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Date
THE GEOLOGY OF THE CENEX MINE
BEAVERLODGE, SASKATCHEWAN

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTERS OF SCIENCE
IN THE
DEPARTMENT OF GEOLOGICAL SCIENCES
UNIVERSITY OF SASKATCHEWAN

by

Delio J. J. Tortosa

Saskatoon, Saskatchewan

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Head of the Department of Geological Sciences

University of Saskatchewan

Saskatoon, Saskatchewan, Canada
ABSTRACT

The Cenex uranium deposit occurs in gneisses and schists of the Tazin Group which represent supracrustal rocks folded and metamorphosed to amphibolite rank during the Hudsonian orogeny. During the late stages of the orogenic uplift, cataclastic deformation caused partial retrogression of the rocks to greenschist facies assemblages and their transformation into mylonites, ultramylonites, and mylonite schist. Continued uplift of these rocks led to their brittle fracture, and contemporaneous erosion on surface resulted in the formation of successor basins in the area.

The orebody occurs at the intersection of northwest and northeast-trending fault zones and the ore is localized in breccia zones, along faults, and in veins and the adjacent wallrocks. The host rocks are quartzo-feldspathic mylonites and ultramylonites and chlorite, sericite, quartz, graphite, feldspar mylonite schist. The uranium-bearing minerals are pitchblende and a uraniferous titanate, which commonly occur finely disseminated in the host rocks.

Cross-cutting relationships between mineralized structures indicate five stages of uranium mineralization separated by fracturing events. The earliest episode of mineralization is associated with late-stage retrograde
metamorphic processes in the mylonite schist, whereas later stages of mineralization are dominated by the intense hematization, carbonatization, and chloritization of the quartzo-feldspathic mylonites and ultramylonites.

Traditional genetic models, which propose magmatic and metamorphic-hydrothermal sources for the uranium and ore-bearing fluid, have been evaluated and found to be inconsistent with the geological history of the rocks and the relative time of emplacement of uranium mineralization.

In the Cenex mine area there appears to have been contemporaneity of late uplift, erosion, and deposition of continental clastics on the one hand, and brittle fracture and uranium mineralization in the basement, on the other. This suggests that the hydrologic system, during and after sedimentation, may have played an important role as a source for ore-bearing fluids. This source would be most important in areas of the basement which were faulted, fractured, and occurred close to the continental clastics — hence the close spatial relationship of the uranium deposits in the Beaverlodge area with the basal unconformity of the Martin Group.
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1. INTRODUCTION

1.1 General

The Cenex mine is located 4 kilometres southwest of Uranium City in the Beaverlodge mining area of Saskatchewan (figure 1-1 and 1-2). This area lies within the Western Craton of the Churchill Province in the Canadian Shield and was a major uranium mining camp for over 30 years. With the closure of the Eldorado Ace-Fay mine, the Cenex mine may well be the last to be described in the area. Of the 16 mines which have operated, few have been described in detail, with the exception of the Ace-Fay-Verna, part of which was studied more than 10 years ago, and the Martin Lake mine and Eagle mine which were studied in the 1950’s. A detailed examination of the Cenex uranium deposit will help to determine whether the concepts of metallogenesis proposed for the Eldorado deposits apply more widely.

Uranium mineralization was discovered in the Cenex mine area in 1948 by Charles Swenson, but it was not until 1966 that Enex Mines Limited successfully delineated the area of mineralization which later became the Cenex uranium deposit. The area lay dormant until 1974 when Eldorado Nuclear Limited purchased the property and carried out a development drilling program with which it established a structural model and determined the ore reserve. Between February 12, 1979 and August 31, 1979, Cenex shipped 33,704 tons of ore to the Eldorado mill with an average grade of 0.17% UO₂ for a total production of 115,514 lbs. The
Figure 1-1: Location of the Cenex mine

Athabasca Basin

Precambrian Shield

Phanerozoic Cover

La Ronge

100 km

108°40'

Uranium City

Eldorado Mine

CENEX MINE

Martin Basin

Goldfields

Lake Athabasca

109°00'

108°40'

59°20'

59°25'
Figure 1-2: Simplified Regional Geology of the Beaverlodge Area (in part after Tremblay, 1972)
mine ceased operations in October 1979.

Throughout the mine development, the geologists were restricted by manpower and production schedules to geologically mapping the mineralized zones. Thus only a limited amount of time could be dedicated by the author to investigations of the host rocks and ore zones underground. In the present study, reliance has been placed on information derived from a combination of underground and surface mapping, geological drill hole logs, geological cross-sections, and sampling of the rocks and ore.

In 1980, several weeks were spent surface mapping and sampling in the Cenex mine area. Outcrops at the mine are limited, but outside the immediate mine area the rocks are well exposed comprising 40-50% of the surface area. The topography is characterized by low relief and disorganised drainage controlled by northeast trending bedrock lithology and structures. Outcrops are well-rounded and in places smoothly polished by the effects of glaciers which advanced from the northeast.

1.2 Previous Geological Studies

1.2.1 Beaverlodge and the Surrounding Area

Regional mapping was carried out by Alcock (1936), Christie (1953), Bell (1959-1962), and Tremblay (1972), of the Geological Survey of Canada. A review of the geological work in the Beaverlodge area before 1968 is given by Tremblay (1972) and his memoir contains a substantial bibliography.
More recently, Sibbald and Lewry (1980) carried out a reconnaissance geological survey just south of Beaverlodge Lake. They proposed that the supracrustal rocks of the area, which comprise the Tazin Group, could be interpreted as an Aphebian sequence.

Langford (1981) completed a study of the cover rocks in the greater Beaverlodge area and encountered a greater variety of rocks than had previously been defined. This led to the establishment of the Martin Group which he considers represents a group of sedimentary successor basins formed during the closing stages of the Hudsonian Orogeny.

Descriptions of uranium deposits in the Beaverlodge area are provided by Christie (1953), Robinson (1955), Griffith (1967), Tremblay (1972), Beck (1969), and Langford (1978). In particular, Robinson, who studied the mineralogy of the uranium deposits, identified a principal mineral association consisting of pitchblende, hematite, chalcopyrite, pyrite, and galena, in gangue composed of calcite, chlorite, and quartz. In addition he noted that some deposits also contain a group of Cu-Co-Ni arsenides and sulphur-arsenides. Most of the deposits are of a simple mineralogy, but a few have a complex mineralogy (Hoewe, 1978).

The wallrock alteration in some of the deposits was studied by Dawson (1955) who noted a reddening of the wallrocks adjacent to mineralized veins and the development of hematite, calcite,
albite, chlorite, and quartz. He attributed the alteration beside radioactive veins as due to retrogressive metamorphism and metasomatism of the rocks, but found it difficult to distinguish between the products which were strictly due to retrogressive metamorphism from those directly connected with the deposition of the radioactive deposits.

Tremblay (1972) believed that uranium mineralization was likely caused by a phase of the hydrothermal action responsible for some of the retrograde metamorphism of the rocks. He suggested that there was an association between the degree of brecciation, mylonitization, hydrothermal alteration, and the extent and intensity of retrogressive metamorphism.

A number of geochronological studies to determine the age and history of uranium mineralization were carried out by Christie (1952), Robinson (1955), Tremblay (1972), and Koeppel (1969). The most detailed study was done by Koeppel who concluded that uranium mineralization took place during six discrete periods covering a time span of more than 2200 Ma. During the first two periods, uranium formed in pegmatitic deposits as uraninite (dated by the U-Pb method at 2400+/−100 Ma and 1930+/−40 Ma). These ages represent the formation of "syngenic" uranium mineralization in the basement and date periods of metamorphism and magmatic activity. The third period is the main episode of formation of "epigenetic" vein-type pitchblende at about 1780+/−20 Ma. Various reworkings affected the deposits to
different degrees at 1110+/-50 Ma, 270+/-20 Ma, and 0-100 Ma. Koeppel emphasized the fact that K-Ar ages on biotite, though variable, roughly coincide with the 1780+/-20 Ma period of uranium emplacement. He attributed this coincidence to a partial loss of argon in the biotite due to a rise in temperature at about this time or during the first period of reworking. However, the K-Ar ages can be interpreted, just as reasonably, as due to a decrease in temperature during late Hudsonian uplift (Stockwell, 1982).

Sassano (1972) studied fluid inclusions and oxygen and carbon isotopic compositions of carbonates in the ore bodies at Eldorado’s Ace, Fay, and Verna mines. He produced a metamorphic-hydrothermal concept for the origin of uranium and the ore-bearing fluids which is discussed in more detail in section 5.2.

Although many geological studies have been completed on the uranium mineralization and the host rocks, geologists are still divided on the origin of these deposits. Furthermore, they have not been able to establish, firmly, the age of the Tazin Group.

1.2.2 The Cenex Mine Area

The only previous geological study of the Cenex mine is a geological report by Meussy and Olson (1976) for Eldorado Nuclear Limited in which they summarized the local geology and established a structural model for the orebody. Turek (1962) emphasized the structural control of the orebody in the adjacent
Cinch mine (figure 1-3) and noted the small particle size of the pitchblende and its intimate association with hematite. Also, he found that the Fe and Mn content of the ore is non-linearly proportional to the U content up to 0.25% U after which they remain constant, a characteristic he thought to be due to a catalytic relationship between Fe, Mn, and U. However, the non-linear relationships are based on very few data points and as such are speculative.

Ambrose (1958), in several reports for Lake Cinch Mines Limited, discussed the structural controls on uranium mineralization in the Cinch mine. He suggested that some of the mineralized structures present in the Cenex deposit are the continuation of some of those in the Cinch mine but offset by the Crackingstone River fault (figure 1-3). Tremblay (1972) analyzed several mineralized samples from the Cinch mine (Pb /Pb method) and determined dates which average 1100 Ma. Age determinations by Collins et al. (1954) on three mineralized samples from the Cinch Lake area range from 900 to 1200 Ma (U/Pb method). Evans and Bingham (1973) carried out a paleomagnetic study of several samples of diabase dikes near the Cinch and Cenex mines, and suggested that the dikes may have been feeders to the Martin volcanics.

1.3 Approach to the Study

The main objective of the present study is to establish the geological history of the rocks and uranium mineralization in the
Figure 2-50 metres Black Bay Cataclastic Zone
Crackingsone River fault 80°
Leonard fault
Guts Lake
Cainex Mine
Cinch Lake
Uranium City Road
Diabase Dihe
Fault (defined, approximate)
shaft
adit
road
Figure 2-1• Figure 2-2
0 250 metres
Cenex mine. By determining the relative time of emplacement of the uranium mineralization during the geological development of the rocks, it is then possible to determine what the most active geological processes were during ore formation. The three genetic hypotheses proposed for the origin of Beaverlodge uranium vein-type deposits (a near surface or surficial origin, a metamorphic-hydrothermal origin, and magmatic-hydrothermal origin) can then be assessed. Each of these are briefly reviewed in the concluding chapter (section 5.2).

1.4 Methods of Investigation

1.4.1 Underground and Surface Mapping

The underground workings were mapped at a scale of 1 inch to 20 feet and mapping was limited to the ore zones except in the upper-most level where the ramp was also partially mapped. Geological sections were constructed using information from geological logs of diamond drill holes at a scale of 1 inch to 20 feet.

Reconnaissance surface mapping around the Cinch and Cenex mines was carried out at a scale of 1 inch to 100 feet and detailed geological mapping in the Cenex mine area was completed at a scale of 1 inch to 40 feet. Specimens of the rocks were collected during mapping to further supplement those gathered underground. Ground control for mapping was obtained by the use of picket lines which had been tied-in with transit surveys to a surveyed benchmark.
Due to the limited underground information, only the geology of levels 1 and 4 are presented in the text. It is on these two levels that the underground mapping is most complete and where fans of horizontal drill holes are present. Geological sections were used to project the position of the contacts and structures onto these levels. Little information is available for the northeastern portion of the mine.

1.4.2 Laboratory Methods

Petrographic descriptions and the classification of the rocks are based on visual estimates of the mineral components since modal analysis would have been too time consuming. One of the difficulties encountered in determining the ore and gangue mineralogy was the fine grain size of the constituents. X-ray line scans were done for the fine-grained ore and gangue minerals, however, only limited success was obtained due to the finely intermixed character of some of the minerals.

Radioluxographs were obtained for the mineralized samples in order to determine the distribution pattern of the radioactive minerals. Specimens were placed on polaroid 8.3 x 10.8 cm, 3000 ASA land film which was covered with a zinc sulphide coated plastic. The polaroid film was then exposed for 3 to 24 hours depending on the grade of the ore. A description of the radioluxograph technique is given by Dooley (1958).
1.5 Terminology

1.5.1 Mine Terms

During the mine operations the levels of the mine were referred to by elevation above sealevel. To simplify the terminology the levels are referred to as: level 1 (720 feet), level 2 (675 feet), level 3 (645 feet), level 4 (618 feet), level 5 (560 feet), and level 6 (510 feet), (figure 1-4). The level of Lake Cinch is 800 feet (244 m) above sealevel.

During development drilling of the orebody by Eldorado Nuclear Limited, several ore zones were outlined and referred to by number. However, during the Cenex mine development the ore zones had to be redefined. Ore zones 17, 18, and 19 were combined to form the River Ore Zone. An ore zone discovered during the Cenex mine development was termed the 20 Ore Zone (figure 1-4).

1.5.2 Classification of Rock Units

A major difficulty encountered in mapping and interpreting the geology of the basement rocks is that mylonitization masks the original nature of the rocks. In areas of intense cataclastic deformation such as at the Cenex mine, it is difficult to select lithological characteristics which are traceable from one drill hole to the next, since the rocks may vary substantially within only a few meters. Thus it became necessary to use a combination of lithologic and cataclastic classification schemes based on:
Figure 1-4: Sketch showing the shape and position of the ore zones, unit 4 and the Crackingstone River fault.
1. The major rock types present (lithologic classification; Travis, 1955).

2. The dominant cataclastic types present (cataclastic classification, Table 1-1; Higgins, 1971).

A rock unit may be characterized by a distinctive lithologic package of rocks such as, amphibolite interlayered with quartzo-feldspathic gneiss, which can be traced from one drill hole to the next. Another rock unit may consist of various leucocratic to melanocratic quartzo-feldspathic gneisses with a color index between 0 and 30%, which by themselves would not constitute mappable units, nor together form a lithologic package, but the common cataclastic texture may indicate that they fall in the range of mylonites and ultramylonites. It is, then, their thinly laminated texture and lack of porphyroclasts which can be traced reliably from one drill hole to the next.

1.5.3 Definitions

Throughout the thesis the term "mylonite" is used in a restricted sense referring to a specific cataclastic rock as indicated on Table 1-1. The use of the term "mylonite zone" refers to the rock units of the mine; "mylonitization" is used to refer to the process by which a mylonite is formed through the crushing, milling, and dynamic recrystallization of the pre-existing rocks under high pressure. The term "cataclastic zone" refers to a zone in which the rocks have undergone cataclasis resulting in either or both mylonitization and brittle fracture.
Table 1-1

CLASSIFICATION OF CATACLASTIC ROCKS

<table>
<thead>
<tr>
<th>Rocks without Primary Cohesion</th>
<th>Rocks with Primary Cohesion</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Catuclasis dominant over neominalization-recrystallization</td>
</tr>
<tr>
<td></td>
<td>Rocks without fluxion (flow) structure</td>
</tr>
<tr>
<td>Approximate Volume percent porphyroclasts in rocks with fluxion (flow) structure</td>
<td>Fault breccia</td>
</tr>
<tr>
<td>&gt;50</td>
<td>Fault breccia</td>
</tr>
<tr>
<td>&lt;50</td>
<td>Microbreccia</td>
</tr>
<tr>
<td>30</td>
<td>Nyolite</td>
</tr>
<tr>
<td>&gt;10</td>
<td>Cataclasite</td>
</tr>
<tr>
<td>&lt;10</td>
<td>Blastomylonite</td>
</tr>
</tbody>
</table>

All rocks are gradational
2. GEOLOGY

2.1 Geological Setting

The Beaverlodge mining area consists of a metamorphic basement complex which is overlain locally and unconformably by upper Aphebian red beds of the Martin Group (figure 1-2) containing mafic to intermediate volcanic flows and sills (Tremblay, 1972). The Martin Group rocks have been folded into a northeast trending syncline and are not metamorphosed.

The basement complex consists mostly of lower Proterozoic supracrustal rocks which were deformed about northeast trending fold axes and regionally metamorphosed to lower amphibolite facies during the Hudsonian orogeny (Tremblay, 1972). The area also underwent widespread granitization and granite intrusion. Towards the late stages of the Hudsonian orogeny much of the metamorphosed and granitized terrane was mylonitized and retrogressively metamorphosed to the greenschist facies.

