To the Graduate Council:

I am submitting herewith a thesis written by Allen Kem Fronabarger entitled "Petrogenesis of the North Harper Creek Uranium Prospect." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

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PETROGENESIS OF THE NORTH HARPER CREEK URANIUM PROSPECT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Allen Kem Fronabarger

March 1980

1112512

DEDICATION

To Chantal

Merci

I have no doubt
the Devil grins,
As seas of ink I spatter.
Ye Gods forgive
my "literary" sins -
The other kind don't matter.

(Robert Service)

ACKNOWLEDGMENTS

My advisor, Dr. Kula C. Misra, and my committee, Drs. John Higgins, Hap McSween, and Larry Taylor have provided me with suggestions and criticism during the progress of this study. Their help has been invaluable to the successful completion of this thesis. Dr. Misra deserves a very special thank you for his continuing patience during our protracted discussions.

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Finally, I would like to recognize my wife, Chantal, who has shown me patience, understanding, and moral support during my studies.

ABSTRACT

The North Harper Creek uranium prospect, Avery County, North Carolina, is located in the late Precambrian Wilson Creek Gneiss within the Grandfather Mountain window of the Blue Ridge province.

Host rocks consist of orthogneisses that have suffered both dynamothermal metamorphism and cataclastic deformation probably during the Taconic orogeny. The protolith consisted of quartz-rich granites, alkali-feldspar granites, and tonalites. Prograde metamorphism, coupled with the onset of cataclastic deformation, reached a maximum of almandine grade producing cataclasites and cataclastic gneisses. Subsequent lowering of temperatures and continued cataclastic deformation under high fluid pressure retrograded the sequence forming chlorite at the expense of mica.

Previous authors have described two types of uranium emplacement; first as substitution within crystals of feldspars, micas, titanite, and zircon, and second as veins within the rock sequence. This study has shown that vein-type uranium mineralization is directly related to the deformation that produced the cataclasites. Uranium was probably transported as complexes from a deeper metamorphic source and deposited as uraninite. Upward movement of fluids enriched in U, CO_2 and O_2 through zones of permeability produced by the cataclasis was responsible for uraninite deposition. It is suggested that as liquids migrated upward, gases were boiled off thus decreasing the stability of the uranyl-complexes. Uraninite was subsequently precipitated in veins

with calcite, pyrite, pyrrhotite, and chalcopyrite. Chlorite, or more probably, a pre-metamorphic precursor of chlorite was co-precipitated with the uraninite.

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CHAPTER I

INTRODUCTION

I. PURPOSE OF STUDY

Uranium mineralization occurs in a variety of host rocks and the classification of uranium deposits has rapidly evolved in recent years (e.g., Little, 1970; Ziegler, 1974; Ruzicka, 1975; Dahlkamp, 1975, 1978; McMillan, 1977, 1978; Mickle, 1978; and Fronabarger and Misra, 1979). Most of the domestic uranium production has been from sedimentary type deposits (Table 1). In recent years, however, igneous and metamorphic rocks have received considerable attention as potential sources of nuclear fuels. The North Harper Creek, North Carolina, uranium prospect is a metamorphic vein-type occurrence. To date, no detailed petrologic study has been published on this mineralization. The object of this thesis is to describe the nature and distribution of uranium mineralization and to interpret its genesis based on data obtained during the study. It is hoped that the results of this study will provide a clearer understanding of those parameters that control uranium mineralization in this and similar type deposits elsewhere.

II. LOCATION OF STUDY AREA

The North Harper Creek prospect is located in the Grandfather Mountain window in the Blue Ridge province of the Appalachian mountains of North Carolina (Figure 1). The prospect is located in Avery country,

Table 1. A Classification of Uranium Deposits[a]

Affiliation	Ore Forming Process	Deposit Type	Characteristic Elements	Characteristic Minerals	Examples
Sedimentary	Adsorption and Complexing	Lignite Phosphorite and Calcrete Black Shale	U, C, Mo, V Se, As.	Carnotite	Dakotas, USA Fla. Phos., USA Chattanooga Shale
	Redox	Roll Fronts Unconformity Veins	U, C, Cu, V, Se, Mo, As.	Uraninite Coffinite	Colo. Plateau, USA Beaver Lodge, Canada
	Detrital Transport	Qtz - Pebble Cong.	U, Th, Ti, REE, Au, Zr, C	Uraninite	Elliot Lake, Canada
	Supergene Enrichment	Supergene Caps.	U, Th, Fe, Al	Coffinite	Rossing, SWA
Igneous	Intrusive Differentiation	Diatremes and Carbonatites Peralkaline and Intrusions Permatities and Veins	Na, K, Th, REE U, Cu	Uraninite, Brannerite,	Orphan Mine, Az, USA Bokan Mountain, Alas. Rabbit Lake, Can.
	Extrusion	Volcanic Ash.	U, Th, REE	Uraninite	Ash Deposits, Italy
Metamorphic	Fluid Movement	Shears Veins	Cu, Ag, Au, Co, Ni, Ti, As, Se.	Uraninite	N. Harper Ck.
	Metasomatism	Metasomites			Mary Kathleen, Aust.

Table 1 (Cont'd)

[a]Fronabarger, A. K., and Misra, K. C., 1979, Classification and distribution of North American uranium deposits: (Abstr.), Abstracts with Programs, Southeastern Section, Geol. Soc. Amer., Blacksburg, Va., v. 11, no. 4, p. 179.

