Fe and a decrease in SiO_2, Na_2O and CaO in shear zones relative to the undeformed rock.

The most comprehensive study reviewed by this writer is that by Kerrich *et al.* (1980) who studied structural and chemical changes in a mylonitized shear zone cutting granite at Mieville, Switzerland. In their work they conclude that chemical exchange between fluids and shear zones is responsible for modification of the original rock composition. In shear zones displaying changes in whole rock geochemistry that formed at greenschist-grade conditions, they note that "deformation was accompanied by pressure solution inviting redistribution of specific minerals by short range diffusive transport".