The late stages of Hudsonian orogenesis in the area were characterized by brittle deformation resulting in the formation of numerous fractures, faults, and breccia zones, and by the deposition of the Martin continental clastics. Some faults, such as the St. Louis fault, the Black Bay fault, and the Boom Lake fault follow zones of previous intense cataclastic deformation. It is along and adjacent to these major faults, in the cataclastic zones, that the most economically significant uranium deposits occur such as the Eldorado Ace-Fay-Verna deposits, the
Cinch mine, and the Rix-Smitty mine. The Cenex uranium deposit occurs in the Black Bay cataclastic zone which is 1 to 1.5 kilometers wide and straddles the Black Bay fault (figure 1-2).

The rocks around the Cenex mine consist of quartzo-feldspathic gneisses, granitic gneiss, quartzitic gneiss, amphibolite, and chlorite schist. These rocks are mylonitized to varying degrees, fractured, brecciated, and intruded by diabase dikes trending west, northwest, and northeast (figure 1-3).

Compositional layering and a primary foliation are folded about northeast trending fold axes. The folds are isoclinal with axial surfaces trending northeast and dipping steeply. A later axial planar foliation, caused by mylonitization, cuts across the earlier foliation in the nose area of folds, and represents the dominant foliation in the rocks.

Sibbald and Lewry (1980) have recognized two major episodes of penetrative deformation in the area lying southeast of the Cenex mine. They observed a schistosity subparallel to primary layering, characterized by a submylonitic to blastomylonitic fabric which are refolded by a later episode of deformation that caused the development of north to northeast trending folds and foliation. This latter episode is tentatively correlated with the development of northeast trending folds and axial planar mylonitic fabric at the Cenex mine. The main difference between the two areas appears to be the greater intensity of mylonitization in the Cenex mine. Northeast of the Cenex mine in
the Mickey Lake area, Thomas (1982) has also noted a similar sequence of folding and fabric development, however, a mylonitic fabric is, apparently, not strongly developed.

The most distinctive feature observed on approaching the rocks of the mine across strike and in a northwest direction is the change from moderately mylonitized rocks (ie. protomylonites and mylonites) to strongly mylonitized rocks (ie. mylonites and ultramylonites), (figure 2-1, table 2-1). This change is most apparent in the quartzo-feldspathic gneisses which are massive, fine grained, and lack a well developed foliation outside the mine area, but which become intensely mylonitized and finely laminated closer to the mine. The rocks in the mine therefore appear to occur in a local zone of intense shearing.

The Black Bay cataclastic zone, the Black Bay fault, the Leonard fault, and structures in the Cinch and Cenex mines are offset by a right-hand displacement along the Crackingstone River fault which strikes east-west and dips 80 south (figures 1-3 and 2-2). Using similar cross-cutting structures in the Cenex and Cinch mines as models, the net slip of the Crackingstone fault is estimated to be about 575 m with the hanginwall moving up and west. It is possible that the structures in the Cenex mine on the first level represent the offset continuation of structures on the fourth level of the Cinch mine.

The Crackingstone River fault consists of a 3 to 5 m wide zone containing brecciated rock and thin seams of fault gouge with an
Table 2-1: Legend and Symbols for figure 2-1

LEGEND

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Lithologic Classification</th>
<th>Cataclastic Classification</th>
<th>Mine Units with Similar Rock Type</th>
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<td>Q-F Gneiss</td>
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<td>c</td>
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<td>Mylonite Gneiss &amp; Blastomylonite</td>
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<td>d</td>
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<td>Protomylonite</td>
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<td>g</td>
<td>Quartzitic Gneiss</td>
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SYMBOLS

- Foliation (dip: unknown, inclined)
- Contact (defined, approximate)
- Folded Contact
- Minor Folds
- Fault (approximate)
- Diabase Dike
- Radioactive Showing
- Raise
- Shaft
Figure 2-2: Major structures and mine workings in the Cinch and Cenex Mines and area.
Figure 2-1: The Geology of the Cenex-Cinch Mines area.
alteration zone up to 50 m wide on either side. The alteration consists of pseudomorphic replacement of original mineral grains by either kaolinite or hematite, leaving the original texture and foliation unchanged.

At the Cenex mine, the lateral and vertical distribution of this alteration is not well known, however, most of the alteration occurs on the footwall of the Crackingstone River fault. Hangingwall gneisses are unaltered on level 1, but on the fourth level there is up to 15 m of altered rock adjacent to the fault. Some parts of the orebody on level 1 are affected by alteration thought to be associated with the Crackingstone River alteration zone. Ore grades here show no significant change due to the effects of this alteration.

2.2 Rock Units

The rocks in the Cenex mine are divisible into seven units which together constitute a northeast trending mylonite zone dipping steeply southeast (figures 2-3, 2-4, 2-5; Table 2-2).

2.2.1 Units 1 and 3

Units 1 and 3 are considered jointly because they have similar mineralogy and texture, but insufficient information is available to determine whether or not they are parts of the same unit.

The units consist of leucocratic to melanocratic quartzo-feldspathic gneisses (plates la and lc) and comprise about one-half of the rocks in the mine.
Figure 2.3: Geology of the Cenex Mine, Level 1
Figure 24: Geology of the Cenex Mine, Level 4
Figure 2-5: Geological cross-section at 100 00 NE.
Table 2-2: Legend and Symbols for figures 2-3, 2-4, and 2-5

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<tr>
<th>ROCK UNIT</th>
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<tr>
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<td>Diabase</td>
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</tbody>
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**SYMBOLS**

- Foliation
- Fault (defined, approximate)
- Contact (defined, approximate)
- Vein (dip: inclined, unknown)
- Breccia
- Mineralized Zone (> 0.1% U 0 )
- Crackingstone River fault alteration zone
Mylonitization has transformed them into mylonites and ultramylonites, and in some places the rocks are so fine grained that they have the appearance of chert on a fresh, broken surface.

The units are characterized by their fine grain size, lack of visible porphyroclasts, and thin laminations which define a major foliation. Specific lithic types are not mappable due to the many variations that occur over a few metres and which are attributed to lithologic and structural variations in the original rocks.

Leucocratic gneiss comprises more than two-thirds of the unit and is fine-grained, orange to red, foliated, and consists of quartz and feldspar with up to 20% biotite. Melanocratic gneiss is similar except that mafic minerals (mostly biotite) constitute from 20% to 40% of the rock. Contacts between the gneisses are gradational over less than a metre.

In thin section, mylonite consists of porphyroclasts of orthoclase, microcline, and plagioclase set in a groundmass of crushed and milled quartz, recrystallized quartz, biotite, and a few opaques (Plate 1a). The porphyroclasts appear roughly spherical to ellipsoidal with the long axis generally parallel to the foliation (plate 1b). Some porphyroclasts are fractured and the gaps and strain shadows are filled with neoformed quartz. The feldspars are slightly sericitized. In ultramylonite, porphyroclasts greater than 0.2 mm across (visible to the eye)
Plate 1: Unit 1 and 3

Photo a: Photograph of a slabbed handspecimen of quartzo-feldspathic gneiss (mylonite) showing porphyroclasts of feldspar in a finely laminated matrix.

Photo b: Photomicrograph of quartzo-feldspathic gneiss (mylonite) showing porphyroclasts of feldspar contained in a fine-grained, predominantly quartz groundmass. Plane polarized light. Scale bar is 1.0 mm.

Photo c: Photograph of a slabbed handspecimen of quartzo-feldspathic gneiss (ultramylonite) showing finely laminated texture and few to no visible porphyroclasts.

Photo d: Photomicrograph of quartzo-feldspathic gneiss (ultramylonite) showing the very fine grain size and laminated texture. Plane polarized light. Scale bar is 1.0 mm.
comprise less than 10% of the rock (plate 1c, 1d).

In both mylonite and ultramylonite, milled quartz is extremely fine grained and occupies from 20-70% of the groundmass. A very light orange color comes from finely disseminated hematite which is also present in feldspar porphyroclasts. Quartz also occurs as thin layers and lenses constituting from 10% to 40% of the groundmass in places and consists of recrystallized quartz grains. Biotite occurs as small flakes which form thin seams aligned parallel to the foliation and which are deflected around porphyroclasts. Muscovite occurs interleaved with the biotite in some places.

An unidentified green to black, semi-opaque mineral is distributed sporadically in the rocks and occurs as clots surrounded by biotite grains. These clots are thought to represent altered mafic porphyroclasts. Subhedral to anhedral grains of pyrite occur in melanocratic ultramylonite and are elongate parallel to the foliation.

In both rock units, recrystallization during mylonitization resulted in the formation of a quartz-biotite-muscovite metamorphic mineral assemblage which, in part, defines the foliation in the rock.

2.2.2 Unit 2

Unit 2 consists of amphibole-feldspar gneiss, quartzo-feldspathic gneiss, and granitic gneiss (plate 2).
comprise less than 10% of the rock (plate 1c, 1d).

In both mylonite and ultramylonite, milled quartz is extremely fine grained and occupies from 20-70% of the groundmass. A very light orange color comes from finely disseminated hematite which is also present in feldspar porphyroclasts. Quartz also occurs as thin layers and lenses constituting from 10% to 40% of the groundmass in places and consists of recrystallized quartz grains. Biotite occurs as small flakes which form thin seams aligned parallel to the foliation and which are deflected around porphyroclasts. Muscovite occurs interleaved with the biotite in some places.

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In both rock units, recrystallization during mylonitization resulted in the formation of a quartz-biotite-muscovite metamorphic mineral assemblage which, in part, defines the foliation in the rock.

2.2.2 Unit 2

Unit 2 consists of amphibole-feldspar gneiss, quartzo-feldspathic gneiss, and granitic gneiss (plate 2).
Plate 2: Unit 2

Photo a: Photograph of a slabbled handspecimen of amphibole-feldspar gneiss (protomylonite) containing quartzo-feldspathic layers.

Photo b: Photomicrograph of the contact area between amphibole-feldspar gneiss an the quartzo-feldspathic layer. Note the microfractures in the quartzo-feldspathic layer. Plane polarized light. Scale bar is 1.0 mm.

Photo c: Photomicrograph of amphibole-feldspar gneiss showing fractured porphyroclasts of hornblende (H). Fractures contain biotite and actinolite (A). Strain shadows contain actinolite. Plane polarized light. Scale bar is 0.5 mm.

Photo d: Photomicrograph of quartzo-feldspar layer under high magnification showing microfractures containing biotite, actinolite, sphene, and quartz. Plane polarized light. Scale bar is 0.5 mm.

Photo e: Photograph of slabbled handspecimen of quartzo-feldspathic gneiss (mylonite gneiss).

Photo f: Photomicrograph of quartzo-feldspathic gneiss (mylonite gneiss) showing layers containing slightly sericitized feldspar porphyroclasts separated by layers of recrystallized quartz. Plane polarized light. Scale bar is 1.0 mm.

Photo g: Photograph of a slabbled handspecimen of granite gneiss showing contact with amphibole-feldspar gneiss.

Photo h: Photomicrograph of granite gneiss showing large plagioclase (albite) porphyroclasts crushed along the cleavage direction. Plane polarized light. Scale bar is 1.0 mm.
Amphibole-feldspar gneiss forms about 80% of the rock unit and has been transformed into protomylonite; the quartzo-feldspathic gneiss and granitic gneiss have been turned into mylonite gneiss and protomylonite respectively. This unit is defined by its predominantly mafic character and less by cataclastic textures. Rock types within the unit are not mappable. The unit is about 15 m thick near surface decreasing to about 10 m on level 4 with no notable changes in thickness occurring along strike. Contacts of unit 2 with units 1 and 3 vary from sharp to gradational over less than a metre.

The amphibole-feldspar gneiss is dark green to grey-black, medium grained and contains quartzo-feldspathic layers from a few centimetres (plate 2a), to a few metres thick. Porphyroclasts of plagioclase and olive-green hornblende occur in a groundmass of biotite, quartz, sphene, epidote, and actinolite. Hornblende porphyroclasts are most abundant and are aligned parallel to the foliation. Strain shadows contain actinolite, and where the porphyroclast is fractured, the gaps are filled with actinolite and biotite (plate 2c).

Many of the feldspar porphyroclasts are clouded by alteration products, however, some of the less altered ones show relict albite twinning. Microprobe analyses of plagioclase indicate a range in composition from oligoclase to andesine. In some fractured porphyroclasts, the gaps contain biotite.

Quartzo-feldspathic gneiss consists of about 50% quartz, 40%
feldspar, and 10% biotite and accessory minerals. In centimetre thick quartzo-feldspathic layers in the amphibole-feldspar gneiss, slightly sericitized and hematized orthoclase feldspar form porphyroclasts which are enveloped and partly replaced by quartz. Actinolite occurs as 0.1-1.0 mm grains in contact with quartz and orthoclase. Microfractures which occur at the contact with amphibole-feldspar gneiss contain actinolite, biotite, sphene, epidote, and quartz (plates 2b, 2d). In thicker layers (Plate 2e) the predominant mafic mineral is biotite which occurs as small flakes forming discontinuous seams parallel to the foliation and also surround porphyroclasts of feldspar (plate 2f). The recrystallized quartz is dark and consists of nearly equigranular grains about 0.2 mm across that display a slight elongation defining part of the foliation. Small amounts of milled quartz occur locally.

Granitic gneiss occurs as layers and boudins up to 0.3 m thick (plate 2g). This rock is orange, medium to coarse grained, with quartz and feldspar comprising about 35% and 65% respectively. Plagioclase porphyroclasts are from 0.4 to 3.0 mm across and are weakly sericitized and hematized. Zones of crushed feldspar occur along cleavage planes in some of the plagioclase grains (plate 2h). White quartz embays and surrounds the porphyroclasts and crushed zones. It consists of slightly elongate, 0.1 to 0.2 mm, recrystallized grains with sutured grain boundaries. A few grains of euhedral pyrite are scattered throughout the quartz.
The granitic gneiss is thought to represent a granite pegmatite which has been moderately crushed and transformed into a protomylonite. The feldspar porphyroclasts and crushed zones of feldspar represent originally much larger grains about 0.5 to 3 cm across.

2.2.3 Unit 4

Most of the unit consists of chlorite, sericite, quartz, feldspar, graphite schist which has been transformed into mylonite schist. Quartzo-feldspathic gneiss, quartzitic gneiss, and granitic gneiss which occupy about 10% of the unit have been turned into mylonite, blastomylonite, and protomylonite respectively (plates 3a, 3c, 3e). The mylonite is similar to that in units 1 and 3. The unit is defined by the characteristic mineralogy and texture of mylonite schist. Contacts with other units are sharp or gradational over less than a metre.

Mylonite schist is grey to grey-green and fine grained consisting of about 30-35% sericite, 15-20% chlorite, 25-30% quartz, 15-20% feldspar porphyroclasts, and up to 10% graphite. Quartz, sericite, chlorite, and graphite form a schistose groundmass to the yellow-orange feldspar porphyroclasts (plate 3b). Locally the proportions of each of the minerals vary and can form sericite-graphite schist, sericite-quartz schist, and feldspar-quartz-sericite schist.

Feldspar porphyroclasts range from 0.1 to 5.0 mm in size, and are partly to completely altered to hematite and white mica.
Plate 3: unit 4

Photo a: Photograph of slabbed hand specimen of mylonite schist showing porphyroclasts of feldspar contained in a fine-grained schistose groundmass.

Photo b: Photomicrograph of mylonite schist showing the lense-like shape of porphyroclasts and the presence of sericite-chlorite seams, and seams of recrystallized quartz. Plane polarized light. Scale bar is 1.0 mm.

Photo c: Photograph of slabbed handsample of quartzitic gneiss. Cross-cutting fractures contain hematite and chlorite.

Photo d: Photomicrograph of quartzitic gneiss showing elongate shape of quartz grains. Crossed-nicols. Scale bar is 0.5 mm.

Photo e: Photograph of slabbed hand specimen of granite gneiss (protomylonite).

Photo f: Photomicrograph of granite (protomylonite). Dark areas are fractured and crushed feldspar; white areas are crushed and recrystallized quartz. Plane polarized light. Scale bar is 1.0 mm.
Chlorite also occurs as flake-like grains forming thin sheets parallel to the foliation. In some grains, graphite occurs along the cleavage planes and in TiO₂ perthite phases. The analysis of the mineral chemistry and the structural modeling indicates that chlorite is a secondary mineral in the chlorite-sillimanite and muscovite-sillimanite replacement zones. At low temperatures, graphite occurs.
The cores of some porphyroclasts are altered to fine-grained hematite with the remainder altered to white mica. Irregular to spherical quartz grains occur in some porphyroclasts. Microprobe analyses of the least altered porphyroclasts (displaying albite twinning) indicate a composition ranging from albite to andesine. In fractured porphyroclasts the interstices are filled with sericite. Quartz occurs as thin layers generally less than 1 mm thick which deflect around porphyroclasts. Quartz grains are either equigranular, with a well-developed foam texture, or can occur as elongate grains with sutured grain boundaries.