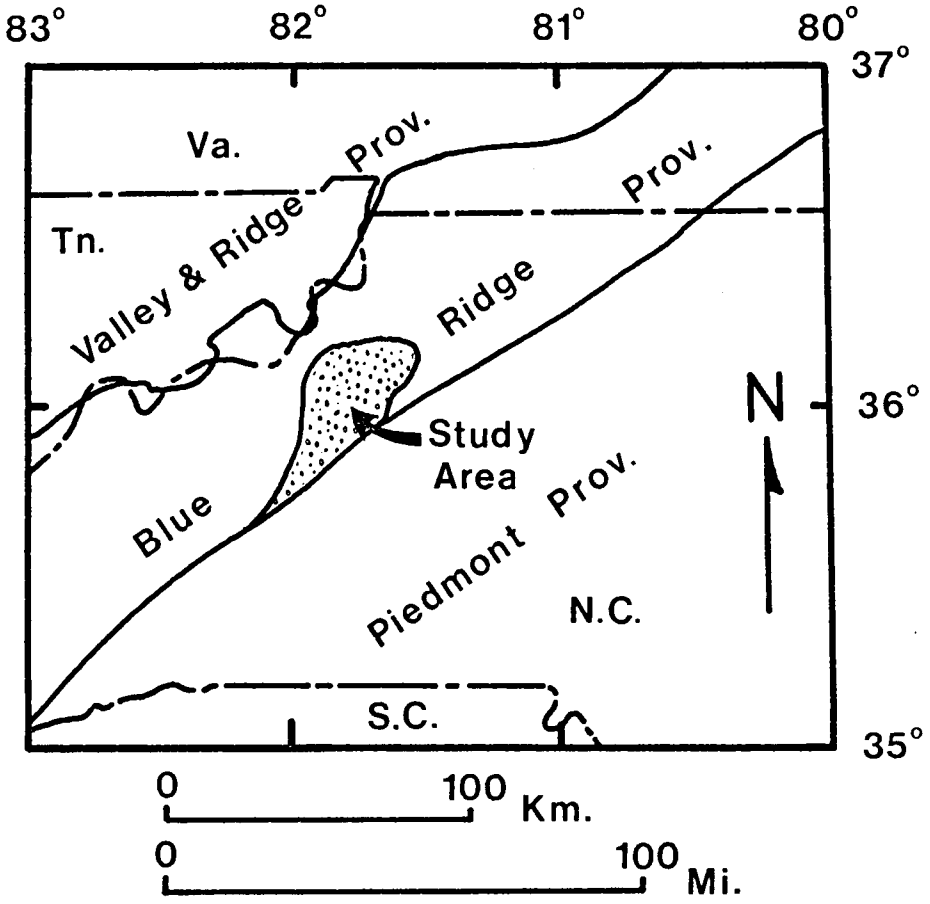


Figure 1. Map showing the Grandfather Mountain Window (stippled area) within the Blue Ridge Province.

North Carolina about five miles east of Pineola on the Forest Service road that connects Pineola to Edgemont. Mineralization occurs in the North Harper Creek drainage basin on the boundary of the Linville and Linville Falls Quadrangles.

III. REGIONAL GEOLOGY

The regional geology and boundaries of the Grandfather Mountain window are illustrated in Figure 2. The window is separated from the Inner Piedmont to the south and east by the Brevard fault zone. The Linville Falls thrust fault marks the northern and northwestern limits of the window, separating it from the rest of the Blue Ridge province. The southwest limit is defined by the Table Rock fault which separates the window from the Table Rock thrust sheet.

Bryant and Reed (1970a) have summarized the earliest geologic mapping in the Grandfather Mountain region. They stated that Maclure (1817) and Kerr (1875) mapped the rocks in the Grandfather Mountain area as "transition age" and being surrounded by gneisses of "Primitive" or "Huronian" age. Keith (1903, 1905) and Keith and Sterrett (1954) mapped much of the Grandfather Mountain area. Keith believed that the area represents a complex syncline that is bounded on the north and west by faults separating volcanic and sedimentary rocks from Precambrian plutonic rocks that override the sediments. Stose and Ljungstedt (1932) Stose and Stose (1944) reinterpreted the Grandfather Mountain area as a structural window.

Figure 2. Regional geology of the Grandfather Mountain Window (after Bryant and Reed, 1970a).

Legend

Cambrian	Ccg	Chilhowee Group
Precambrian	pCg	Grandfather Mountain Formation
	pCw	Wilson Creek Gneiss
	pCbr	Blowing Rock Gneiss
	pCmg	Metagabbros and metadiorites

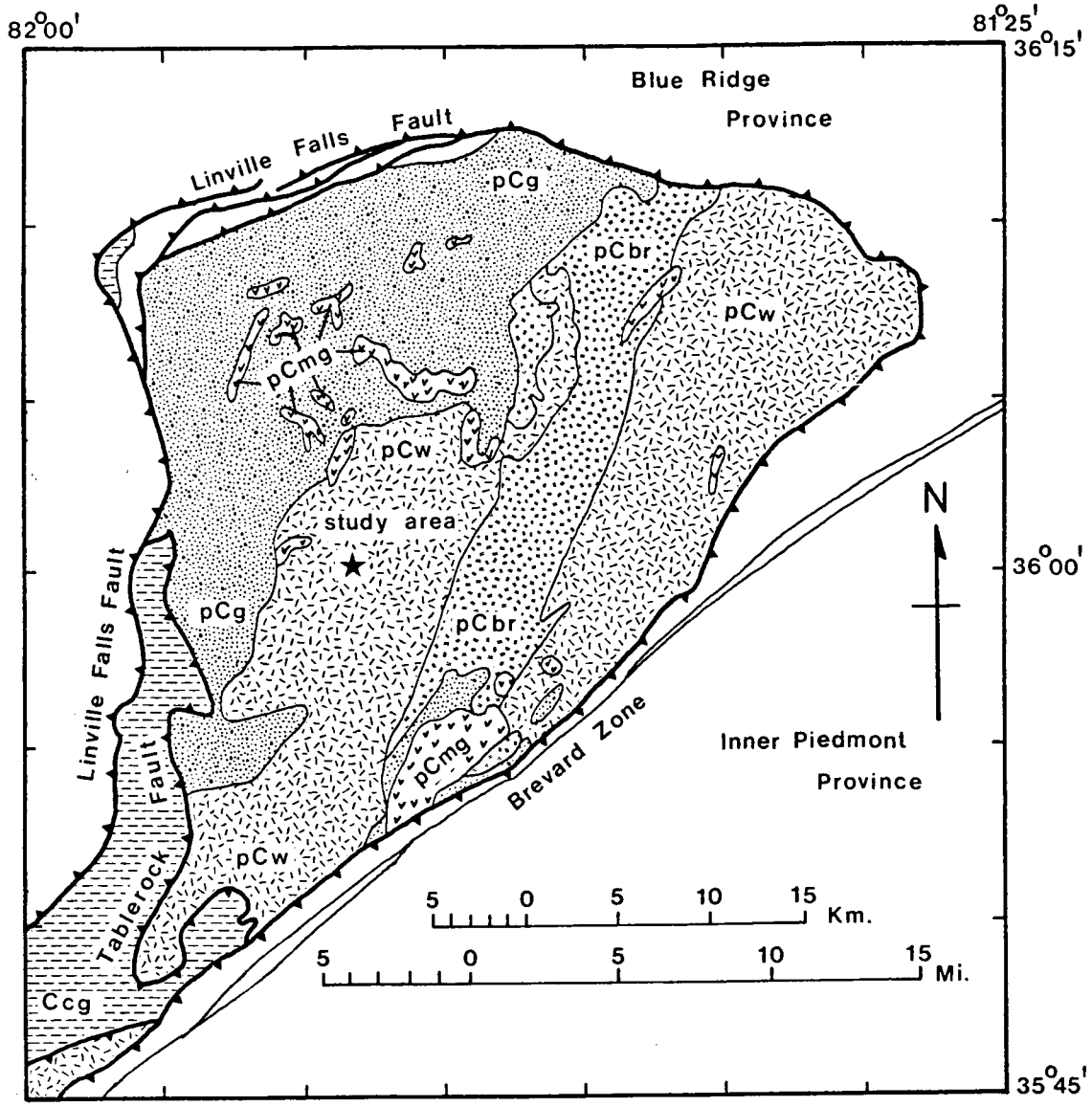

82°00'
81°25'
36°15'
36°00'
35°45'
Blue Ridge
Province
Linville Falls Fault
pCg
pCbr
pCw
pCmg
study area
Linville Falls Fault
Tablerock Fault
Brevard Zone
Inner Piedmont
Province
Ccg
N
5 0 5 10 15 Km.
5 0 5 10 15 Mi.

Figure 2.