Seams of sericite, generally less than 5 mm thick, consist of very fine-grained sericite flakes aligned roughly parallel to the foliation. Similar sized grains of chlorite are dispersed throughout the seams. In some places, recrystallized and unoriented muscovite and chlorite grains occur in a groundmass of sericite.

Chlorite also occurs as flake-like grains forming thin seams parallel to the foliation. In some grains graphite occurs along the cleavage planes and a TiO polymorph (anatase) occurs in 2 places. Microprobe analysis of the chlorite indicates a composition at the boundary between prochlorite and pycnochlorite. Analyses also indicate the presence of small quantities of potassium in the chlorite structure which suggests replacement from biotite.

Albite, hematite, and calcite occur in thin veinlets parallel
to and cross-cutting the schistosity. It is uncertain whether these minerals constitute a part of the metamorphic mineral assemblage, or whether they were introduced later.

Layers of fine-grained quartzitic gneiss up to 1 m thick occur in sharp contact with mylonite schist. This rock is pale white and consists of 95% recrystallized quartz which is cut by thin veinlets of chlorite and hematite (plate 3c). Foliation is not apparent in hand specimen but is clearly seen in thin sections and is defined by elongate quartz grains (plate 3d). The foliation is at an angle of about 35° to the dominant foliation in the unit. The quartz grains appear to have a unimodal grain size averaging 0.5 mm and display sutured grain boundaries.

Lenses of granitic gneiss occur in sharp contact with mylonite schist. The rock is pale orange, medium to coarse grained, and consists of K-feldspar and plagioclase porphyroclasts 1-3 mm across set in a white, fine-grained, quartz groundmass (plates 3e, 3f). The groundmass has about 75% recrystallized quartz and 25% fine-grained crushed quartz and feldspar. Recrystallized quartz grains are from 0.1 to 0.5 mm, elongate, and have sharp grain boundaries. Traces of chlorite occur scattered throughout the groundmass. The granite gneiss is thought to represent a granite pegmatite which has been moderately crushed and transformed into a protomylonite. The rock is similar to the granitic gneiss (protomylonite) in unit 2.
This unit consists mostly of layered quartzo-feldspathic gneiss in the southwestern part of the unit changing to non-layered, quartzo-feldspathic gneiss in the northeast (plates 4a, 4c). Granitic gneiss occupies the extreme northeastern part of the unit in the lower levels and is described in detail in section 2.2.6. Mylonitization has turned the layered quartzo-feldspathic gneiss into mylonite gneiss, the non-layered gneiss into mylonite and ultramylonite, and the granite gneiss into protomylonite. Boundaries between the rock types are not mappable.

In hand specimen and diamond drill hole logs the layered quartzo-feldspathic gneiss generally consists of leucocratic layers 1-5 mm thick separated by melanocratic layers 1-5 cm thick. Feldspar porphyroclasts, which make up about 40% of the rock, tend to concentrate in leucocratic layers and are contained in a groundmass of recrystallized quartz. Both plagioclase and K-feldspar are slightly sericitized, and fractures, where present, are filled with neoformed quartz and chlorite.

In melanocratic layers, biotite occurs as small grains, in places intergrown with muscovite, forming a foliated groundmass to feldspar porphyroclasts (plate 4b). Biotite also fills gaps in fractured porphyroclasts. Thin lenses of recrystallized quartz and small grains of zircon occur in the biotite groundmass. The recrystallized quartz consists of nearly
Plate 4: Unit 5

Photo a: Photograph of slabbed handspecimen of layered quartzo-feldspatic gneiss (mylonite gneiss).

Photo b: Photomicrograph of layered quartzo-feldspatic gneiss showing layers of recrystallized quartz, milled quartz, and fine-grained biotite. Crossed-nicols. Scale bar is 0.5 mm.

Photo c: Photograph of slabbed handspecimen of non-layered quartzo-feldspatic gneiss (mylonite and ultramylonite) showing large porphyroclasts of feldspar contained in a very fine-grained laminated groundmass.

Photo d: Photomicrograph of quartzo-feldspatic gneiss (ultramylonite) showing a layer of recrystallized quartz surrounded by mostly milled quartz. Crossed-nicols. Scale bar is 0.5 mm.
equidimensional grains averaging 0.2 mm across, that display sharp grain boundaries and a foam texture. Milled quartz occurs irregularly and in lesser amounts than the recrystallized quartz.

Non-layered, quartzo-feldspathic gneiss is grey to orange and fine grained. It consists of 20-40% feldspar porphyroclasts set in an aphanitic, laminated, siliceous groundmass (plate 4c). Plagioclase and K-feldspar grains can vary from 1 to 10 mm across but large porphyroclasts constitute less than 10% of the rock. The groundmass is made up of milled quartz but also contains thin lenses of recrystallized quartz partly defining the foliation (plates 4f). Biotite occurs as small oriented flakes within recrystallized quartz lenses and in places is interleaved with muscovite, and also occurs in strain shadows to porphyroclasts.

Recrystallization during mylonitization apparently resulted in the formation of a quartz-biotite-muscovite metamorphic mineral assemblage similar to that in units 1 and 3.

2.2.5 Unit 6

This unit is 3 to 8 m thick and consists of interlayered amphibolite and quartzitic gneiss. The proportions of each rock type are variable and thought to be due to changes in the lithology and structure of the original rocks prior to mylonitization. Mylonitization has transformed the amphibolite and quartzitic gneiss into protomylonite and blastomylonite respectively. Contacts with the adjacent units are either sharp or gradational over less than a metre. Granitic gneiss occupies
Plate 5: Unit 6

Photo a: Photograph of slabbed handspecimen of quartzitic gneiss (blastomylonite).

Photo b: Photomicrograph of quartzitic gneiss (blastomylonite) showing altered feldspar porphyroclasts contained in recrystallized quartz. Plane polarized light. Scale bar is 1.0 mm.

Photo c: Photomicrograph of quartzitic gneiss under high magnification showing elongate quartz grains and sutured grain contacts. Crossed-nicols. Scale bar is 0.5 mm.

Photo d: Photograph of slabbed handsample of amphibole-feldspar gneiss (protomylonite) containing thin quartz-rich layer.

Photo e: Photomicrograph of amphibole-feldspar gneiss showing feldspar porphyroclasts in a biotite groundmass. Crossed-nicols. Scale bar is 0.5 mm.

Photo f: Photomicrograph of amphibole-feldspar gneiss showing chloritized amphibole porphyroclasts in a biotite and chlorite groundmass. Crossed-nicols. Scale bar is 0.5 mm.
a) The layers, which range from 0.5 to 1.0 cm thick, are formed by the preferential concentration of porphyroclastic and of chlorite (plate 9b). The porphyroclasts, oriented parallel to the foliation, consist of from 90% to 93% or more mafic minerals...
the extreme northeastern part of the unit on the lower levels, however, its extent is not well defined. It has been transformed into a protomylonite and is described in section 2.2.6.

Quartzitic gneiss is pale grey and white, fine-to-medium grained, and thinly layered with no obvious foliation visible in handspecimen (plate 5a). The layers, which range from 0.5 to 1.0 cm thick, are formed by the preferential concentration of porphyroclasts and of chlorite (plate 5b). The porphyroclasts, comprising about 10% of the rock, are partly to completely sericitized and weakly hematized. Some of the least altered ones display albite twinning.

Quartz, which constitutes about 80% of the rock, occurs as elongate grains with sutured boundaries that define a foliation parallel to the layering (plate 5c). Chlorite-rich layers comprise about 10% of the rock and consist of flakey grains oriented parallel to the layering.

Amphibolite consists of from 50% to 95% or more mafic minerals and exhibits some compositional layering. That with more than 95% mafic minerals is green, nearly massive, fine-to-medium grained, and contains amphibole porphyroclasts (optically identified as cummingtonite) within a minor amount of chlorite groundmass. Some of these porphyroclasts are slightly carbonatized. Chlorite also occurs in seams a few millimetres thick which are nearly parallel to a poorly defined foliation. No feldspar porphyroclasts were observed in the rock.
Amphibolite with 50% to 95% mafic minerals is grey to black, fine-to medium-grained, and slightly foliated (plate 5d). It is characterized by feldspar-amphibole layers 1-2 cm thick separated by thinner feldspar-biotite layers consisting of slightly sericitized plagioclase porphyroclasts contained in a foliated groundmass of biotite (plate 5e). The plagioclase exhibits albite twinning indicating an albite-oligoclase composition. Biotite flakes forming the groundmass are pseudomorphically replaced by chlorite in some places. The feldspar-amphibole layers consist of porphyroclasts of pseudomorphosed clinoamphibole and plagioclase contained in a foliated groundmass of biotite and chlorite (plate 5f). The clinoamphibole is altered to chlorite which is non-pleochroic and can be distinguished from the pleochroic chlorite in the groundmass; the plagioclase has been replaced by a fine-grained mixture of sericite and white mica (possibly kaolinite).

The chloritization of amphibole and the kaolinitization of plagioclase are believed to be alteration affects related to the Crackingstone River fault.

2.2.6 Unit 7

Unit 7 consists of granitic gneiss and quartzo-feldspathic gneiss which have been transformed into protomylonite and mylonite respectively. Granitic gneiss occurs in the northeastern part of the unit and changes to quartzo-feldspathic gneiss in the southwest. The granitic gneiss is orange,
Plate 6: Unit 7

Photo a: Photograph of slabbed handspecimen of quartzo-feldspathic gneiss (protomylonite).

Photo b: Photomicrograph of quartzo-feldspathic gneiss showing feldspar porphyroclasts in a recrystallized and crushed quartz groundmass. Crossed-nicols. Scale bar is 0.5 mm.

Photo c: Photograph of slabbed handspecimen of granite gneiss (protomylonite) showing a poorly developed foliation.

Photo d: Photomicrograph of granite gneiss showing plagioclase, microcline, and orthoclase feldspar porphyroclasts in a milled and partly recrystallized quartz groundmass. Crossed-nicols. Scale bar is 0.5 mm.
observes the original mineralogy of the quartz-feldspathic ground, but pre-existing textures and major minerals are still
medium-to-coarse grained, and moderately to poorly foliated (plate 6a, 6c). It consists of 30-60% albite, microcline, and orthoclase porphyroclasts ranging from 0.5 to 5 mm across, contained in a fine-grained quartz groundmass (plates 6b, 6d).

The groundmass consists of about equal proportions of recrystallized quartz and milled quartz. The recrystallized quartz grains are 0.1 to 0.2 mm in size with, generally, sharp contacts. Chlorite occurs in gaps in fractured porphyroclasts, in strain shadows, and is interleaved with muscovite. Zircon and anatase(?) occur as accessory minerals.

Alteration associated with the Crackingstone River fault obscures the original mineralogy of the quartzo-feldspathic gneiss, but pre-existing textures and major minerals are still preserved in some places and indicate that the rock is similar to quartzo-feldspathic gneiss in units 1, 3, and 5.

2.3 Metamorphism

The rocks in the Cenex mine have been affected by more than one period of metamorphism. The minerals in strain shadows, microfractures, and recrystallized in the groundmass represent the metamorphic minerals formed during mylonitization; porphyroclasts represent the metamorphic minerals formed prior to mylonitization. However, many porphyroclasts, particularly plagioclase, are altered and thus their usefulness as indicators of the pre-existing metamorphic grade is limited.
2.3.1 Prograde Metamorphism

The metamorphic index minerals which formed prior to mylonitization occur as relics in the rocks and are best preserved in units 2 and 6 (figure 2-6). These units are composed mostly of amphibole-feldspar gneiss and amphibolite, and indicate amphibolite facies metamorphism. This represents the same metamorphic grade as the regional (prograde) metamorphism which affected the pre-Martin rocks in the area (Tremblay, 1972; Kupricka and Sassano, 1972).

In the other units, a few calcic plagioclase porphyroclasts may also reflect the originally higher grade prior to mylonitization. However, many plagioclase porphyroclasts range from albite to andesine, possibly due to albitization during retrograde metamorphism. The irregular albitization of plagioclase during retrograde metamorphism has also been noted in mylonite zones in northeast Alberta (Watanabe, 1965).

Granitic gneiss in units 5, 6, and 7 is similar to Tremblay’s "metasomatic granite" which formed during regional metamorphism and is commonly found throughout the area (Tremblay, 1972). The granitic gneiss is thought to originally have been a granitic intrusion which was emplaced prior to mylonitization and which is better exposed to the northeast of the Crackingstone River fault (figure 2-1). Granitic gneisses which form boudins and layers within units 2 and 4 are in sharp contact with the surrounding rocks and are believed to represent granite pegmatites which formed during metamorphism and which later were moderately
Figure 2-6: The Distribution of Metamorphic Facies on Section 100+00 NE

Metamorphic Facies    Mineral Assemblage

Prograde
(preserved relics)

Lower Amphibolite
(Minimum)
Hornblende-Plagioclase
Cummingtonite-Plagioclase

Retrograde

Middle Greenschist
(biotite zone)
Quartz-biotite-muscovite
Quartz-biotite-actinolite-epidote

Lower greenschist
(chlorite zone)
Quartz-sericite-chlorite-graphite
+/−albite,+/−calcite,+/−hematite
crushed and transformed into protomylonites.

2.3.2 Retrograde Metamorphism

All the rocks in the mine have been affected by greenschist facies retrograde metamorphism. The presence of recrystallized or neoformed minerals occurring parallel to and partly defining the rock fabric, and their presence in strain shadows and in gaps in fractured porphyroclasts, indicate that the retrograde metamorphism and mylonitization were contemporaneous.

The change from amphibolite to greenschist facies is commonly taken as a change in the composition of amphibole from hornblende to actinolite (Turner and Verhoogen, 1960). In addition three chemical criteria are used here which indicate a decrease in metamorphic grade for amphiboles (revised after Longiaru, 1980), and these are:

iv
1. A decrease in the Al content.
2. A decrease in the Fe/Fe+Mg ratio.
3. An increase in the Fe/Al ratio

Eleven microprobe chemical analyses were made on olive-green amphibole (hornblende) occurring as porphyroclasts, and blue-green amphibole (actinolite) occurring in strain shadows and as separate grains in the amphibole-feldspar gneiss and quartzo-feldspathic gneiss of unit 2 (plates 2c, 2d). Figure 2-7 indicates that the amphibole in strain shadows formed at a lower metamorphic grade than the adjacent amphibole porphyroclasts.
The compositional variations of amphibole porphyroclasts (solid triangles) and amphibole in adjacent strain shadows (solid circles) in unit 2. The boundary between actinolitic and hornblendic amphiboles is set at an atomic proportion of Si  = 7.375 per unit cell (Al  = 0.625), (Leake, 1978).
All Y (atomic proportion)
Mylonitization of the pre-existing metamorphic rocks in unit 2 apparently was initiated under greenschist facies metamorphic conditions at a slightly lower grade than the (lower) amphibolite facies regional metamorphism.

The biotite zone of the greenschist facies is indicated by the assemblage: actinolite-biotite-epidote-sphene-quartz which occurs in the amphibole-feldspar gneiss in unit 2. Strain shadows to amphibole porphyroclasts in unit 6 contain chlorite and biotite, and in units 1, 3, 5, and 7 the metamorphic mineral assemblage is quartz-biotite-muscovite+-chlorite. These metamorphic minerals represent at least the biotite zone of the greenschist facies.

The chlorite zone of the greenschist facies is indicated in unit 4 by the assemblage quartz-sericite-chlorite-graphite, with the possible addition of albite, hematite, and calcite occurring in some parts of the unit, although these could be later additions. The chlorite has an Fe/Fe+Mg ratio of about 0.5 and some grains contain small amounts of potassium. These characteristics suggest the replacement of biotite by chlorite, and suggests that the rocks in unit 4 were retrogressively metamorphosed under at least middle greenschist metamorphic conditions, similar to the adjacent units, prior to retrogression to lower greenschist facies.

2.3.3 The Distribution of Retrograde Metamorphic Assemblages

There is a roughly symmetrical pattern of retrograde metamorphism displayed in the rock units about unit 4 (figure
Figure 2-8: Stages in the Development of the Mylonite Zone

A schematic diagram illustrating the three stages in the development of the mylonite zone in the Cenex mine.