According to Bryant (1962) and Bryant and Reed (1970a, 1970b) who remapped the Grandfather Mountain window, the oldest rocks encountered in the window are gneissose to phyllonitic metagabbros and metadiorites (pCmg) which were emplaced during Grenville time (about 1.0 to 1.1 b.y.). The Wilson Greek Gneiss (pCw) and the blowing Rock Gneiss (pCbr) were also emplaced as plutonic complexes during Grenville time but later than the metadiorites and metagabbros. This age is supported by Davis et al. (1962), Odom and Fullagar (1971), and Fullagar and Odom (1973) who found the crystallization age of these rocks by U/Pb and Rb/Sr methods as being at least 1 b.y. old. During late Precambrian time, the Grandfather Mountain Formation (pCg) was deposited unconformibly on the older plutonic rocks. Rankin et al. (1969) dated zircons in the felsic volcanic units of the Grandfather Mountain Formation as having a crystallization age of 850 m.y. During middle and late Paleozoic time (about 450 to 250 m.y.) one or more periods of regional dynamothermal metamorphism probably affected all the earlier rocks. The timing of this event is supported by structural evidence within and outside the window (Bryant and Reed, 1970a). Bryant and Reed (1970a, 1970b) and this study have shown that the rocks within the window were progressively metamorphosed to the greenschist facies of Fyfe et al. (1958) which is equivalent to the low grade metamorphism of Winkler (1976). From late Paleozoic through perhaps early Mesozoic time, Precambrian crystalline rocks were thrust westward over the Grandfather Mountain window rocks for a distance of about 35 miles (Bryant and Reed, 1970a). Cataclastic deformation of the lower block occurred during this

thrusting event. During the Triassic, diabase dikes were emplaced in the lower block. Subsequent erosion exposed the Grandfather Mountain window.

More recently, Wagener (1978) reinterpreted the origin of the Wilson Creek Gneiss. He proposed that the Wilson Creek Gneiss formed from the autometamorphism (due to radioactive decay) of the lower part of the Grandfather Mountain Formation. Subsequent plutonic activity emplaced igneous rocks in the lower units of the metamorphosed Grandfather Mountain Formation. In the weatern limb of the Wilson Creek Gneiss (the region containing the North Harper Creek prospect), he believed that the bulk (about 80 percent) of the Wilson Creek Gneiss was derived from the Grandfather Mountain Formation. According to him, it is ". . . a general rule in the western half of the Wilson Creek Gneiss (west of the Blowing Rock Gneiss) that wherever Bryand and Reed (1970a, plate 1) mapped zones of phyllonite, the rock is demonstrably metasedimentary of a mixture of metasedimentary and metavolcanic lithologies" (Wagener, 1978, pp. 8-9). He reinterpreted the unconformity between the crystalline basement and the Grandfather Mountain Formation (Bryand and Reed, 1970a and Schwab, 1977) to be a hiatus in deposition of the Grandfather Mountain Formation. Wagener agreed with Bryant and Reed that the existing rocks were metamorphosed during a thrusting event that occurred during middle and late Paleozoic time. He did not consider, however, that the structure is a window. In fact, he correlated the Wilson Creek Gneiss and the Blowing Rock Gneiss with the Cranberry Gneiss to the north, thus refuting a thrust contact to

the northeast of the window. To support this hypothesis, he stated that radioactive anomalies can be traced north across the thrust contact without interruption (Wagener, 1979, personal communication).

Table 2 summarizes Bryand and Reed's (1970a) and Wagener's (1978) interpretations of the formation of the Wilson Creek Gneiss. As the North Harper Creek prospect is located entirely within the Wilson Creek Gneiss, the origin of this gneiss is central to the development of a model for the origin and localization of the uranium in the study area. Whether the Wilson Creek Gneiss is an orthogneiss as suggested by Bryant and Reed or a paragneiss as suggested by Wagener is discussed in Chapter III of this report.

IV. WILSON CREEK GNEISS

The North Harper Creek uranium prospect is located entirely within the bounds of the western limb of the Wilson Creek Gneiss (Figure 2). The following discussion of the Wilson Creek Gneiss is summarized from Bryant and Reed (1970a, pp. 50-115) and is intended to provide the reader with a broad view of the petrology and structure of the Wilson Creek Gneiss.

The Wilson Creek Gneiss occurs in two areas in the Grandfather Mountain window that are separated by the Blowing Rock Gneiss. The east arm of the Wilson Creek Gneiss consists of nonlayered quartz monzonitic gneiss, layered gneiss, blastomylonite and phyllonite, and dioritic gneiss which is commonly sheared to blastomylonite and phyllonite. The western arm of the Wilson Creek Gneiss consists

Table 2. Summary of the Evolution of the Wilson Creek Gneiss According to Bryant and Reed (1970a) and Wagener (1978)

m.y. ago	Bryant and Reed (1970a)	Wagener (1978)
195		
	Intrusion of Diabase	
230		
250 ---		
	Metamorphism; Formation of Phyllonites; Thrusting	Prograde low rank metamorphism in Grandfather Mtn. Fm.; Retrograde metamorphism of the Wilson Creek Gneiss
345		
435		
350 ---		
570 ---		Autometamorphism of the lower Grandfather Mtn. Fm. Forming the Wilson Ck. Gn.

1000 ---	Emplacement of Wilson Creek Gneiss	Emplacement of Grenville Plutons

primarily of nonlayered quartz monzonitic gneiss and minor massive, light-colored quartz monzonite. The North Harper Creek uranium mineralization occurs in the nonlayered quartz monzonitic gneiss of the western arm. The composition of the Wilson Creek Gneiss varies from diorite to granite while the average composition is quartz monzonite. Many areas show conspicuous cataclastic foliation. Calcic plagioclase is retrograded to albite, sericite, and epidote. Quartz is often strained or recrystallized. In outcrops, the Wilson Creek Gneiss often contains dikes and pods of mica-poor quartz-feldspar pegmatite that consist of quartz, perthite, and plagioclase with local occurrences of allanite and garnet. Segregation lenses, stringers and veins of quartz, quartz and chlorite, quartz and microcline, or quartz, calcite, microcline and chlorite are common. Southwest of the Harper Creek prospect, the Wilson Creek Gneiss contains xenoliths of finely layered amphibole gneiss in a coarse pegmatitic phase. Bryant and Reed noted two mineral assemblages in the Wilson Creek Gneiss: (1) porphyroclasts of microline, plagioclase, biotite, quartz and rare muscovite, and (2) quartz, plagioclase, sericite, microcline, biotite, chlorite, and epidote with accessory zircon, stilpnomelane, carbonate, allanite, and fluorite.

V. PREVIOUS EXPLORATION ACTIVITY

Figure 3 is a map of the North Harper Creek prospect showing the surface indications of uranium mineralization and the location of drill holes in the area. Radioactivity in the area was first reported by Stow (1955) and the U.S. Geological Survey (1955, 1968a, 1968b).