STAGE I: All the rocks in the mine undergo mylonitization under middle greenschist facies conditions.

STAGE II: Mylonitization is localized in unit 4 and occurs under lower greenschist facies conditions.

STAGE III: Deformation changes from mylonitization to brittle deformation as the rocks are uplifted.
STAGE III
Active zones of microbrecciation and shearing

STAGE II

STAGE I
Active zone
This pattern is interpreted to be the result of mylonitization of the pre-existing metamorphic rocks, initially at a depth characterized by middle greenschist metamorphic conditions and affecting all the rocks in the mine (Stage I, figure 2-8), followed by mylonitization localized in unit 4 at a shallower depth and lower metamorphic grade (chlorite zone), (Stage II, figure 2-8). There is no mineralogical evidence in support of a decrease in pressure in unit 4. Perhaps this is because the pressure difference between middle and lower greenschist facies is not detectable in these alumina-poor rocks. However, a decrease in pressure is implied by the fact that the first signs of brittle deformation in the mylonite zone occur in unit 4 in the form of microbrecciation and shearing (Stage III, figure 2-8). The microbrecciation and shearing occur parallel to the schistosity in unit 4, and are interpreted as a further decrease in the width of the active mylonite zone, but at a depth shallow enough to result in the brittle fracture of the rocks.

2.4 Structure

Uranium mineralization in the Cenex mine occurs in breccias, faults, and veins in the River Ore Zone and the 20 Ore Zone. The main structures defined in the orebody are: the Breccia Zone, the Shear Zone, the River Zone fault, and the 20 Zone fault (figure 2-9).

2.4.1 The Breccia Zone

Brecciated rocks of units 3 and 4 constitute the Breccia Zone
which is shaped like a synform plunging 70 in a southerly direction. The Breccia Zone is subdivided into a west arm consisting of microbreccia, and a hinge area and east arm consisting of fault breccia. Although the microbreccia and fault breccia were mapped together as a continuous zone they are not cogenetic; relative ages are discussed in section 2.4.6.

Microbreccia consists of 1 mm to 3 cm fragments of mylonite schist set in a fine-grained groundmass of minute fragments of mylonite schist, and of sericite, chlorite, quartz, and titania polymorphs (Plates 8a, 8c; page 76). The microbreccia is described in some geological logs as "unoriented feldspar and quartz augen and clasts in a mafic groundmass or separated by layers of schist", reference is also made to "contorted mylonite schist" occurring in some portions. These features attest to the inhomogeneity of the microbreccia.

The position occupied by microbreccia is represented by the area with a gentle slope on the structure contour diagrams of the Breccia Zone (figure 2-10 and 2-11). These diagrams indicate that the microbreccia, for the most part, is contained within and is concordant with unit 4 (see also figure 2-9). The microbreccia thickens from about 1 m on level 1 to about 5 m on level 4, and pinches-out about 70 m southwest of the hinge area. In some places, rocks of unit 4 adjacent to the microbreccia are contorted over about a metre; in most places, the microbreccia and adjacent rocks are in sharper contact. A small zone of
Figure 2-9: Major Structures as Viewed on Level 4, Conex Mine

Location of the major structures on level 4 and referred to in the text; also indicated is the position of the reference plane used to construct the structure contour diagrams (045 , 70 SE).

SYMBOLS

UNIT 4

BRECCIA
Figure 2-10: Structure Contours: Breccia Zone, Hangingwall

Structure contours of the hangingwall of the Breccia Zone; also indicated is the configuration of the Breccia Zone at each level of the mine (viewed in perspective).

SYMBOLS

Structure contour representing points of equal distance above the reference plane. (distances are in feet)

Data point

Dashed line is the footwall of the Breccia Zone on the level.

Solid line is the hangingwall of the Breccia Zone on the level.

Line a---b is a reference line representing the intersection of the reference plane and level 1.
Figure 2-11: Structure Contours: Breccia Zone, Footwall

SYMBOLS

Structure contour representing points of equal distance (in feet) above the reference plane.

Data point

Line a---b is a reference line representing the intersection of the reference plane and level 1.
microbreccia occurs on the footwall of unit 4, but it is unmineralized and only of local extent (figure 2-9).

Fault breccia in the hinge area and east arm of the Breccia Zone consists mostly of fragments of unit 3, ranging from 1 to 5 cm across, contained in either a chlorite or carbonate matrix. The fragments are either tightly packed and unrotated, or they display some rotation, and are contained in a carbonate-rich matrix comprising from 25 to 50% of the rock (plate 9a; page 78). The fault breccia represents more than one period of fracturing, and the cross-cutting relationships are discussed in section 2.4.6.

The position occupied by fault breccia is represented by the area with a steep slope on the structure contour diagrams of the Breccia Zone (figure 2-10 and 2-11). The steep contours reflect the cross-cutting relationship between this portion of the Breccia Zone and the foliation in the rocks. The zone of fault breccia pinches-out above level 2, but thickens in the lower levels and develops a pod-like shape in the hinge area (figure 2-9 and 2-10). This geometry persists into the east arm of the Breccia Zone where a pod of breccia is 3-5 m thick, and about 30 m long, extending an estimated vertical distance of about 90 metres; the long axis of the pod rakes 60° southeast in the plane formed by the east arm of the Breccia Zone. The shape of this breccia pod coincides with the shape of the mineralized zone which it contains, as shown on levels 4, 5, and 6 in the east arm.
Generally the fault breccia grades into unfractured rock over about a metre, but in some places, such as on level 5, the fault breccia is bounded by faults. During the mining operations by Cinch Lake Mines Limited a similar pod of mineralized fault breccia was mined-out further to the southeast along the River Zone fault, but information from this area is limited.

In the Breccia Zone, cross-cutting relationships indicate that the fault breccia formed later than the microbreccia. The continuity which is apparent from microbreccia to fault breccia is partly attributed to the fact that they were mapped together, and partly to the fact that the hinge area appears to have been a structurally weak zone resulting from earlier microbrecciation and shearing which subsequently formed the locus for the later brecciation and faulting.

2.4.2 The Shear Zone

The Shear Zone consists of sheared rocks of units 3 and 4 and is divided into a northeast and southwest portion separated by the hinge area of the Breccia Zone (figure 2-9). These portions strike northeast with a dip of about 70° southeast, and are roughly parallel to the foliation. Both portions of the Shear Zone vary from 3 to 5 m in width, but precise boundaries are difficult to define particularly in the mylonite schist since it is difficult to distinguish between the foliations in drill core.

The southwest portion of the Shear Zone occurs on the
hangingwall side of unit 4 and incorporates microbreccia and mylonite schist. It extends southwest past the limit of microbrecciation and continues unmineralized out of the mine area. Outside the ore zone, in rocks of unit 4, the Shear Zone consists of undulating, graphite covered shear surfaces spaced a few centimetres apart. Thin sections show mylonite schist to have been crushed and milled in places, forming an ultramylonite.

In the mineralized part of unit 4 the Shear Zone consists of undulating mineralized surfaces spaced from a few centimetres to generally less than 0.5 m apart. No obvious slickensides were observed on mineralized surfaces, however, on the 5th level, lineations on one graphite covered, unmineralized, shear surface have a pitch of 90°.

In the lower levels, the northeast portion of the Shear Zone occurs in the quartzo-feldspathic gneisses near the contact with unit 4 (figure 2-9). It consists of several mineralized faults spaced generally less than 0.5 m apart cutting quartzo-feldspathic gneisses. In the upper levels, the Shear Zone incorporates rocks of unit 4, and the position where the Shear Zone enters unit 4 is represented approximately on structure contours of the hangingwall contact of the unit (figure 2-12). The change in rock types incorporated in the Shear Zone is apparently due to the change in thickness of the unit rather than a change in the orientation of the Shear Zone. Shearing in this northeast portion of the Shear Zone seems to diminish above
level 1 as does the associated mineralized zone, however, the Shear Zone continues, mineralized, below level 5 in the quartzo-feldspathic gneisses.

Cross-cutting relationships between the Shear Zone and other structures in the hinge area of the Breccia Zone are not certain from the available information. However, there appears to be a right-hand displacement of about 5 m between the northeast part and the southwest part of the Shear Zone along structures in the hinge area (figure 2-9). The apparent offset is likely due to a combination of movements during late brecciation and faulting.

2.4.3 Faults

The River Zone fault is an arcuate shaped fault containing a few centimetres of hardened fault gouge and, in places, some pitchblende. The fault appears to originate in the Shear Zone and splays to a southeast strike with a 70° dip southwest, and extends out of the mine area. In the upper levels of the hinge area (figure 2-3), arcuate subsidiary faults and veins occur on the footwall side of the River Zone fault; in the lower levels, these veins pinch-out and only a few subsidiary faults are present (figure 2-4).

On level 1 the east-west trending diabase dike is offset by a right-hand displacement of about 10 m along the southeast part of the River Zone fault. On the 4th level, the offset is a left-hand displacement of about 25 m. The dip and strike of the dike changes from 070°, 60° southeast, on the hangingwall side of
the fault, to 080°80 ′ southerly on the footwall side. Both these features indicate a counterclockwise rotational movement of the hangingwall with respect to the footwall rocks, with the center of rotation at about level 2.

The 20 Zone fault is a curved fault trending generally northwest and dipping about 70° southwest, originating as a splay off the River Zone fault (figure 2-9). The fault pinches-out above level 1 and below level 5. Movement has caused a left-hand strike displacement of a few centimetres in the quartzo-feldspathic gneisses. The small magnitude of the displacement indicates that most of the displacement of the diabase dike is due to movement along the River Zone fault.

2.4.4 Veins

In the 20 Ore Zone, carbonate veins ranging from a few centimetres to about 0.3 m thick occur in rocks in the footwall of the 20 Zone fault (figure 2-9). The veins strike northwest and dip at 60 to 70° southwest, and extend from a few metres up to 25 m in length. They are disposed 'en echelon' with respect to the 20 Zone fault, and pinch-out above level 1 and below level 5. The wallrocks to these veins are hematized and mineralized.

In the hinge area of the River Ore Zone on level 1, several curved carbonate veins occur on the footwall side of the River Zone fault which pinch-out below level 2. The largest vein in the mine, termed "vein 16", occurs in the hangingwall of the River Ore Zone (figure 2-3) and is exceptional in that it strikes
parallel to the foliation, but has a northwest dip of 70 to 80°, cutting across the foliation in unit 3. The vein is composed mostly of carbonate and contains fragments of wallrock. It is about 0.1 to 0.5 m wide and extends 50-70 m southwest from the hinge area. It pinches-out to the northeast near the hinge area of the Breccia Zone, and below level 3 where it merges with the Shear Zone.

2.4.5 The Effect of Deformation on Unit 4

Structure contours of the hangingwall and footwall contacts of unit 4 (figures 2-12 and 2-13) indicate that the unit increases in thickness from 2-5 m in the northeast to about 15-20 m in the southwest. This increase in thickness is mostly due to the additional thickness brought about by the presence of concordant zones of microbreccia contained in the unit. Below level 5, and further to the southwest, brecciated zones are absent and the thickness of the unit decreases.

The structure contours indicate the presence of a flexure in the unit between sections 99NE and 100NE, with an axis raking at about 80° northeast in the plane of the unit (figure 2-12 and 2-13). Other variations in the structure contours reflect small changes in the orientation and thickness of the unit.

On level 4 the hangingwall contact of unit 4 appears to be offset by a left-hand strike displacement of about 5 m along structures in the hinge area of the Breccia Zone (figure 2-9). This offset is difficult to detect on the structure contours.
Figure 2-12: Structure Contours: Unit 4, Hangingwall

Structure contours of the hangingwall of unit 4 showing where the Breccia Zone emerges.

SYMBOLS

- Structure contour representing points of equal distance (in feet) above the reference plane.

- Breccia Zone: (H= hangingwall; F= footwall)

- Line a--b is a reference line representing the intersection of the reference plane and level 1.

- Area representing the intersection of the northeast part of the Shear Zone and the hangingwall of unit 4.
Figure 2-13: Structure Contours: Unit 4, Footwall

**SYMBOLS**

Structure contour representing points of equal distance (in feet) above the reference plane.

Data point

Line a---b is a reference line representing the intersection of the reference plane and level 1.
because of the low density of data points present in this area. Nevertheless, it is in the same direction as that for the diabase dike which occurs further to the southeast along the River Zone fault and is of similar magnitude. Towards the upper levels the offset in the hangingwall contact diminishes until it is not obvious on level 1.

The position where the Breccia Zone emerges from within unit 4 is shown on figure 2-12. In the upper levels, the Breccia Zone emerges at a low angle nearly parallel with the hangingwall contact of unit 4. It separates the rocks of unit 3 from those of unit 4 and consists mostly of microbreccia (figure 2-3). In the lower levels, the Breccia Zone emerges at an angle of about 60 relative to the unit 4 hangingwall contact, and consists of fault breccia. The change from microbreccia to fault breccia occurs at about the second level, but the contact is not mappable.

2.4.6 Cross-cutting Relationships

In the west arm of the River Ore Zone, microbreccia composed of fragments of mylonite schist, is cut by the southwest portion of the Shear Zone. The Shear Zone, in turn, is offset by a combination of movements within the hinge area of the Breccia Zone and by the River Zone fault and the 20 Zone fault. Fault breccia is cut by the River Zone fault and some of its subsidiary faults and associated veins (figure 2-9).

In the hinge area and east arm of the Breccia Zone, fault breccia consists mostly of fragments of mylonite, ultramylonite,
and some of mylonite schist. Obvious fragments of microbreccia have not been seen. However, fragments of siliceous cataclasite are present, which is a rock similar to microbreccia except that the fragments are much smaller. The presence of cataclasite fragments in the hinge area and east arm may represent the expression of microbrecciation in rocks of unit 3.

The diabase dike which cuts across the units (figure 2-9), is offset by the River Zone fault; however, there are much smaller unmapped diabase dikes which occur in several places: locally as isolated segments in fault breccia; truncated by the Shear Zone; and as fragments of diabase in veins. In one case, uranium mineralization occurs at the contact of a diabase dike with the wallrocks and it is possible that the dike fills a mineralized fracture. From these observations, the intrusion of diabase is thought to have occurred at various times during the faulting and brecciation, mostly prior to the development of the late faults and veins, but after mylonitization and microbrecciation.

Two periods of brittle deformation are distinguished on the basis of cross-cutting relationships between the various structures (figure 2-14). During the first period, structures nearly concordant with the foliation were developed such as the microbreccia in the west arm of the Breccia Zone, and the Shear Zone. During the second and later period, structures discordant to the foliation were developed such as the fault breccia in the hinge area and east arm of the Breccia Zone, the River Zone fault
and the 20 Zone fault, and their subsidiary faults and veins.

The microbreccia and Shear Zone are believed to be the result of a further decrease in the width over which deformation took place in unit 4, but at a shallower depth than mylonitization. The microbreccia is regarded as a transitional stage from mylonitization to brittle fracture in unit 4, since it has characteristics which indicate deformation without loss of cohesion, yet, it consists of fragments of mylonite schist.

The change from the development of microbreccia and the Shear Zone (Period I) to the formation of fault breccia and the faults and veins cutting across the foliation (Period II), is considered to be the result of a continuation of the uplift which characterized the development of the mylonite zone.
<table>
<thead>
<tr>
<th>STRUCTURE</th>
<th>PERIOD I</th>
<th>PERIOD II</th>
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<tbody>
<tr>
<td></td>
<td>Parallel to the Foliation</td>
<td>Discordant to the Foliation</td>
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<tr>
<td>MICROBRECCIA</td>
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<td>Breccia Zone: west arm</td>
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<td>SHEAR ZONE</td>
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<tr>
<td>FAULT BRECCIA</td>
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<tr>
<td>Breccia Zone: east arm, hinge area</td>
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<td>FAULTS AND VEINS</td>
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<td>DIABASE INTRUSIONS</td>
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Figure 2-14: Relative ages determined by cross-cutting relationships
3. THE OREBODY

3.1 Introduction

The orebody consists of the River Ore Zone which produced about 75% of the ore mined, and the 20 Ore Zone which accounted for the remainder (figures 1-4 and 3-1). The ore grade was determined using a 'beta scaler' used to measure beta radiation and which was calibrated against chemically analysed samples of ore. Mineralized areas were defined by taking traverses across the backs of mineralized drifts at three metre intervals. A number of mineralized areas were defined in this manner on each level and together these comprise the two main ore zones.

3.2 The River Ore Zone

The River Ore Zone is made up of a number of mineralized zones which are generally coincident with the Breccia Zone. In detail, however, the shape of the ore zone varies from one level to the next as indicated in figure 3-1 and this is attributed to changes in the extent of mineralization along ore controlling structures.

The general geometry of the River Ore Zone is represented using structure contours of the hangingwall and footwall contacts (figure 3-2). Information used to construct the diagram was derived from cross-sections of the ore zone used by Cenex Limited to calculate the ore reserve. The structure contours indicate a more continuous zone of mineralization than is depicted on each level and this is attributed to the fact that contouring tends to smooth-out the irregularities in the ore zone.
Figure 3-1: Horizontal Projection of the Ore Zones

SYMBOLS

Level 1
Level 2
Level 3
Level 4
Level 5
Level 6
Figure 3-2: Structure Contours of the River Ore Zone

Structure contours of the hangingwall and footwall of the River Ore Zone showing the average grade.

SYMBOLS

Contours of the hangingwall representing points of (approximately) equal distance (in feet) above the reference plane.

Contours of the footwall

Estimated position where shear-zone ore in the west arm changes to breccia-type and vein-type ore in the east arm.

ASSAY (% UO₃)

- 38
- > 0.1 < 0.2
- > 0.2 < 0.3
- > 0.3 < 0.5
- > 0.5

Line a---b is a reference line representing the intersection of the reference plane and level 1.
The area with a gentle slope on the structure contours represents the portion of the ore zone which is nearly concordant with the foliation. These contours indicate that the ore pinches-out with increasing depth in the west arm of the ore zones with the ore limit raking at about 60° northeast. The area with a steep slope on the structure contours represents the portion of the ore zone which is discordant to the foliation. Along section 101NE the footwall contours show a ridge representing the intersection of the River Ore Zone and the 20 Ore Zone.

The thickness of the ore zone varies from 1 to 3 m, decreasing in places to less than a metre. Ore grades range from 0.1% to 1% UO₂ and no systematic lateral and vertical variations occur. However, high grade ore (0.5% - 1% UO₂) occurs in the mid-levels around section 100NE.

The east arm of the River Ore Zone has essentially the same geometry as the Breccia Zone which contains the ore (figure 3-1). The ore grade is not as variable as in the hinge area and east arm, and high grade portions are absent.

3.3 The 20 Ore Zone

The 20 Ore Zone occurs in rocks on the footwall side of the River Ore Zone (figures 1-4 and 3-1). It is roughly the shape of a wedge partly connected to the River Ore Zone at its southeast end. The largest portion of the ore zone occurs in the mid-levels of the mine and is related to the numerous mineralized
carbonate veins in the footwall of the 20 Zone fault. Alteration envelopes about these veins impart a bright red color to the mineralized wallrocks. Above and below the mid-levels, the ore zone quickly pinches-out as does the 20 Zone fault and associated veins. However, the Shear Zone occurring in the northwest part of the ore zone continues mineralized into the lower levels. The ore grade throughout the 20 Ore Zone varies from 0.1% to 0.5% UO₂ but increases locally up to about 1% where the 20 Zone fault and Shear Zone intersect.

3.4 Ore Types

The mineralized rocks which form the orebody are classified as shear-zone ore, breccia-type ore, and vein-type ore (figure 3-3). Shear-zone ore occurs in parts of the southwest portion of the Shear Zone in unit 4 and in the the northeast portion which cuts the undivided quartzo-feldspathic gneisses. The ore-mineral assemblage consists of: pitchblende, uraniferous titanate, flakey (Fe) chlorite, calcite, albite, hematite, titania polymorphs, and sericite, with Ba-U-silicate and also barite occurring locally.

Breccia-type ore represents mineralized fault breccia and occurs in the hinge area and east arm of the River Ore Zone and in some parts of the 20 Ore Zone. Vein-type ore occurs in the hinge area of the River Ore Zone in the upper levels, in "vein 16", and forms the largest portion of the 20 Ore Zone. The breccia-type and vein-type ores comprise the largest portion of the orebody, and the ore-mineral assemblage for both these ore
types consist of: pitchblende, uraniumiferous titanate, Mg-chlorite, calcite, dolomite, and hematite. Titania polymorphs occur in minor amounts. This mineral assemblage is common to most Beaverlodge uranium vein deposits.

3.4.1 Shear-Zone Ore

In unit 4, shear-zone ore is restricted to the Shear Zone and typically consists of sheared and mineralized mylonite schist and microbreccia (plates 7 and 8). The mineralized mylonite schist is grey to black, fine-grained, and contains altered porphyroclasts of feldspar. It breaks easily along undulating chlorite-rich seams nearly parallel to the foliation which in places contain visible hematite, calcite, and pitchblende. Radioluxographs of mineralized mylonite schist indicate that the radioactive minerals are finely disseminated throughout the rock, but preferentially accumulate in zones roughly parallel to the foliation (plates 7a, 7b). In thin section, the various ore and gangue minerals occur as small disseminated grains and in thin seams in the rock (plates 7c, 7d). In one specimen, seams of flakey (Fe) chlorite contain filaments of pitchblende displaying an anastomizing texture (plates 7c, 7e, 7f). In some of the higher grade samples, Ba-U-silicate and some barite crystals form a matrix to fragments of mineralized mylonite schist.
Figure 3-3: General Distribution of Ore-Types

Horizontal projection of the mineralized zones showing the general distribution of ore-types.

SYMBOLS

- Shear-zone ore
- Breccia-type and vein-type ore

--- Level 1
--- Level 2
--- Level 3
--- Level 4
--- Level 5
--- Level 6
Plate 7: Shear-Zone Ore (mineralized mylonite schist)

Photo a: Photograph of a slabbed handspecimen of mineralized mylonite schist.

Photo b: Radioluxograph of mineralized mylonite schist showing finely disseminated radioactive minerals.

Photo c: Photomicrograph of mylonite schist showing filaments of pitchblende (P) contained in an Fe-chlorite veinlet (Chl). Reflected light. scale bar is 0.1 mm.

Photo d: Photomicrograph of mylonite schist showing opaque filaments of pitchblende and a titanium oxide polymorph (anatase?) contained in a sericite groundmass and occurring parallel to the schistoscity. Crossed-nicols. Scale bar is 0.5 mm.

Photo e: X-ray line scan for uranium over area encompassed by photo c. Field of view is 0.2 mm wide.

Photo f: X-ray line scan for iron over same area as photo c. The white area represents the presence of Fe-chlorite. Field of view is 0.2 mm wide.
Plate 8: Shear-zone ore (Mineralized microbreccia)

Photo a: Photograph of a slabbed handspecimen of mineralized microbreccia.

Photo b: Radioluxograph of handspecimen showing the distribution of radioactive minerals.

Photo c: Photomicrograph of microbreccia showing fragments of mylonite schist contained in a crushed matrix of mostly sericite, quartz, and opaques. Plane polarized light. Scale bar is 0.2 mm.

Photo d: X-ray line scan for silica over a portion of the microbreccia (photo c). Field of view is 0.2 mm wide.

Photo e: X-ray line scan for uranium over the same area as photo d. Field of view is 0.2 mm wide.

Photo f: X-ray line scan for titanium over the same area as photo d. Field of view is 0.2 mm wide.
Where the Shear Zone incorporates microbreccia, the radioactive minerals are disseminated in the groundmass of the microbreccia. X-ray line scans over a small portion of the rock indicate that the presence of a fine-grained U-Ti phase which preferentially accumulates around the perimeter of fragments (plate 8d, 8e, 8f). Small grains of pitchblende occur in some parts of the groundmass.

Where the Shear Zone cuts quartzo-feldspathic gneisses in the hangingwall of unit 4 (figure 2-9), pitchblende occurs in the faults which form the Shear Zone, however, information from this area of the mine is limited and specimens of the ore are not available.

3.4.2 Breccia-Type Ore

Breccia-type ore typically consists of carbonate cemented fault breccia containing hematized and mineralized fragments of mylonite and ultramylonite (plate 9a). The fragments are brick red from disseminated hematite and are impregnated with calcite and microcrystalline (Mg) chlorite. These alterations are described in section 4.6. The fragments are generally surrounded by a 1-3 mm thick rim of fine-grained calcite and are contained in a matrix of coarse-grained calcite. Fine-grained calcite also occurs as small fragments less than 1 cm across, contained in the coarse-grained carbonate matrix.

Radiolucoxographs of carbonate-cemented breccia-type ore indicate that the radioactive minerals occur disseminated throughout many
Plate 9: Breccia-Type Ore

Photo a: Photograph of a slabbed hand specimen of mineralized fault breccia. Note the calcite rims around some of the mylonite fragments.

Photo b: Photomicrograph of one of the fragments of mylonite with a white internally reflecting U-Ti mineral occupying the central portion of a veinlet (medium grey). Reflected light. Scale bar is 0.1 mm.

Photo c: X-ray line scan for uranium over area represented by photo b. Field of view is 0.2 mm wide.

Photo d: X-ray line scan for titanium over area represented by photo b. Field of view is 0.2 mm wide.

Photo e: Radioluxograph of mineralized fault breccia showing showing the distribution of radioactivity in the fragments. Note the film of radioactivity around some of the rims of carbonate. Scale same as photo a.

Photo f: Photomicrograph of mineralized fragment showing pitchblende grains (P) occurring in a veinlet (V) containing calcite, hematite, and chlorite. Reflected light. Scale bar is 0.1 mm.

Photo g: X-ray line scans for uranium taken over area represented by photo f. Field of view is 0.2 mm wide.

Photo h: X-ray line scans for calcium taken over same area as photo g. Field of view is 0.2 mm wide.
Plate 10: Breccia-Type Ore

Photo a: Photograph of slabbed handspecimen of mineralized fault breccia. The fragments are not rotated very much, and are contained in a dark, microcrystalline (Mg) chlorite matrix. Small calcite veinlets cut the breccia.

Photo b: Radioluxograph of mineralized fault breccia showing the distribution of radioactive minerals. Scale same as photo a.

Photo c and d: Photomicrographs of small grains of pitchblende (P) contained in a microcrystalline chlorite (Chl) groundmass and surrounded by specular hematite (H) and calcite (Ca). Photo c: plane polarized light; Photo d: reflected light. Scale bars are 0.1 mm.

Photo e: Photograph of slabbed handspecimen of high-grade ore. Thin white veinlets are calcite. Large white areas are later stage calcite.

Photo f: Radioluxograph of high-grade ore showing the distribution of radioactive minerals. Scale same as photo e.

Photo g: Reflected light photograph over a portion of high-grade ore with pitchblende displaying a dendritic texture. The pitchblende occurs in a microcrystalline chlorite groundmass containing disseminated hematite and calcite. Scale bar is 0.02 mm.

Photo h: Reflected light photograph of irregular pitchblende grains occupying part of a small fragment which occurs in fine-grained microcrystalline chlorite, calcite, and hematite. Scale bar is 0.05 mm.
of the fragments (plate 9e). Some fragments, however, do not appear radioactive because of the lower concentration of radioactive minerals and limited exposure time. In the fragments, pitchblende occurs as very fine grains less than 0.01 mm in size, disseminated in a mixture of fine-grained hematite and calcite. Small veinlets which cut the foliation in the fragments contain fine-grained uraniferous titanate and small pitchblende grains (plate 9).

Another form of breccia-type ore occurs locally in the hinge area and consists of red to brown fragments of mylonite and ultramylonite in an microcrystalline chlorite groundmass (plate 10). The fragments are generally less than 2 cm across, angular, irregular, and have been extensively replaced by microcrystalline chlorite, hematite, and calcite. The rock is cut by veins containing calcite, similar to the fine and coarse-grained calcite of the carbonate-cemented mineralized fault breccia. The presence of these calcite veins cutting microcrystalline chlorite-cemented fault breccia indicate that it formed earlier than the carbonate-cemented fault breccia.

Radioluxographs of the mineralized microcrystalline chlorite-cemented fault breccia indicate fine radioactive disseminations, irregularly distributed point sources of radioactivity, and large 1-2 cm, strongly radioactive patches (plate 10b, 10f). The disseminated radioactivity is likely related to the very fine-grained pitchblende mixed with hematite
and calcite which also occur disseminated throughout the rock fragments. The point sources of radioactivity are attributed to the presence of minute grains of pitchblende contained in a microcrystalline chlorite groundmass (plate 10c, 10d). Large radioactive patches occur in an extremely well hematized specimen in which pitchblende occurs as interconnected veinlets with a dendritic texture (plate 10g). Pitchblende also forms a major portion of what appear to be small (less than 1 cm) intensely hematized fragments (plate 10h).

3.4.3 Vein-Type Ore

Vein-type ore consists of mineralized carbonate veins and faults and their adjacent wallrocks. Typically, the veins contain calcite, with the uranium occurring mostly as disseminations in the mineralized wallrocks. The disseminated uranium mineralization is similar to that which occurs in fragments of mineralized fault breccia (breccia-type ore). There are, however, occurrences of colloform pitchblende along the River Zone fault, and massive pitchblende occurs in some parts of "vein 16", but these occurrences are uncommon in the orebody.

A radioluuxograph from a specimen of "vein 16" containing altered diabase fragments (plate 11) indicates that the radioactive minerals are concentrated in the rim of the fragments and decrease in concentration towards the center. The uranium minerals consist mostly of fine-grained uraniferous titanate and some fine-grained pitchblende (plate 11d, 11e, 11f).
Plate 11: Vein-Type Ore

Photo a: Photograph of slabbed handspecimen of vein-breccia consisting of altered and mineralized diabase fragments contained in a carbonate matrix.

Photo b: Radioluxograph of vein-breccia composed of diabase fragments showing the distribution of radioactivity. Note that the radioactivity is distributed around the rim of the diabase fragments.

Photo c: Photomicrograph of a portion mineralized diabase fragment. Plagioclase laths have been altered to a mixture of sericite and chlorite. Dark minerals are fine-grained hematite, pitchblende, anatase, and a uraniferous titanate. Plane polarized light. Scale bar is 0.5 mm.

Photo d: Reflected light photomicrograph of fine-grained pitchblende (P) in altered diabase. Bright areas are anatase. Dark areas are altered plagioclase laths. Scale bar is 0.02 mm.

Photo e: X-ray line scans for uranium over area containing opaque grains in photo c. Field of view is 0.2 mm wide.

Photo f: X-ray line scans for titanium over same area as photo e. Field of view is 0.2 mm wide.
In the D3 ore zone, the southwest portion consists of quartz-calcite ore which extends below the 35th level (Figure 3-1). The southwest portion of the ore zone consists of quartz-calcite and minor amounts of feldspar.
3.5 The Distribution of Ore Types

The change from shear-zone ore in the west arm of the River Ore Zone, to breccia-type and vein-type ores, occurs near the hinge area (figure 3-3). Although the transition zone is difficult to define, it is estimated as occurring in the area which is roughly coincident with the change from a gentle to a steep slope on the structure contour surfaces of the River Ore Zone and the Breccia Zone.

The distribution of ore types in the River Ore Zone is also represented by the intersection of the structure contours of the Breccia Zone with those of the River Ore Zone (figures 3-4 and 3-5). The stippled areas show the portion of the ore zone occurring mostly outside the Breccia Zone. Most notable is area 'a' (figure 3-4) consisting of shear-zone ore occurring in mylonite schist and which is coincident with the high grade portion of the River Ore Zone (compare with figure 3-2).

In the 20 Ore Zone, the northwest portion consists of shear-zone ore which extends below the 5th level (figure 3-3). The southeast portion of the ore zone contains mostly vein-type ore with some veins containing enough fragments that they resemble breccia-type ore.

3.6 Host Rock Alterations

The main types of alterations which affect the mineralized quartzo-feldspathic mylonites and ultramylonites of unit 3 are: hematization, chloritization, carbonatization, and albitization.
Figure 3-4: Distribution of Ore-Types: Breccia Zone, Hangingwall

Distribution of ore-types as indicated on the structure contours of the hangingwall of the Breccia Zone; superimposed on the contours is the southwestern limit of the River Ore Zone.

SYMBOLS

The portion of the ore zone occurring in rocks on the hangingwall of the Breccia Zone.

a: shear-zone ore in mylonite schist.
b: vein-type ore in quartzo-feldspathic gneisses in unit 3.
c: mineralized microbreccia (shear-zone ore)
d: mineralized fault breccia (breccia-type ore)

The ore limit

Estimated position where shear-zone ore in the west arm changes to breccia-type and vein-type ore in the east arm.
Figure 3-5: Distribution of Ore-Types: Breccia Zone, Footwall

The distribution of ore-types as indicated on structure contours of the footwall of the Breccia Zone; superimposed on the structure contours is the southwestern limit to the River Ore Zone.