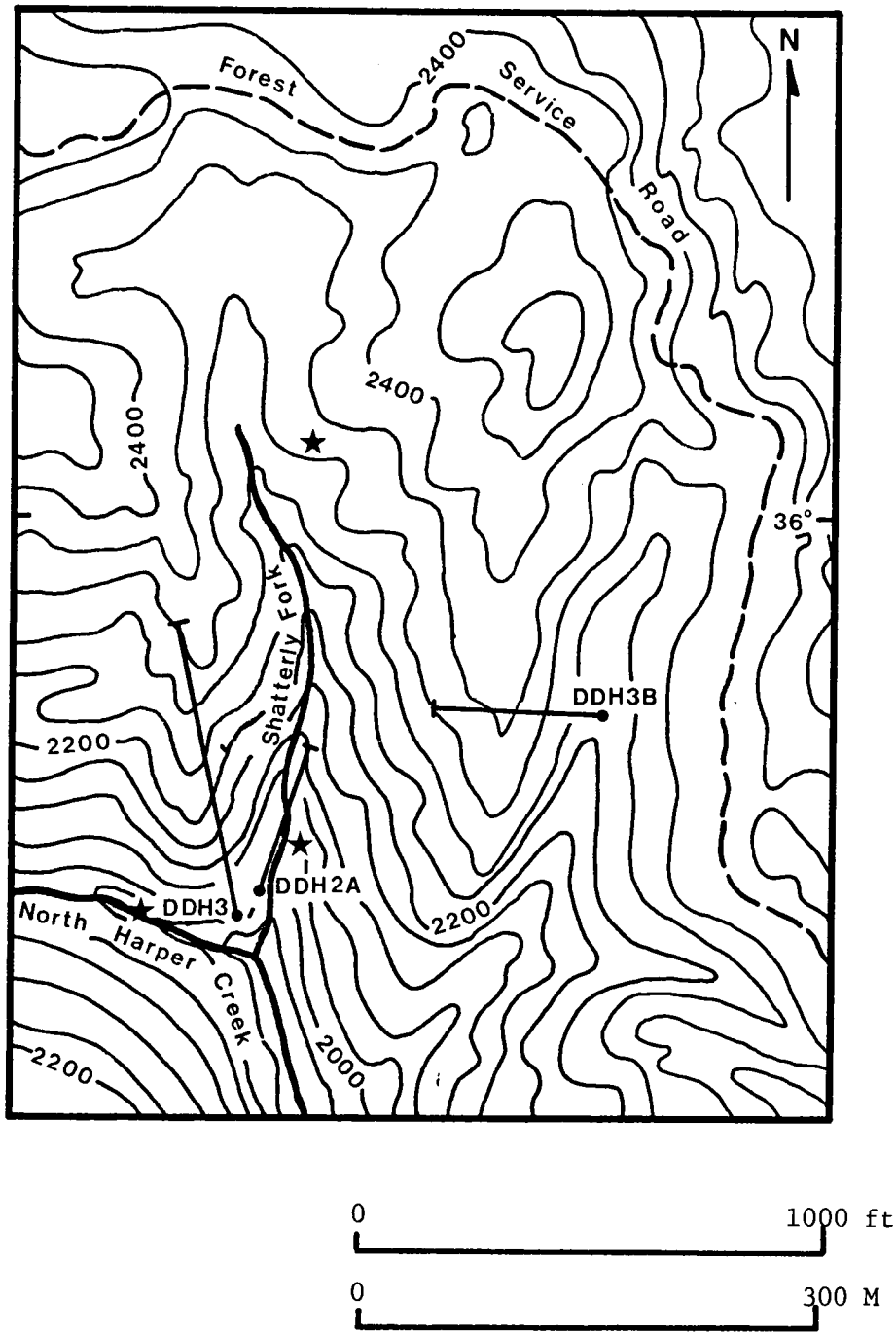


Figure 3. Topographic map of the North Harper Creek Uranium Prospect. Stars indicate the location of surface mineralization. Lines labeled "DDH" indicate the surface trace of the three drill holes studied. (After Bryant and Reed, 1970a, and FRAMCO, unpublished map.)

Stow noted that uraninite occurs in veins and in schistose zones. A uraninite vein about one centimeter wide and about five meters long extending into the North Harper Creek stream bed gave a radiometric geiger counter reading of greater than 20 MR/hr and another schistose zone gave a reading of 17 MR/hr; one chlorite zone gave a reading of 8 MR/hr. Stow found that the uraninite bearing veins often cross-cut the metamorphic lineation in this area. Geiger counter readings from outcrops in the prospect area gave background counts of about 0.2 MR/hr. Five selected analyses of samples taken from the prospect averaged 0.2 MR/hr.

Walker et al. (1963) noted that the North Harper Creek occurrence is hosted by schists and gneisses containing pitchblade bearing veins of simple mineralogy.

Exploration activity including core drilling was conducted in three prospects in the general region of Harper Creek. The data so obtained were compiled by S. J. Melikersick of E. J. Longyear Company in 1955 and 1956 but were not published. Information about the uranium mineralization in these prospects, based on Melikersick's compilation and reported by Bryant and Reed (1966), is summarized below.

The three prospects studied by Melikersick are: (1) Ripshin Ridge, near North Carolina highway 181 in the Linville Falls quadrangle; (2) Little Lost Cove, north of the road between Edgemont and Pineola in the Linville quadrangle; and (3) the North Harper Creek prospect at the boundary of the Linville and Linville Falls quadrangles. At Ripshin Ridge, the radioactive mineral was reported to be torbernite,

$Cu(UO_2)_2 \cdot 12H_2O$, and the radioactivity did not extend below the depth of the first bulldozed cut. At Little Lost Cove, the torbernite occurred in a phyllonite zone that lacked horizontal and vertical continuity. Both the Ripshin Ridge and the Little Lost Cove prospects were interpreted as resulting from supergene enrichment of disseminated uraninite.

At North Harper Creek, three types of mineralization have been described. They are: (1) disseminated uraninite in gneisses, pegmatites, and phyllonites, (2) torbernite veins in the phyllonites at the surface, and (3) veins containing uraninite in the Wilson Creek Gneiss. The disseminated uraninite mineralization was reported in a pegmatite outcropping about 350 feet downstream from Bard Falls. Further evidence of disseminated uraninite mineralization was provided in samples of brecciated granitic rock that had a radioactivity 1.5 times above the background. Torbernite mineralization was reported in the phyllonites near Shatterly Fork, containing up to 0.28 percent U_3O_8 as well as about 0.1 percent copper and trace amounts of gold, silver, and ThO_2. In core drilling, some paper-thin uraninite veins containing not more than 0.1 percent U_3O_8 were encountered. Pyrite, pyrrhotite, and chalcopyrite veinlets running parallel to the foliation were found in the Harper Creek prospect.

The preliminary report (U.S. ERDA, 1976) of the National Uranium Resource Evaluation (NURE) project noted that 11,000 tons of speculative reserves of uranium exist in the Grandfather Mountain window. They did not discuss the nature of their calculations nor the origin of the deposit.

Greenberg et al. (1977) have described the North Harper Creek prospect as belonging to the Rössing class of granitic uranium deposits that exhibit significant syngenetic mineralization. They state that this class of deposits is hosted in migmatitic and alaskite granulites, which usually form under high temperature anatectic conditions. They further note that uranium mineralization probably was concentrated during reworking (anatexis) of older rocks. The greatest potential of uranium mineralization would be found where metasomatic alteration occurred. Unfortunately, they do not provide any data showing that such high metamorphic conditions existed in the prospect area.

Galipeau and Ragland (1977) conducted a radiometric survey of the North Harper Creek area. They found that radioactivity in the prospect was diffuse rather than from a point source. The background radioactive intensity in the prospect was determined to be about 200 cps, with a range from 100 to 350 cps. Using a scintillation counter, they determined the concentration of the radioactive constituents in samples by using autoradiography, Galipeau and Ragland found that the radioactivity in thin sections of mica gneiss and Wilson Creek Gneiss was in opaque minerals associated with layers of sericite. They agreed with Bryant and Reed that the radioactive opaques are uraninite. Furthermore, they conclude that the uranium was emplaced during the consolidation of the magma.

Beaucom et al. (1977), Heffner and Ferguson (1978), and Price and Ferguson (1978) have published regional multi-element analyses of

sediments and groundwaters taken in the Winston-Salem and Charlotte 1° x 2° NTMS quadrangles which include the Grandfather Mountain window. Selected portions of this raw data are from the North Harper Creek prospect.

CHAPTER II

METHODS OF INVESTIGATION

I. SAMPLE COLLECTION

Samples were collected from exposures in the study area during the 1978 and 1979 calendar years. In addition, splits were taken from cores previously owned by the French American Metals Corporation (FRAMCO) and stored at the University of North Carolina, Chapel Hill.

Most of the rocks collected in the field were heavily weathered due to saprolitic alteration at the surface. As exposure is poor in the area, only a few samples were collected which were used primarily as support material for the suite collected from the FRAMCO cores. Core samples were taken from three drill holes; DDH-2B, DDH-3, and DDH-3B. Locations of drill hole samples used in this study are indicated in Appendix I.

II. NUMBERING OF SAMPLES

All surface samples are consecutively numbered and prefixed by the letters "HC." All drill core samples are prefixed by the drill core number (e.g. DDH-2A, DDH-3, and DDH-3B). The number following the drill hole number denotes the depth in feet from the surface at which the sample was collected (Appendix I).

III. ANALYTICAL TECHNIQUES

Several analytical techniques were used during the course of this study. They include: transmitted and reflected light microscopy, X-ray powder diffraction (XRD), electron microprobe (EMP) analysis, and autoradiography.

Seventy-two thin-sections and 22 polished-sections were studied to describe the mineral assemblages and textural features present in the rocks. Identification of some minerals was supplemented by XRD techniques where necessary. A fully automated MAC-400 S electron microprobe was used to determine chemical compositions of feldspars and garnets in selected samples. Several of the mineral phases such as titanite, chlorite, uraninite, pyrite, pyrrhotite, and chalcopyrite were also analyzed qualitatively with the energy dispersive system attached to the EMP. Where possible, Bence-Albee correction factors were applied to the elemental concentration obtained during the analysis. Autoradiographs of thin-sections were obtained by placing a thin-section on an unexposed negative. Exposure times ranged from 24 hours to two weeks.

The data obtained from these techniques are discussed in Chapter III.

CHAPTER III

PETROLOGY

I. INTRODUCTION

The North Harper Creek suite has undergone both regional dynamothermal and cataclastic metamorphism. As a result, a lithologic classification system that draws upon both cataclastic and thermal attributes has been adopted. Nomenclature for cataclastic rocks used in the present report (Figure 4) is based on the terminology given by Higgins (1971) and Bell and Etheridge (1973). Cataclastic rocks in the Harper Creek suite range from protomylonites to mylonitic schists and gneisses (Appendix I). When naming rocks in this suite, the author has adopted the following method. Mineral names are written in increasing abundance before the metamorphic rock descriptor. In the case of cataclasites, the degree of cataclasis is placed after the rock descriptor. For example, an oligoclase-microcline-quartz-sericite granofelsitic mylonite gneiss would be a mylonite gneiss of granofelsic origin, with diagnostic minerals oligoclase, microcline, etc. in increasing order of abundance.

The suite of samples studied belong to the Wilson Creek Gneiss. They include granofelsites, granofelsic cataclasites, and cataclastic gneisses. These rocks are in no particular stratigraphic order and are randomly "intercalated."

<table>
<tr><td rowspan="2">Rocks Without Primary Cohesion</td><td colspan="4">Rocks With Primary Cohesion</td></tr>
<tr><td colspan="3">Cataclasis Dominant Over Neomineralization-Recrystallization</td><td>Neomineralization-Recrystallization Dominant Over Cataclasis</td></tr>
<tr><td></td><td>Rocks Without Fluxion Structure</td><td colspan="2">Rocks With Fluxion Structure</td><td>Rocks With Fluxion Structure</td></tr>
<tr><td>Fault Breccia</td><td>Microbreccia</td><td colspan="2">Protomylonite</td><td rowspan="2">Mylonite Gneiss (Mylonite Schist)</td></tr>
<tr><td rowspan="2">Fault Gorge</td><td rowspan="2">Cataclasite</td><td rowspan="2">Mylonite</td><td rowspan="2">Phyllonite (variety)</td></tr>
<tr><td>Blastomylonite</td></tr>
<tr><td></td><td></td><td>Ultramylonite</td><td></td><td></td></tr>
</table>

Figure 4. Classification of cataclastic rocks. (After Higgins, 1971)

II. MINERAL ASSEMBLAGES AND TEXTURES

Detailed mineralogic and textural studies of the North Harper Creek suite have led to the recognition of five different mineral assemblages (A1 to A5), some of which appear to overlap in time due to mineralogic adjustments to both thermal and dynamic processes (Figure 5). Assemblage A1 was formed by plutonic activity in the late Precambrian. Assemblage A2 was formed by prograde metamorphism, possibly of Taconic age. After this thermal event reached maximum temperatures, a retrogradation of existing minerals occurred forming assemblage A3. Cataclasis started after the onset of progradation and ended before the termination of retrogradation, thus forming the A4 assemblage. Supergene alteration of rocks exposed at the surface at a later time produced assemblage A5. Bryant and Reed (1970a) used the term "retrogradation" to indicate conversion of high-temperature assemblages to those stable at lower temperatures, and therefore it includes both the prograde A2 assemblage and retrograde A3 assemblage of this report. This report has adopted the following terminology. Prograde metamorphism is used to indicate increasing temperatures and the subsequent mineralogic adjustments to those temperatures. Retrograde metamorphism is used to indicate decreasing temperatures and the subsequent mineralogic adjustments to the temperatures. Irrespective of the terminology used, a good correlation exists between the A2 and A3 assemblages of this report and Bryant and Reed's (1970a) retrograde assemblage.