SYMBOLS

The portion of the ore zone occurring in the rocks in the footwall of the Breccia Zone.

- e: represents shear-zone ore in mylonite schist.
- f: represents vein-type and breccia-type ore in the quartzo-feldspathic gneisses of unit 3.
- g: mineralized microbreccia (shear-zone ore)
- h: mineralized fault breccia (breccia-type ore)

Ore Limit

Estimated position where shear-zone ore in the west arm changes to breccia-type and vein-type ore in the east arm.
Any alterations which may accompany the uranium mineralization in unit 4 are difficult to distinguish from the metamorphic mineral assemblage present in the mylonite schist (i.e., calcite, albite, hematite, flakey (Fe) chlorite, sericite, quartz, and titania polymorphs). It is notable, however, that graphite was not detected in the mineralized samples of mylonite schist.

3.6.1 Hematization

Disseminated, sub-microscopic, hematite pigment occurs in feldspar porphyroclasts and throughout the groundmass which surrounds them in unmineralized quartzo-feldspathic mylonites and ultramylonites in units 1 and 3, and to some extent in most quartzo-feldspathic gneisses in the mine. The presence of disseminated hematite results in the characteristic orange to red color of the quartzo-feldspathic gneiss. The hematization appears to have formed during the mylonitization of the pre-existing quartzo-feldspathic rocks. This type of hematization is regional in extent (Tremblay, 1972) and is distinguished from the hematization associated with uranium mineralization in which the quartzo-feldspathic rocks are brick-red to brown, and hematite occurs in much greater concentration. Hematite associated with uranium mineralization occurs as aggregates of fine grains which preferentially replace the groundmass to porphyroclasts and define a ‘pseudomorphic’ foliation in some places.
3.6.2 Carbonatization

Calcite occurs as very fine grains disseminated throughout the mineralized quartzo-feldspathic mylonites and ultramylonites in unit 3. The disseminated calcite occurs mixed with fine-grained hematite which, together, preferentially replace the groundmass surrounding porphyroclasts.

In carbonate-cemented fault breccia (breccia-type ore), the disseminated calcite occurs in mineralized fragments and is believed to be cogenetic with the fine-grained calcite forming rims around the fragments. The disseminated calcite may represent the carbonatization of the rocks during the formation of the fine-grained calcite.

3.6.3 Chloritization

Microcrystalline (Mg) chlorite replaces the quartz-rich groundmass around feldspar porphyroclasts in mineralized mylonites and ultramylonites of unit 3. In fault breccia, some fragments are completely replaced by the microcrystalline chlorite and the only evidence of the original foliation are thin seams of fine-grained hematite mixed with very fine-grained calcite. The chlorite which replaces the mineralized quartzo-feldspathic rocks is the same as that which forms a matrix to rock fragments for some of the fault breccia in the hinge area of the Breccia Zone.

3.6.4 Albitization

In the mineralized mylonites and ultramylonites of unit 3, many
porphyroclasts of untwinned plagioclase have a composition in the range of albite and oligoclase. It is not clear how much of the apparent albitization is due to retrograde metamorphism and how much is due to the mineralizing process. However, it appears that in the mineralized rocks, untwinned, low-Ca plagioclase is more common than in the unmineralized rocks outside the orebody. This suggests that albitization is more complete in the mineralized rocks of unit 3 and partly the result of the mineralizing process, whereas in the unmineralized rocks, the plagioclase has only been affected by retrograde metamorphism.

3.6.5 The Distribution of Alteration Assemblages

In the 20 Ore Zone, the extent of hematization is roughly coincident with the shape of the ore zone as viewed on each level (figure 3-1). Uranium mineralization is closely associated with hematite as well as calcite and microcrystalline chlorite and thus the distribution of uranium serves as a good indicator. However, it is not clear from descriptions in geological logs how much of the hematization in the quartzo-feldspathic gneisses cut by the northeast portion of the Shear Zone is the result of the mineralizing processes, and how much represents hematite formed during mylonitization.

In the River Ore Zone the distribution of alteration types is represented by projecting representative samples and diamond drill hole intersections onto the structure contours of the hangingwall of the Breccia Zone, and then drawing boundaries on
Figure 3-6: Alteration in the Breccia Zone and Adjacent Rocks

Structure contours of the hangingwall of the Breccia Zone indicating the extent of uranium mineralization and hematization, and the boundary between the predominantly carbonate and predominantly chlorite matrix in the Breccia Zone.

SYMBOLS

Uranium mineralization.

Uranium mineralization, hematization and carbonatization.

Uranium mineralization, hematization, carbonatization and a predominantly carbonate matrix to the breccia.
the contours using the latter as data points. The change from a predominantly carbonate to a predominantly chlorite matrix to the breccias is roughly estimated on figure 3-6, but no distinction is made between chlorite types due to lack of data. However, the breccia with the microcrystalline (Mg) chlorite matrix occurs mostly in the hinge area and east arm, while that with flakey (Fe) chlorite occurs mostly in the west arm.

Alteration of the rocks in the River Ore Zone display lateral changes from east to west (from b to a, figure 3-6). Hematization accompanied by chloritization, carbonatization, and albitization are limited to the east arm and hinge area of the Breccia Zone and immediately adjacent rocks. It does, however, extend into the west arm for a short distance. Lack of hematization in the west arm reflects the presence of shear-zone ore in unit 4 which apparently has not been significantly affected by hematization, carbonatization, chloritization, or albitization. The extent of hematization in the upper levels of the mine is difficult to define because there is a problem differentiating between the hematization related to the emplacement of uranium mineralization and hematization due either to oxidation by present day surface waters, or hematization associated with the Crackingstone River fault alteration zone.

The distribution of alteration types in the River Ore Zone indicates a decrease in hematization, chloritization, carbonatization, and albitization towards unit 4. Notably the
ore zone pinches-out a short distance into unit 4. Of importance, as well, is the probable change in permeability which occurs in the River Ore Zone from east to west as indicated by the change from fault breccia, faults, and veins in the east, to the Shear Zone and microbreccia in the west. These changes in alteration, uranium mineralization, and permeability suggest that the source of hydrothermal fluids was from outside unit 4.

3.7 The Sequence of Ore Deposition

The relative time of emplacement of uranium mineralization is determined by the cross-cutting relationships between the various mineralized and unmineralized structures in the orebody. The first episode of uranium mineralization occurred during the development of the Shear Zone (Period I), and is represented by shear-zone ore (figure 3-7). Microbreccia, which pre-dates the Shear Zone, is unmineralized except where it is incorporated in the Shear Zone. The emplacement of uranium mineralization during this period does not appear to be accompanied by significant alteration of the host rocks.

The second episode of uranium mineralization occurred during the development of fault breccia, faults, and veins, and is represented by breccia-type and vein-type ores (Period II, figure 3-7). The emplacement of uranium mineralization during this period was accompanied by intense hematization, chloritization, carbonatization and some albitization of the quartzo-feldspathic mylonite and ultramylonite host rocks.
<table>
<thead>
<tr>
<th>STAGE</th>
<th>Fault Breccia</th>
<th>Fault Breccia</th>
<th>Faults &amp; Veins</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPISODE I</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>EPISODE II</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>OLDER</td>
<td>Shear-zone ore</td>
<td>Breccia-type ore</td>
<td>Vein-type ore</td>
</tr>
</tbody>
</table>

Figure 3-7: Brittle deformation and uranium mineralization history
This second episode of uranium mineralization can be subdivided into four stages (figure 3-7). Stage I is represented by fault breccia consisting of mineralized fragments contained in a microcrystalline chlorite matrix. Some of these fragments may represent remobilized shear-zone ore (plate 10h). Stage II is represented by the carbonate veins which cut across Stage I fault breccia (plate 10e), consisting of coarse and fine-grained calcite. In some parts of the orebody, Stage II is represented by fragments of mylonite and ultramylonite rimmed by fine-grained calcite (figure 3-8). Stage 3 is represented by coarse-grained calcite forming the matrix to mineralized fragments with calcite rims of Stage 2. Veins and faults containing dolomite, calcite, and pitchblende, cut across the mineralized fault breccia and represent the 4th and final stage.

The second episode of mineralization appears to have been characterized by repeated periods of fracturing followed by wallrock alteration and ore deposition. There appear to be few changes in the ore and gangue mineralogy throughout this time and the majority of the ore occurs disseminated in altered quartzofeldspathic mylonites and ultramylonites. These characteristics suggest that the brittle deformation and introduction of mineralizing fluids occurred over a short time period in which the source and nature of the solutions remained fairly constant.
Vein containing dolomite, calcite, pitchblende, and chlorite

STAGE 4

Calcite B

STAGE 3

Disseminated Calcite (calcite A)

STAGE 2

Radioluxograph of Breccia-type ore

2 cm

Sketch of a sample of Breccia-type ore

Diagramatic illustration of stage 2, 3, and 4 in breccia-type ore
4. ORE AND GANGLUE MINERALS

Unlike many uranium deposits in the Beaverlodge area which are dominated by pitchblende occurring in veins cutting altered rocks, the Cenex deposit is largely made up of disseminated uranium minerals which occur finely mixed with alteration minerals replacing the host rocks. The fine grain size and lack of open space filling textures hinders the determination of textural relationships betweenuraniferous and alteration minerals. However, this limitation does not hamper the unravelling of the mineralization history since it is closely tied to periods of fracturing and brecciation as discussed in the previous chapter (section 3.7).

4.1 Pitchblende

Grains of pitchblende ranging from less than 0.01 mm to 0.05 mm are disseminated throughout the altered rocks of unit 3. The very fine-grained pitchblende is difficult to detect even with a microprobe since the grain size of the mineral approaches the size of the area affected by the electron beam (about 5 microns). However, where it is detected, the pitchblende occurs mixed with hematite and calcite forming a fine-grained mass. Larger grains (about 0.05 mm) are angular, slightly cracked, and occur in an microcrystalline chlorite groundmass (plate 10c, 10d).

Pitchblende also occurs as small grains in minute veinlets which cut the mineralized rocks of unit 3, and which also contain microcrystalline chlorite, calcite, hematite, and a
K-phylllosilicate (plate 9f, 9g, 9h). Small veinlets also occur in mylonite schist containing flakey chlorite and filaments of pitchblende and calcite (plate 7c, 7e, 7f).

Colloform pitchblende is uncommon in the orebody but does occur in places along the River Zone fault (plate 12a). The colloform grains have syneresis cracks which are filled with carbonate.

4.2 Uraniferous Titanate

Uraniferous titanate occurs as small grains disseminated in rocks of unit 3 and 4, and in parts of the microbreccia. Fragments of mylonite schist in the microbreccia are rimmed by small opaque grains with a pale white internal reflection. X-ray line scans over these grains indicate that some contain uranium and titanium while others contain only titanium (plate 8e, 8f). These two phases are optically indistinguishable, and the uraniumiferous titanate is atypical of brannerite. In mylonite schist a similar mineral occurs as very fine grains, either disseminated in the rock, or forming thin seams nearly parallel to the foliation (plate 7d).

In unit 3, uraniumiferous titanate occurs as fine grains with pale white to yellow internal reflections and occurs in minute veinlets cutting across the fabric of the rocks (plates 9b). The uraniumiferous titanate in units 3 and 4 may represent either a fine grained mixture of pitchblende and titanium oxide, or possibly very fine grained brannerite.
Plate 12: Ore and Gangue Minerals

Photo a: Photomicrograph of colloform pitchblende grains displaying syneresis cracks. The pitchblende grains are cut by fractures containing calcite (dark areas). Reflected light. Scale bar is 0.2 mm.

Photo b: Photomicrograph of veinlet occurring in mylonite schist containing a Ba-U-silicate which consists of radiating fibres. Plane polarized light. Scale bar is 0.1 mm.

Photo c: Specular hematite occurring as spherical grains contained in a groundmass of Mg-chlorite. The grains consist of an inner grain of quartz, and outer mantle of specular hematite, and an outer corona of strands and filaments of hematite. Reflected light microphotograph. Scale bar is 0.5 mm.

Photo d: Barite occurring as subhedral grains surrounded by a fine-grained groundmass of Ba-U-silicate. Plane polarized light. Scale bar is 0.5 mm.

Photo e: Photomicrographs of pyrite grains in Mg-chlorite groundmass containing disseminated hematite and calcite. Plane polarized light. Scale bar is 0.5 mm.

Photo f: Photomicrograph of subhedral to euhedral quartz grains (Q) around the edge of fragment. Calcite which forms the matrix (Ca) exhibits growth rings along which occur small anhedral grains of quartz. Crossed-nicols. Scale bar is 0.5 mm.

Photo g: Photomicrograph of mylonite schist with grain of albite (Ab) occurring in microfracture cutting across the schistosity. Crossed-nicols. Scale bar is 0.5 mm.

Photo h: Photomicrograph of quartzo-feldspathic mylonite of unit 3 with partly sericitized and albitized plagioclase porphyroclast surrounded by fine-grained hematite (dark). Note the destruction of the albite twinning in the original plagioclase. Crossed-nicols. Scale bar is 0.5 mm.
4.3 Ba-U-Silicate

Microprobe analyses of a radioactive, waxy yellow mineral occurring in sheared mylonite schist, indicate the presence of U, Ba, and Si. This is the same elemental composition as barium uranophane \((\text{Ba(UO}_2\text{)}\cdot\text{(SiO}_2\text{)})\), however, the three strongest diffraction peaks of barium uranophane do not match those of the yellow mineral. The Ba-U-Silicate may be a polymorph of barium uranophane, but further investigations of the crystal structure would be required to confirm this.

The Ba-U-Silicate occurs in shear-zone ore as a fine-grained groundmass to mineralized and unmineralized fragments of mylonite schist and also to small grains of barite (plate 12d). It also forms as aggregates of yellow-green radiating fibres within thin veinlets parallel to the schistosity (plate 12b).

4.4 Hematite

Unmineralized quartzo-feldspathic gneisses in the mine contain disseminated, sub-microscopic hematite occurring in feldspar porphyroclasts and in the surrounding groundmass in about equal but low concentrations. In the mineralized quartzo-feldspathic gneisses of unit 3, hematite also occurs in disseminated form but is present in much higher concentrations, and preferentially replaces the groundmass (plate 12h). This fine-grained hematite forms irregular masses which also may contain disseminated pitchblende and calcite.

Specular hematite comprises up to 10% in some places, and forms
spherical, 0.2 - 0.3 mm grains contained in a groundmass of microcrystalline chlorite (plate 12d). The grains consist of an inner core of quartz which is about 0.1 mm in diameter, an outer mantle of specular hematite, and an outer corona composed of strands and filaments of hematite.

4.5 Barite

Barite occurs as small subhedral grains surrounded by a fine-grained groundmass of Ba-U-Silicate in mineralized mylonite schist (plate 12f). Most grains display a sharp contact with the groundmass, but in some places they contain embayments filled with radiating fibres of Ba-U-Silicate. Barite forms a minor proportion of the mineralization in the mylonite schist and apparently occurs only where Ba-U-Silicate is present. The Ba-U-Silicate and barite are regarded as secondary in origin.

4.6 Pyrite

Pyrite occurs as anhedral grains and aggregates of grains contained in a groundmass of microcrystalline chlorite (plate 12e). The pyrite grains have a form and distribution which is similar to that of specular hematite grains in other samples and are generally absent or occur in small amounts in samples containing specular hematite.

4.7 Quartz

Unlike many of the uranium deposits in the Beaverlodge area, quartz is conspicuously absent throughout most of the Cenex deposit. It occurs locally in the east arm of the River Ore Zone
where it forms euhedral to subhedral grains around the rim of mylonite, ultramylonite, and cataclasite fragments (plate 12f). Calcite, which forms the matrix to the fragments, exhibits growth rings along which occur small anhedral grains of quartz and disseminated hematite. Quartz also forms the core to specular hematite grains (plate 12c).

4.8 Albite

Albite occurs as small subhedral laths lining the walls of thin veinlets in mylonite schist (plate 12g). In mineralized quartzo-feldspathic gneisses of unit 3 many porphyroclasts of untwinned, sericitized plagioclase (plate 12h) are low in calcium and range in composition from albite to oligoclase.

4.9 Titania Polymorphs

Titanium oxide occurs as aggregates of grains which form thin seams parallel to the schistosity in mylonite schist, and occur in veinlets cutting the mineralized quartzo-feldspathic gneisses of unit 3. Small, high relief grains of anatase occur throughout the quartzo-feldspathic gneisses and mylonite schist. Similar grains occur in some flakey chlorite pseudomorphs of biotite (plate 13e, 13f). Most of the titanium oxide polymorphs are considered to be a product of retrogressive metamorphism, the result of Ti released from minerals such as biotite and hornblende during retrogression to chlorite and actinolite respectively.
Plate 13: Gangue Minerals

Photo a: Photomicrograph of a seam of Fe-chlorite occurring in mylonite schist. The Fe-chlorite seam contains filaments of pitchblende and carbonate. Plane polarized light. Scale bar is 0.5 mm.