Assemblage	Time: Early ---------- Late	Typical Mineralogy* Q	K	P	M	B	G	E	Z	T	Cc	Ch	Py	Po	Cp	U	A	F	H	L	Cl
A1	Plutonism	X	X	X	X	X			X	X						X	X				
A2	Prograde	X			X	X	X	X		X											
A3	Retrogrd.	X			X	X						X									
A4	Cataclasis	X			X	X		X		X											
(VA4)	U Veins										X	X	X	X	X	X		X			
A5	Super. Alt.																	X	X	X	

*Q = Quartz
K = Orthoclase
P = Plagioclase
M = Muscovite
B = Biotite
G = Garnet
E = Epidote
Z = Zircon
T = Titanite
Cc = Calcite
Ch = Chlorite
Py = Pyrite
Po = Pyrrhotite
Cp = Chalcopyrite
U = Uraninite
A = Apatite
F = Fluorite
H = Hematite
L = Limonite
Cl = Clays

Figure 5. Relative timing of the events that produced the mineral assemblages discussed in the text.

Assemblage A1

The first assemblage consists of quartz, plagioclase, microcline, muscovite, and biotite in decreasing order of abundance.

The quartz is generally medium grained, shows undulose extinction, and is often fractured and filled by later quartz. Some grains contain acicular needles of a mineral which resembles rutile. Due to the wavy extinction and fracturing, this quartz is considered to be porphyroclastic (Figure 6a). The long axis of the wavy extinction boundaries are most often in the direction of the rock schistosity. Myrmekite (Figure 6b) can commonly be found in non-cataclastic zones.

The composition of several plagioclase grains determined using the electron microprobe is albite (Ab_{95}-Ab_{98}). Within the limits of analytical error, no zonation is preserved nor are there any significant differences in compositions between feldspars analyzed in cataclastic and non-cataclastic zones. They exhibit albite twinning with rare carlsbad twins. The plagioclase commonly exhibits bent crystals and micro-fractures filled by recrystalline quartz and sericite (Figures 6c and 6d). Some are crushed or slightly stretched. All of these deformational features become more prominent in cataclastic zones. Much of the plagioclase shows some degree of alteration. Non-cataclastic zones commonly contain plagioclase with altered cores and clear rims. The alteration of plagioclase in cataclastic zones varies from altered cores and clear rims to almost completely altered grains. The alteration products in the plagioclase include abundant sericite and varying amounts of calcite and epidote. The dominant alteration products of highly altered grains are epidote and sericite.

Figure 6. Igneous assemblages.

a. Photomicrograph of sample DDH2A-67.5 under crossed nicols showing recrystallized (A2-Q) quartz forming from porphyroblastic (A1-Q) quartz augen. The augen is surrounded by sericitic (A2) muscovite.

b. Photomicrograph of sample DDH2A-12 under crossed nicols showing saussuritized myrmekite in the plutonic (A1) assemblage.

c. Photomicrograph of sample DDH2A-32 under crossed nicols showing strained and saussuritized plagioclase in the plutonic (A1) assemblage.

d. Photomicrograph of sample DDH2A-32 under crossed nicols showing saussuritized plagioclase and quartz, both of the plutonic (A1) assemblage.

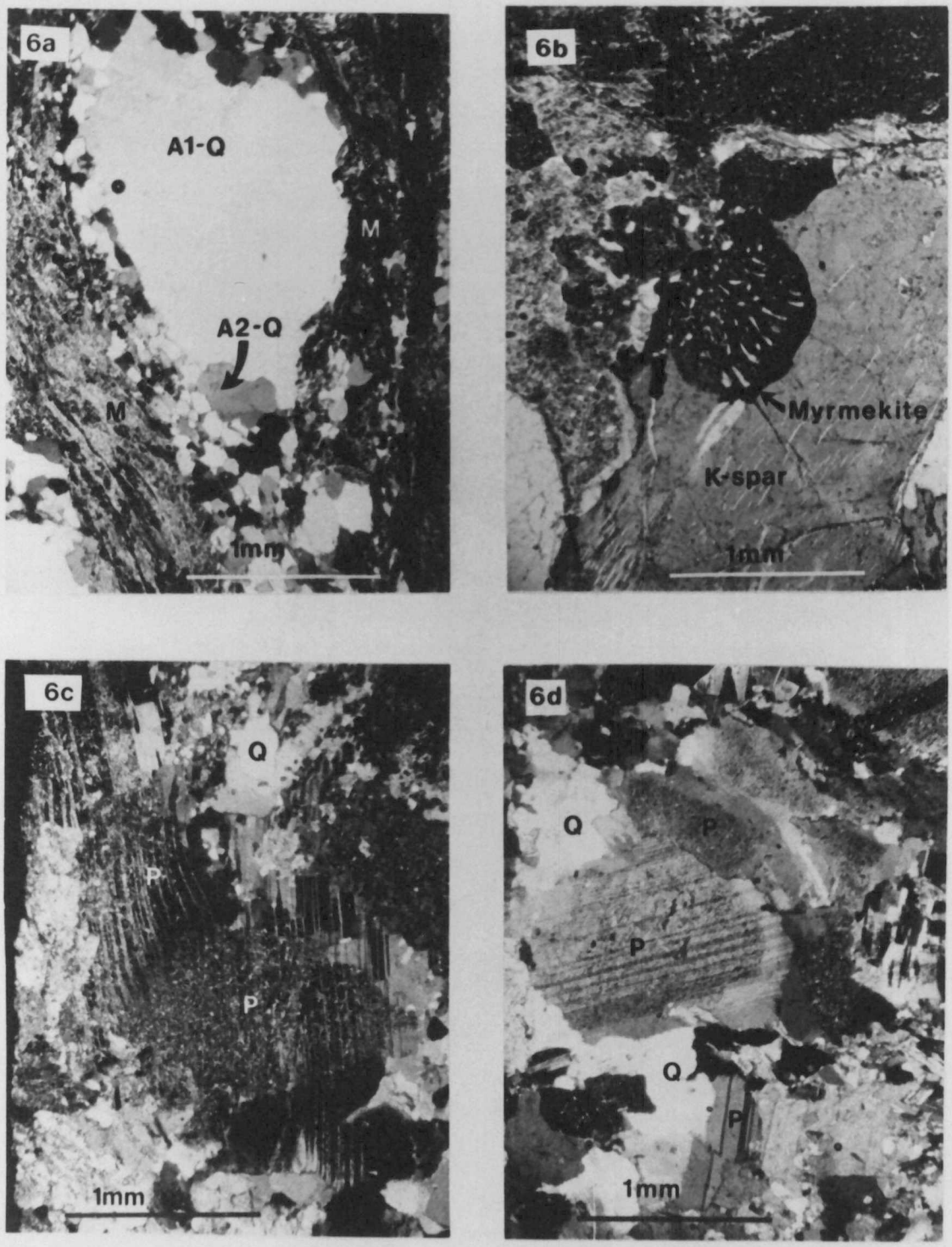

6a
A1-Q
M
A2-Q
M
1mm
6b
Myrmekite
K-spar
1mm
6c
Q
P
P
1mm
6d
Q
P
P
Q
P
1mm

Figure 6.