Photo b: Photomicrograph of calcite in a groundmass of microcrystalline Mg-chlorite. The opaques consist of specular hematite clusters. Note the corroded texture at the boundaries of the calcite grain. Plane polarized light. Scale is 0.2 mm.

Photo c: Photomicrograph of Mg-chlorite (Chl) occurring in a calcite groundmass (Ca) and displaying a framboidal outline. Plane polarized light. Scale bar is 0.2 mm.

Photo d: Photomicrograph of fine-grained (A) and coarse-grained (B) calcite. The film separating the calcite types contains Mg-chlorite and specular hematite (opaques). Plane polarized light. Scale bar is 0.5 mm.

Photo e: Photomicrograph of mylonite schist showing chlorite grains contained in a sericite groundmass (white). Note small opaque grains of anatase occurring in and around the chlorite grains. Plane polarized light. Scale bar is 0.1 mm.

Photo f: Same as photo e, except in reflected light showing distribution of white grains of anatase. Dark, irregular areas are pits on the polished surface. Scale bar is 0.1 mm.
4.10 Chlorite

Chlorite occurs in two modes in the ore zones. A flakey chlorite occurs as thin seams nearly parallel to the fabric in the mylonite schist and is associated with pitchblende filaments (plate 13a). The chlorite grains are 0.1 - 0.2 mm in size and are texturally and optically similar to that which occurs throughout the mylonite schist and which occurs as flakes with the cleavage aligned parallel to the schistosity. The grains display a pleochroism from green to light green, and have low interference colors.

A microcrystalline chlorite occurs in mineralized quartzo-feldspathic gneisses of unit 3. Commonly, single individual grains are not visible and the microcrystalline chlorite occurs as irregular zones which replace the groundmass to porphyroclasts (plate 13b). It also forms the groundmass to some of the fault breccia (section 4.4.2). The chlorite is green, non-pleochroic, and commonly displays a distinctive 'anomalous blue' interference color which is characteristic of penninite. In some places the microcrystalline chlorite occurs as small grains contained in a calcite groundmass (plate 13c). Under crossed-nicols these grains consist of radiating fibres of chlorite. Where calcite occurs in a groundmass of microcrystalline chlorite, the calcite grains exhibit sharp, concave contacts with the chlorite (plate 13b).
Figure 4-1: Chlorite Composition

The chemical composition of chlorites in the Cenex mine and in other uranium deposits/occurrences.

SYMBOLS

- Flakey, oriented chlorite \( \) mine units
- Microcrystalline chlorite \( \) 3 and 4
- Fe-chlorite associated with pitchblende in a mineralized sample of mylonite schist (photo 7b)
- Microcrystalline chlorite in altered diabase
- Range in composition and average composition.
- Chlorite from red-altered zone, Kazan-type uranium mineralization, N.W.T. (data from Miller, 1980).
- Chlorite from Australian unconformity-related uranium deposits: Jabiluka, Ranger I, Narbalek (data from Ewers and Ferguson, 1978).
the unaltered diabase.

Flakey chlorites occurring in mylonite schist, microbreccia, and in the Shear Zone have the same composition which suggests that late stage retrograde metamorphic processes may have still been active during the initial emplacement of uranium mineralization in the Shear Zone. No gradual change in composition is apparent between flakey and microcrystalline chlorites, which suggests that the mineralizing fluids responsible for the formation of microcrystalline chlorite were derived from an independent source. The second episode of uranium mineralization, which accounts for the major part of the orebody and is dominated by microcrystalline chlorite, therefore, does not appear to be directly related to retrogressive metamorphic processes in unit 4.

4.11 Dolomite

Dolomite comprises about 95% of the carbonate vein material in "vein 16". The dolomite consists of interlocking 1 to 3 mm grains with finely disseminated hematite occurring along the cleavage and between grain boundaries. The presence of hematite imparts a slightly orange hue to the dolomite. Small grains of calcite intergrown with dolomite were detected in places, but comprise less than 5% of the total carbonate.

4.12 Calcite

Calcite occurs in veins, as disseminations in mineralized quartzo-feldspathic gneisses, and as a matrix to fault breccia.
Two types of calcite can be distinguished in the fault breccia. Fine-grained calcite occurs as 1 to 3 mm rims around the perimeter of fragments, and as small pieces contained in a matrix of coarse-grained calcite (plate 13d and figure 3-8). The rims consist of 0.2 - 0.5 mm interlocking calcite grains and contain tiny inclusions of microcrystalline chlorite and hematite. The calcite rims are either in sharp contact with the fragments, or separated by a thin film of hematite and microcrystalline chlorite. The coarse-grained calcite consists of 1 to 2 mm interlocking grains which display undulating extinction in places. The coarse-grained calcite is separated from fine-grained calcite by a film of hematite and microcrystalline chlorite (plate 13d). Very fine-grained calcite occurs disseminated in the mineralized quartzo-feldspathic gneisses and is finely mixed with very fine-grained hematite. This disseminated calcite and the fine-grained calcite forming rims around fragments are believed to be cogenetic (see section 3.7).

4.12.1 Isotopic Composition of Carbonates

Disseminated calcite (calcite A), coarse-grained calcite (calcite B), and dolomite which formed during Stage 2, 3, and 4 of the second episode of mineralization were analysed for their carbon and oxygen isotopic compositions as part of a course in stable isotope geochemistry. Although not a comprehensive study, the results have been incorporated into the thesis to provide further information with which to judge what the possible sources for the mineralizing fluids may have been, and in order to
compare the isotopic results with those from other mines in the Beaverlodge area.

Disseminated calcite from a fragment of mineralized mylonite in breccia-type ore was analysed by removing the fine-grained calcite rims and outer portion of the fragment and analysing the remainder. It was not possible to separate the fine-grained calcite rims for analysis. Coarse-grained calcite was hand-picked from the matrix to the rimmed fragments and an effort was made to separate clean white calcite without the addition of other contaminants such as hematite, chlorite, and small fine-grained calcite fragments. Minor amounts of calcite are intergrown with the dolomite sampled from stage 4, but its effect on the isotopic composition of the dolomite is not considered to cause significant error because the oxygen and carbon fractionation factors between calcite and water and dolomite and water are similar (Friedman and O'Neil, 1977), and the amount of calcite in the sample is below 5%. The carbonate samples were analysed using conventional analytical techniques (McCrea, 1950).

The isotopic composition of the carbonates is presented in Table 4-1 and plotted on figure 4-2. No correlation is evident between the $^{13}\text{C}$ and $^{18}\text{O}$ values. Stage 3 calcite from the Cenex deposit has a similar isotopic composition to most of those from the Eldorado deposits except for some carbonates in the Bolger open pit which have very negative $^{13}\text{C}$ values (Sassano et al., 1971).
Table 4-1: Isotopic Composition of Carbonates

The isotopic composition of carbonates from Stages 2, 3, and 4 of uranium mineralization in the Cenex mine.

<table>
<thead>
<tr>
<th>#</th>
<th>CARBONATE TYPE</th>
<th>18O</th>
<th>13C</th>
<th>STAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calcite A (disseminated)</td>
<td>+16.2</td>
<td>-1.0</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Calcite B (coarse-grained)</td>
<td>+12.0</td>
<td>-2.1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Calcite B</td>
<td>+12.7</td>
<td>-2.9</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Dolomite</td>
<td>+18.6</td>
<td>-4.0</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 4-2: Isotopic Composition of Carbonates

Oxygen and carbon isotopic compositions for the carbonates in the Fay mine and Bolger pit (Eldorado), and the Cenex mine.

SYMBOLS

\[ \begin{align*}
\text{GENEX MINE} \\
\text{1 Calcite A (Stage 2)} \\
\text{2 Calcite B (Stage 3)} \\
\text{3 Calcite B (Stage 3)} \\
\text{4 Dolomite (Stage 4)} \\
\text{E LDORADO MINE} (after Sassano et al., 1971) \\
\times \text{ Type a (white calcite) } & \text{ Fay mine} \\
+ \text{ Type a (calcite) } & \text{ Bolger pit} \\
\circ \text{ Type A (pink calcite) } & \text{ Fay mine} \\
\circ \text{ Type A (brown calcite) } & \text{ Bolger pit} \\
\bullet \text{ Type B (dolomite) } & \text{ Fay mine} \\
\blacksquare \text{ Type C (white calcite) } & \text{ Fay mine} \\
\triangle \text{ Type D (white calcite) } & \text{ Bolger pit} \\
\square \text{ Type D (white calcite) } & \text{ Bolger pit} \\
\diamond \text{ Type E (yellow calcite) } & \text{ Bolger pit} \\
\end{align*} \]

Range in isotopic composition (Eldorado samples) and the average isotopic composition for each carbonate type (calculated from data from Sassano et al., 1972).
The oxygen isotopic composition of the carbonates at the Cenex mine may be explained as three alternatives:

1. The carbonate for each stage formed from more than one fluid, each with a different isotopic composition but at the same temperature.

2. The carbonate for each stage formed from one fluid, but at different temperatures.

3. A combination of 1 and 2 in which both the temperature and isotopic composition of the fluid(s) changed during each stage of mineralization.

The second explanation seems unlikely since a variation in the temperature of the fluid at a constant oxygen isotopic composition should be indicated by a linear relationship between the $^{13}$C and $^{18}$O values of the carbonate, assuming equilibrium precipitation (Robinson, 1974). Even though the specific temperature(s) at which the carbonates formed is not known, the third possibility is preferred since it is most consistent with the geological history of progressive uplift of the rocks and decreasing temperature in the mylonite zone. This view is elaborated upon in section 5.3.

The carbon isotopic composition of the carbonate is dependent on a number of factors including temperature, Eh, and pH, which are not known and which therefore makes the isotopic data difficult to interpret. However, the range of $^{13}$C values suggest that graphite or organic carbon have not significantly influenced the isotopic composition of the fluid from which these carbonates were derived.
5. DISCUSSION

5.1 The Geological History of the Rocks in the Cenex Mine

The amphibolite facies metamorphism of the rocks in the Cenex mine represents the prograde regional metamorphism which affected the rocks in the Beaverlodge area during Hudsonian orogenesis. Retrograde metamorphism followed soon after during the late stages of orogeny as the rocks were mylonitized during regional uplift (figure 5-1). Mylonitization of the pre-existing metamorphic rocks in the Cenex mine is believed to have taken place, initially, at a depth characterized by middle greenschist facies metamorphic conditions (biotite zone) which affected all the rocks in the mine. Later mylonitization, which was localized in unit 4, occurred at a shallower depth and lower metamorphic grade (chlorite zone). Finally, the rocks were lifted to a depth shallow enough to result in their brittle fracture. It may be that the mylonitization of the rocks induced the retrogressive metamorphism by allowing water to enter the rocks along intergranular boundaries causing hydration reactions to take place within the mylonite zone. Beach (1980) has noted the importance of hydration processes and hydrolysis reactions in shear zones due to the large scale of fluid ingress.

The development of microbreccia is regarded as a transitional phase between mylonitization and brittle fracture of the rocks in unit 4 (see section 2.4.6.). Structures which developed early (ie. Period I) were affected by the waning retrograde metamorphic processes in unit 4. This supports the view that mylonitization
Figure 5-1: The geological history of the rocks in the Cenex mine
accompanied by retrogressive metamorphism) and brittle fracture represent consecutive events during late Hudsonian orogenesis in this area and not distinct periods of tectonism separated by an erosional period as suggested by Kupricka and Sassano (1972).

The recalculated U-Pb ages on uraninite in the granitic gneisses in the Beaverlodge area indicate that the main period of metamorphism, granitization, and granite intrusion occurred around 1860 ma (Bell, 1981). K-Ar ages of minerals vary from 1720 to 1790 ma (Koeppel, 1969; Tremblay, 1978; Stevens et al., 1982), and it is within this time period that the retrograde metamorphism, mylonitization, and uplift of the rocks in the Cenex mine is assumed to have occurred. The timing of prograde and retrograde metamorphism in the Cenex mine and, by analogy, in other parts of the Beaverlodge area, is therefore consistent with that in other areas of the Churchill Province in Saskatchewan affected by Hudsonian orogenesis, such as, the Flin Flon area (Muherejee et al., 1971) and the Cree Lake Mobile Zone (Lewry and Sibbald, 1980).

Of particular interest is the striking similarity between the geological history of the rocks in the Cenex mine and that indicated by Nielson et al. (1981) for the Precambrian rocks of northeast Alberta. The Hudsonian orogeny in northeast Alberta is marked by prograde metamorphism and anatexis around 1900 Ma (Rb-Sr age) followed by retrograde metamorphism, mylonitization, uplift, and cooling around 1790 Ma (K-Ar). Sedimentary, volcanic,
and volcanoclastic rocks of the Waugh Lake Group are believed to have been deposited in tectonically active and controlled sedimentary basins during the period of uplift, and were metamorphosed under middle greenschist facies conditions around 1760 Ma (K-Ar age on biotite from the metasediments, Baadsgaard and Godfrey, 1972).

As uplift continued during the late stages of orogeny in the Beaverlodge area, deformation in the Cenex mine became localized within the least competent rocks (unit 4) and changed from mylonitization to fracturing, faulting, and brecciation. Initially deformation occurred within the most active part of the mylonite zone (unit 4) forming the microbreccia and the Shear Zone (Period I), but continued deformation and uplift led to the development of fault breccia in unit 3, as well as, the River Zone fault, the 20 Zone fault, and their subsidiary faults and veins (Period II).

Uranium mineralization began during the development of the Shear Zone (Period I), and apparently was not accompanied by significant alteration of the mylonite schist in unit 4. Microbreccia is unmineralized except where it is incorporated in the Shear Zone. This first episode of uranium mineralization occurred at a time when retrogressive metamorphic processes in unit 4 are thought to have been still active, as indicated by the similarity of the chlorite in mineralized veinlets comprising the Shear Zone and the chlorite in mylonite schist. The second
episode of uranium mineralization occurred later during the formation of fault breccia, faults, and veins (Period II). Uranium mineralization at this time was accompanied by the hematization, carbonatization, chloritization, and possibly some albitization of the quartzo-feldspathic rocks in unit 3. By this time retrogressive metamorphic processes in the mylonite zone were inactive due to the lower temperature of the rocks, and hydrothermal fluids circulated through the open spaces.

Diabase dikes are offset by mineralized structures, such as the River Zone fault, but post-date mylonitization and microbrecciation. Since these dikes are believed to have been the feeders to the Martin volcanic flows and sills (Evans and Bingham, 1973), then the emplacement of uranium mineralization occurred roughly at about the same time as the deposition of the Martin clastics and the accompanying volcanic activity.

Recalculated U-Pb ages on pitchblende from the Beaverlodge deposits by Bell (1981) give an initial age around 1740 Ma, which is slightly younger than the retrogressive metamorphism and mylonitization of the rocks (around 1790 Ma, Tremblay, 1978). This initial age for pitchblende coincides roughly with late uplift, cooling, and brittle fracture of the rocks, and as well, is within the time limits set for the deposition of the Martin Group (Tremblay, 1972; Evans and Bingham, 1973; Stockwell, 1982).

Near the Cenex mine the Beaverlodge Formation of the Martin Group consists of a basal conglomerate overlain by sandstones
which were probably deposited in a valley against the Black Bay fault (Smith, 1952). An erosional period followed after which the upper formations of the Martin Group were deposited (Langford, 1981). Since the source areas for the Martin Group were from the northwest and northeast, and transport and deposition was short and swift (Smith, 1952; Tremblay, 1972), it seems reasonable to assume that the uplift represented by the geological history of the rocks in the Cenex mine, was accompanied by erosion on surface which, on a more regional scale, would have resulted in the deposition of the detritus in this part of the Martin basin.

The geological history of the rocks in the Cenex mine supports the view that late stage Hudsonian orogenesis, the development of successor basins, and the emplacement of uranium mineralization, were contemporaneous. The geological environment during the time of uranium mineralization appears to have been characterized by the erosional unroofing of uplifted terranes, particularly cataclastic zones, with the concurrent deposition of the clastic components in adjacent successor basins.