Microcline in the suite commonly shows gridiron twinning. Sometimes, micrographic and perthitic feldspars can be found often containing minute inclusions of sericite and quartz. As seen in the plagioclase, calcite can be found in or near microfractures or as inclusions and at grain boundaries. Calcite forming from microcline is extremely rare and in fact, cases have been noted where plagioclase is completely saussuritized whereas the K-feldspar is not altered at all. The alteration of feldspars increases with the intensity of cataclastic deformation.

Muscovite is coarse grained and most commonly shows preferred orientation. In cataclastic zones, however, some A1 muscovite clasts are rotated and surrounded by late muscovite (Figure 7a). Muscovite often forms along intergranular boundaries. In the cataclastic zones, it often has ragged edges and grades into sericitic muscovite of the A2 assemblage. Like the sericitic muscovite, the A1 muscovite is often retrograded to chlorite. Biotite is less common than muscovite, however, it exhibits all of the same textural features. It is porphyroclastic and well foliated to rotated, bent and broken in the cataclastic zones. It is often retrograded to chlorite. Occasionally, biotite contains inclusions of uraninite. The uraninite is included along the basal plane of the biotite.

Accessory minerals include uraninite, titanite, allanite, zircon, and apatite. The uraninite is disseminated throughout the rock suite and is often armored by titanite. The allanite armors the uraninite and is pale orange. Gray titanite not associated with the uraninite

Figure 7. Metamorphic, cataclastic, and vein assemblages.

a. Photomicrograph of sample DDH2A-57.7 under crossed nicols showing rotated A1 assemblage muscovite enclosed by later A2 assemblage muscovite.

b. Photomicrograph of sample DDH3-843 under crossed nicols showing a mass of recrystallized (A2) quartz forming from adjacent plutonic (A1) quartz.

c. Photomicrograph of sample DDH2A-141.4 under crossed nicols showing a complex (A4-3) vein containing uraninite, chlorite, quartz, calcite, pyrite, pyrrhotite, and chalcopyrite. The vein is enclosed by prograde (A2) and retrograde (A3) assemblages. Penetration of the complex vein by subsequent cataclastic fluids is visible. The direction of penetration is from lower right to upper left in the direction of the arrow.

d. Photomicrograph of sample DDH2A-111.5 under crossed nicols showing the (A4-2) vein associated containing calcite, chlorite, and quartz.

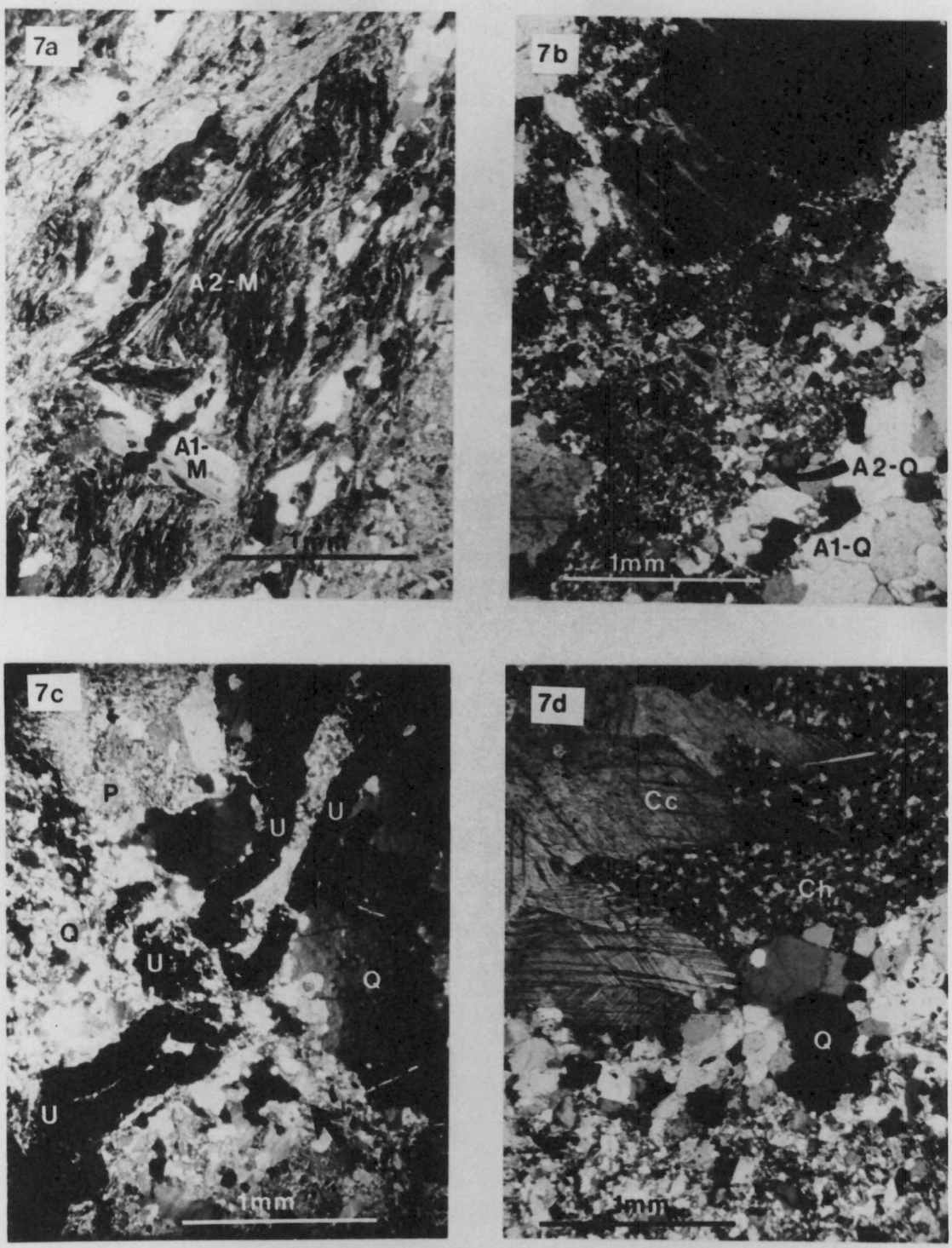


Figure 7.

occurs most often near the micas in the suite. Zircon and apatite occur as rare, minute disseminations throughout the rock.

Assemblage A2

The second assemblage consists of quartz, sericitic muscovite, biotite, calcite, epidote, and garnet. The relative abundance of each of the constituents depends on the intensity of cataclasis and the relative amounts of Al minerals available for prograde reaction.

Quartz in this assemblage is derived from the Al assemblage quartz and is recrystallized (Figures 6a and 7b). It is usually fine grained, polygonal and has uniform extinction. Rutile needles or other inclusions are absent to very rare in the recrystalline quartz. Often the recrystalline quartz forms polygonal masses within augens that are stretched in the direction of schistocity. Recrystalline quartz masses often grade into quartz veins that appear to have formed by precipitation from a solution.

The sericitic muscovite is distinguished from the Al muscovite by its very fine grain size and its excellent foliated habit (Figure 7a). The abundance of sericite increases with the intensity of cataclasis. It is always well foliated and often contorted to fill intergranular spaces and microfractures. With few exceptions, when filling fractures, the sericite is parallel to the fracture wall and does not follow the metamorphic schistocity of the rock. In cataclastic zones, it forms pressure shadows around the prophyroclastic Al minerals. Much of the muscovite in the A2 assemblage has been retrograded to chlorite.