Eisbacher (1980), in a study of the successor basins in parts of the Cordillera of British Columbia, noted that the most important factor in the initiation of successor basin sedimentation was the contemporaneous uplift and emergence of metamorphic and plutonic complexes along basin hinges. The geological history of the Cenex mine and its location relative to the Martin Group appear to indicate that a similar model may be
applicable for the Beaverlodge area. Furthermore, the contemporaneity of uplift, erosion, sedimentation, and uranium mineralization, suggest that the hydrologic system during sedimentation and afterwards may have played an important role in a highly faulted and fractured area such as around the Cenex mine, and very likely many of the other parts of the Beaverlodge district which are fractured, faulted, and lie close to the unconformity between the Martin Group and the basement.

5.2 Genetic Hypotheses

Genetic hypotheses for Beaverlodge uranium deposits can be subdivided into three categories based on what are believed to be the sources of the uranium and the ore-bearing fluids. The classic Lindgren hydrothermal model was first proposed for the Beaverlodge uranium deposits by Robinson (1955). He believed that there was a transition from "syngenetic" uraninite-bearing pegmatites to "epigenetic" hydrothermal pitchblende-bearing veins. The source of the uranium and the ore-bearing fluids were thought to be derived from the late stages of granite crystallization. This view was later supported by Beck (1969) who suggested that the uranium-bearing fluids were released during the late stages in the granitization of the rocks in the area.

A metamorphic-hydrothermal source was proposed by Sassano et al (1972) based on studies of the Eldorado mine. They believed that the fluids responsible for the deposition of the ore and gangue minerals were probably present as pore fluids in the supracrustal
rocks. These fluids, they believed, remained in a closed system during orogenesis, and that the accumulation of the ore and gangue mineral constituents in the fluid was due to a redistribution of elements originally present in the rock during metamorphism. The minerals were then deposited into fractures and other dilatant zones as they were formed. Tremblay (1978) supported a metamorphic-hydrothermal origin, as well, but emphasized that the mineralization stage was one of the last stages in the granitization process. Along a similar vein, Hoeve (1982), noted that the Beaverlodge uranium deposits display a Na-Ti-U association which he links to Na-metasomatism during regional metamorphism and accompanying magmatic activity in the area. In this model, metamorphic-hydrothermal fluids expelled in deep structural levels react with country rocks resulting in the addition of Na and Ca to the rocks, and the loss of K, Mg, Fe, Ti, and U. At structurally shallower levels he suggested that the intensity of Na-metasomatism diminishes and that the leached constituents are precipitated.

A superficial origin for the uranium deposits was first suggested by F. R. Joubin (1955) who thought that most of the pitchblende occurrences were "surface phenomena", having formed near the unconformable Tazin-Martin Group contact. The overlying cover rocks he believed acted as a protective blanket for the uranium deposits after their formation. Johns (1970) later also pointed out that the uranium mineralization occurred close to the Martin Group-basement unconformity but did not elaborate much
further. The concept of a superficial origin lay dormant for the most part until the mid 1970's when the unconformity-type deposits began to be discovered in the Athabasca basin. Langford (1974, 1977) proposed a supergene origin for the Beaverlodge uranium deposits emphasizing the geochemical similarities with the Colorado sandstone uranium deposits in the U. S. A., and the fact that the uranium deposits occur where terrestrial rather than marine sandstones are present. He suggested that groundwaters during the early deposition of terrestrial cover rocks are capable of transporting and depositing uranium in sufficient quantity and at sufficient grade to constitute orebodies, citing the Australian calcrete uranium deposits as an example. Miller (1980), in a study of the uranium mineralization in the Baker Lake area N. W. T., which is geologically similar to Beaverlodge, suggested that Kazan-type uranium mineralization originated from the reduction of oxidizing, uranium bearing groundwaters moving through permeable horizons in the terrestrial cover rocks. Because of the similarity in geological environment, this concept would be applicable for uranium mineralization in the Beaverlodge area.

In the light of the results of the present study, a classic hydrothermal origin from late stage granite crystallization or granitization is inconsistent with the geological history of the rocks and the timing of ore emplacement. The most likely igneous or high grade metamorphic source rocks i.e. the granitic gneiss of units 5, 6, and 7, predates the mylonitization and therefore was
a solidified mass well before ore emplacement. Although diabase dikes intruded during the time of mineralization, there is no direct correlation between the intrusion of diabase and the presence of uranium mineralization in the Cenex mine, or for that matter, anywhere throughout the Beaverlodge area.

A metamorphic-hydrothermal origin is the most widely accepted view, but it remains unclear from the literature whether metamorphic-hydrothermal refers to prograde or to retrograde metamorphism. It is not likely that the ore-bearing fluids originated during the late stages of prograde metamorphism since the ore was emplaced much later, after mylonitization and retrograde metamorphism. The Na-Ti-U association discussed earlier also exists in the Cenex uranium deposit, but can be explained as due to a combination of retrograde metamorphism and later alteration accompanying uranium mineralization. Retrograde metamorphism can account for the apparent Na-metasomatism, and the association of uranium with titanium reflects the fact that TiO polymorphs, which are believed to have formed during retrograde metamorphism, reacted with uraniferous fluids and resulted in the formation of U-Ti phases.

Alternatively, it is difficult to conceive how retrogressive metamorphism could have resulted in the expulsion of metamorphic-hydrothermal fluids into dilatant zones in the rock since the process of retrogression involves hydration reactions which require the addition of water (Beach, 1980). However, in
the early episode of mineralization some interplay may have existed between late-stage retrograde metamorphic processes and an ore-bearing fluid, since retrograde metamorphism in unit 4 seems to have still been active during the initial period of deformation. However, the second (and major) episode of uranium mineralization post-dates mylonitization and retrogressive metamorphism and, furthermore, the chlorites associated with uranium mineralization bear no chemical relationship to chlorites associated with retrograde metamorphism in unit 4. For these reasons, the ore-bearing fluid(s) are believed to have originated from sources independent of retrogressive metamorphism. A near surface or superficial origin for the uranium and the ore-bearing fluids, therefore, is preferred based on the geological environment in which uranium mineralization took place, and the lack of other suitable sources.

5.3 A Geological Model

A geological model for the genesis of an ore deposit requires that there be a source of elements and a method for transporting and concentrating them. The transport and precipitation of uranium has been dealt with at length in a number of studies such as those by Langmuir (1978), Rich et al. (1977), Garrels and Christ (1965), Hostetler and Garrels (1962), and others. There appear to be no reasons why processes of transport and deposition for uranium as determined by these authors should not be generally applicable to the Cenex uranium deposit. As such, these aspects of uranium ore genesis have not been dealt with in
The ubiquity of carbonate, hematite, and Mg-chlorite throughout the orebody indicate that the fluids depositing them must have been rich in Ca, CO\textsubscript{2}, Fe, U, and Mg, and that uranium likely occurred in solution as uranyl carbonate complexes or uranyl hydroxyl complexes, depending on the temperature of the fluid (Sergeyeva et al., 1972). The fact that uranium mineralization and the host rock alterations are so closely associated strongly suggests that the processes involved in the host rock alteration also formed the uranium-bearing minerals. The mineralogical changes which occurred during the second episode of uranium mineralization appear to involve mostly the dissolution of quartz and some feldspar in the quartzo-feldspathic gneisses of unit 3 with concurrent replacement by chlorite, hematite, pitchblende, uraniferous titanate, and carbonate. These mineralogical changes appear to reflect a change from oxidizing, acidic fluids to moderately alkaline and more reduced ones.

As discussed earlier, the hydrologic system which operated during sedimentation and afterwards may have provided the source for the ore-bearing fluid. It is possible to use the oxygen isotopic data for the carbonates from Stages 2, 3, and 4 to test this hypothesis and, given certain assumptions, see if the calculated oxygen isotopic of the fluids from which the carbonates precipitated are consistent with a groundwater or near surface origin.
The source of a fluid can be estimated from a knowledge of the oxygen isotopic composition of the water in the fluid, which can be calculated knowing the oxygen isotopic composition of a mineral which formed from that fluid, and its temperature of formation (Taylor, 1974). For one scenario, the carbonates from Stages 2, 3, and 4 are assumed to have formed at about 250, 150, and 100°C, respectively, reflecting decreases in depth as the rocks were being uplifted. The assumption of a decreasing temperature for the fluid for each stage during the second episode of mineralization is consistent with the temperature changes in the ore fluids for the stages of mineralization at the Eldorado mine (Sassano et al., 1971), and also with the temperature history of the rocks at the Cenex mine as indicated by their geological history. Although very high initial fluid temperatures were indicated at Eldorado (around 500°C), in the Cenex mine the temperature for Stage 2 has to be consistent with or lower than the temperature which has been inferred for lower greenschist facies metamorphism of about 300°C (Turner and Verhoogen, 1960), and for this reason a temperature of about 250°C is chosen. The temperatures for Stages 3 and 4 are consistent with the fluid inclusion temperatures for the late stages of mineralization in the Eldorado mine.

Based on these assumptions, the calculated oxygen isotopic composition of the water in the ore fluid for the last three stages of mineralization in the Cenex mine indicate decreasing 18O values concurrent with a decrease in depth and in temperature
(Table 5-1, figure 5-2). The decrease in the $S_0$ of the fluids is believed to represent the oxygen isotopic shift which descending meteoric waters would undergo due to isotopic exchange with silicate country rocks over decreasing depths to the depositional site. The greater the fluid penetration, the greater the oxygen isotopic exchange with the country rocks, and consequently, the higher the $S_0$ content of the water. The $S_0$ value of the ore fluid in the last stage is in the range of meteoric water which suggests a low penetration and low temperature of emplacement.

It is important to note that even if the temperature estimates were lowered to 200, 100, and 50 °C (i.e., a lower geothermal gradient), essentially the same interpretation would hold except that in this case, the $S_0$ value of the ore fluid in the last stage would be well within the range of meteoric water.

Meteoric waters moving over the surface and circulating through fractures, faults, and breccia zones in rocks near surface can leach the necessary ore constituents from the rocks to form orebodies as has been shown by Doi et al. (1975) for the uranium deposits in Neogene sedimentary rocks of Japan. They conclude that the uranium ore was derived by leaching uranium from the surrounding granitic rocks by Ca-Na-HCO$_3$-rich groundwaters, and $\delta^{18}O$ was reduced by adsorption onto carbonaceous matter in the sediments.

Furthermore, Cole (1981), in a study of the
Table 5-1: Calculated Oxygen Isotopic Composition of the Ore Fluids

<table>
<thead>
<tr>
<th>STAGE</th>
<th>CARBONATE</th>
<th>$\delta^{18}O$</th>
<th>TEMPERATURE (°C)</th>
<th>$\delta^{18}O_{H_2O}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>dolomite</td>
<td>+18.6</td>
<td>100</td>
<td>-2.4</td>
</tr>
<tr>
<td>3</td>
<td>calcite</td>
<td>+12.7</td>
<td>150</td>
<td>+0.2</td>
</tr>
<tr>
<td>2</td>
<td>calcite</td>
<td>+16.2</td>
<td>250</td>
<td>+8.7</td>
</tr>
</tbody>
</table>
Figure 5-2: A geological model for the origin of the ore-forming fluids and uranium mineralization in the Cenex uranium deposit.
geothermal-groundwater regime in a fault-bounded graben filled with quaternary sedimentary rocks in northern Utah, USA, found that the waters from hot springs and wells in the area were characterized by strong oxygen isotopic shifts and were depleted in deuterium. He concluded that since the $\delta^{18}O$ values were similar to those from nearby mountain spring waters from much higher elevations, then the source of the water in the hot springs originated from higher elevations in the mountains adjacent to the graben. Meteoric waters from the mountains, he believes, infiltrate to depths of several kilometers in a 'near normal geothermal gradient' and are heated to temperatures of about $125^\circ C$ where they undergo geochemical rock-water interactions before returning to surface. It seems quite plausible then that the inferred oxygen isotopic shift in the ore-bearing fluids at the Cenex mine can take place in a near surface environment. A similar geothermally active area is envisioned for Beaverlodge.

The ore fluids are thought to have reached temperatures which might be considered too high for this type of geological environment. However, Nisbet and Fowler (1982) have shown, through the use of thermal modelling, that rapid rates of erosion and sedimentation can significantly alter the geothermal gradient in an area. It seems quite possible that, in the Beaverlodge area, which was characterized by rapid rates of erosion and sedimentation during Martin deposition, temperatures of up to $250^\circ C$ could have existed within a few kilometers of the surface in areas of rapid uplift.
Rapid horizontal variations in the geothermal gradient and in topographic relief are thought to have resulted in convective circulation systems characterized by meteoric-hydrothermal fluids. The widespread distribution of uranium deposits and occurrences and the associated host-rock alteration, therefore, may represent an expression of a geothermal system which existed during the time of Martin sedimentation.
6. CONCLUSIONS AND RECOMMENDATIONS

Through detailed geological investigations of the Cenex uranium deposit, the initial objectives of establishing a geological framework and the geological history of the rocks in the Cenex mine have been met. The relative timing of events is consistent with the geochronological ages which are available in the Beaverlodge area, and the timing of prograde and retrograde metamorphism also closely parallels that of the Shield area of Alberta, as well as, that of the Flin Flon area and the Cree Lake Mobile Zone, Saskatchewan.

In the Cenex mine, mylonitization and retrogressive metamorphism occurred during regional uplift in the late stages of the Hudsonian orogeny. The deformation continued at shallow depths and resulted in the formation of zones of microbreccia in unit 4 followed later by the development of fault breccias, faults, and fractures. No significant time period appears to have separated these events and all are thought to be part of continuous deformation.

It is during this period of late uplift and brittle deformation that deposition of successor basins of the Martin Group took place, and when the main episode of uranium mineralization occurred. The fact that there is contemporaneity of late uplift, erosion, and deposition of continental clastics in areas of high relief on the one hand, and brittle fracture and uranium mineralization in the basement, on the other, strongly suggests
that the hydrologic system during and after sedimentation could have played an important role as a source for ore-bearing fluids. This source would be most important in areas of the basement which were faulted, fractured, and occurred close to continental clastics - hence the close spatial relationship of uranium deposits in the Beaverlodge area with the basal unconformity of the Martin Group.

The traditional genetic models, which propose magmatic and metamorphic hydrothermal sources for the uranium and the ore-fluid, have been evaluated and found to be inconsistent with the geological history of the rocks and the timing of uranium mineralization. The pre-existing rocks had to undergo mylonitization and retrogressive metamorphism prior to mineralization and thus a direct source via granitization, granite intrusion, or the late stages of prograde metamorphism, is not likely.

An exploratory study of the oxygen and carbon isotopic composition of carbonates from the last three stages of mineralization is consistent with a meteoric or groundwater source and provides a preliminary working hypothesis.

Recommendations for Further Study

A more detailed isotopic study of the carbonates should be undertaken to confirm the results of this work and should be expanded to take into account all stages of mineralization.
Temperatures for each stage should be determined from either fluid inclusions in the carbonates, or from the isotopic composition of coexisting minerals.

A more detailed investigation of wallrock alteration should be undertaken to determine the sequence of mineral replacement in the quartzo-feldspathic mylonites and ultramylonites, and to determine the changes in the chemistry between altered and unaltered rocks. This would result in a better understanding of the chemical nature of the ore fluids, and how they may have changed when they interacted with the wallrocks. This could have a direct bearing on what caused the deposition of the uranium minerals.

Although the geological history as determined for the Cenex uranium deposit is consistent with the available geochronological data for the Beaverlodge area, more specific ages should be determined for:

1. U-Pb ages for early pitchblende in mylonite schist (Shear-Zone Ore), disseminated pitchblende in Breccia-type ore, and colloform pitchblende in late stage veins.

2. K-Ar ages on biotite from the quartzo-feldspathic gneisses (unit 3), and on sericite from mylonite schist (unit 4).


A more detailed investigation should be done to determine how much of the apparent albitization in the mineralized quartzo-feldspathic mylonites is due to retrograde metamorphism.
and how much can be attributed to wallrock alteration during uranium mineralization. This study would involve a statistically significant number of microprobe analyses of plagioclase, both in the mineralized zone and outside, since the effects of albitization due to retrograde metamorphism appear to be irregular.

Although the geology of the Cenex uranium deposit has been described in some detailed, conclusions on ore genesis, the relationship between retrogressive metamorphism and ore genesis, and more precise relationships between uranium mineralization to Martin sedimentation and volcanism, are far from complete. Further work in these areas may help to clarify some of the problems and provide a clearer picture of the geological environment in which uranium mineralization took place.
REFERENCES


Tremblay, L.P. (1978): "Geological setting of the Beaverlodge-type of vein-uranium deposit and its comparison to that of the unconformity-type"; Short course in uranium deposits: Their mineralogy and origin Short course handbook vol. 3, Mineralogical Association of Canada Editor: M.M. Kimberley.