Biotite that can be definitely related to the A2 assemblage is quite rare. When present, it is fine grained and intercalated with the sericitic muscovite. Like the muscovite, it is often retrograded to chlorite.

Calcite and epidote are formed from the same period of deformation that formed the other A2 minerals but is restricted to alteration of plagioclase and perthite of A1 assemblage (Figures 6c and 6d). Epidote is always fine grained and contained as inclusions in or near plagioclase and perthite. Calcite is euhedral and fine to medium grained. It occurs both as inclusions in the feldspars and as vein fill. The vein fill is in association with the other A2 minerals. The calcite inclusions in the feldspars occur both in healed microfractures and at grain boundaries between two feldspars. Sericite is also included in the feldspars. Saussuritization increases with increasing cataclasis. A gradation from slightly altered feldspars to completely saussuritized grains can be seen in the rock suite.

Electron microprobe analysis of the garnets show that they are not compositionally zoned and are principally almandine with minor components of spessartine and pyrope. Texturally, they range from crushed to euhedral. When crushed, the fractures are filled by sericitic muscovite and recrystalline quartz. Euhedral garnets are most often found in association with micaceous lenses while crushed garnets are near less ductile minerals such as quartz and feldspars. The garnets are always armored by sericite and recrystalline quartz. Most are free of inclusions, however one garnet studied contained

inclusions of quartz. The quartz inclusions have the same morphology of the A2 quartz described earlier.

Assemblage A3

Retrogradation of A1, A2, and early A4 assemblages is evident from the chlorite that forms from the muscovite, sericitic muscovite, and biotite in the host rocks. Furthermore, some biotite formed during the retrograde event. As the A4 assemblage is directly related to the deformational textures observed in the rocks and the A2 assemblages are related to thermal retrogradation, they are separated even though they overlap and testify to a continuous metamorphic event.

As determined by optical, X-ray diffraction, and electron microprobe methods, the chlorite varies in composition from pennine to clinochlore. The pennine forms acicular masses and reacts from the muscovite and sericitic muscovite in the cataclastic rocks. Clinochlore has a laminated habit and forms from the same micas. These chlorites may or may not follow the regional schistosity of the A2 assemblages suggesting that they were formed during and after the event that produced the A2 assemblage.

Assemblage A4

Cataclastic deformation is responsible for this assemblage. It formed under a high directed stress and at high fluid pressures with variable temperatures. The assemblage consists of recrystallized quartz, sericitic muscovite, biotite, titanite, and accessory epidote. The cataclastic deformation that formed this assemblage may be syn-metamorphic in age.

Veins

Cataclastic deformation provided zones of secondary permeability along which mineralizing fluids were able to flow, precipitating veins that account for the bulk of uraninite mineralization found at the prospect. Some of the veins cut across the granofelsites and granofelsic cataclasites indicating their post-deformational nature. Others are restricted to cataclastic zones and are cut by subsequent cataclastic veins indicative of their syn-deformational formation. In one case (Figure 7c), a uraninite vein was formed and subsequently was partially broken through by a small cataclastic penetration zone. This penetration zone appears to have formed by fluid injections in at least one direction. Both limbs of the vein are undisturbed but plastically deformed and at the point of penetration, the uraninite vein has been displaced up to five millimeters. It is possible, however, that the zone was offset in a direction perpendicular to the plane of the thin-section.

Although the textural relationships of the veins are consistently the same, the cores studied cut the veins at various places. As a result, the entire assemblage is rarely seen in any single vein at the same time. For this reason, each vein association is described separately even though they are interpreted as a single assemblage.

Calcite-fluorite veins. Only one example of this assemblage has been found in the samples studied. It consists of calcite and fluorite. Both minerals are euhedral and fill vug space. The vugs show fluorite with an elongate prismatic habit and calcite with a common prismatic

habit. Calcite is most abundant, is white and appears to have no inclusions. The vein cross-cuts both granofelsic and cataclastic zones.

Chlorite-calcite-quartz veins. Recrystalline quartz forms along the walls of the veins and is most abundant near concentrations of earlier quartz (Figure 7d, page 28). This quartz clearly originates from the wall rock but does fill the vein. It is very fine grained, has uniform extinction and is polygonal. No inclusions have been found in the quartz.

Calcite precipitates on the recrystallized quartz or, where quartz is absent, on the walls of the vein. Grains are euhedral, fine grained and white in hand sample.

The center of the vein is filled by chlorite. Its composition has been determined to be thuringite by X-ray diffraction and electron microprobe studies. This Fe^{+3}-rich chlorite forms very small euhedral crystals, or "balls," and is the most abundant mineral in this vein assemblage.

Uraninite bearing veins. These veins have the most complex mineralogy and are of economic importance. They consist of uraninite in addition to recrystalline quartz, chlorite, sericite, pyrrhotite, pyrite, chalcopyrite, and calcite.

Recrystallized quartz is formed both from the wall rock quartz and from the solutions that formed the other minerals. The recrystallized quartz formed along the walls and is most abundant where wall rock quartz is present (Figure 7d). Solution precipitated quartz is

present throughout the vein as stringers and isolated grains. All quartz is very fine grained, has uniform extinction, and contains no inclusions.

Chlorite and uraninite form an intimate mixture and appear to be coprecipitates. Often, small botroydal blebs of uraninite can be found alternating in layers of chlorite (Figure 8a). In other cases, one can find uraninite reacting with chlorite and being redissolved (Figure 8b). Furthermore, dessication cracks in uraninite may be filled with chlorite (Figure 8c). In most cases, however, uranite and chlorite are intermixed with no clear evidence of the order of precipitation or equilibrium conditions (Figure 8d). X-ray and electron microprobe examination has shown the chlorite to be near the clinochlore composition. This chlorite may have retrograded from the sericite found in the vein. Stringers of chlorite can be found to extend from the uraninite-chlorite mixture into the center of veins where the chlorite has clearly formed from the fine grained sericitic muscovite.

Pyrrhotite and pyrite occur in the center of the vein and along the walls. Pyrrhotite is polygonal and twinned (Figures 9a and 9b). Pyrite is found with pyrrhotite as fine grained crystals. It has also been identified in the center of the veins. Chalcopyrite occurs as indistinct masses in the center of the veins with uraninite and pyrrhotite. It is very fine grained and does not form euhedral crystals. Calcite sometimes occurs in the center of the vein with pyrrhotite. It also occurs along the walls of the vein. It is fine grained and euhedral. When present, the calcite is in contact with uraninite.

Figure 8. Uranium vein assemblages.

a. Photomicrograph of sample DDH2A-140 under reflected light showing botryodal uraninite in a complex vein.

b. Photomicrograph of sample DDH2A-141.4 under reflected light showing uraninite reacting with chlorite in a complex vein.

c. Photomicrograph of sample DDH2A-141.4 under reflected light showing dessication cracks in uraninite filled by later chlorite.

d. Photomicrograph of sample DDH2A-141.4 under reflected light showing uraninite and chlorite coexisting in a complex vein.

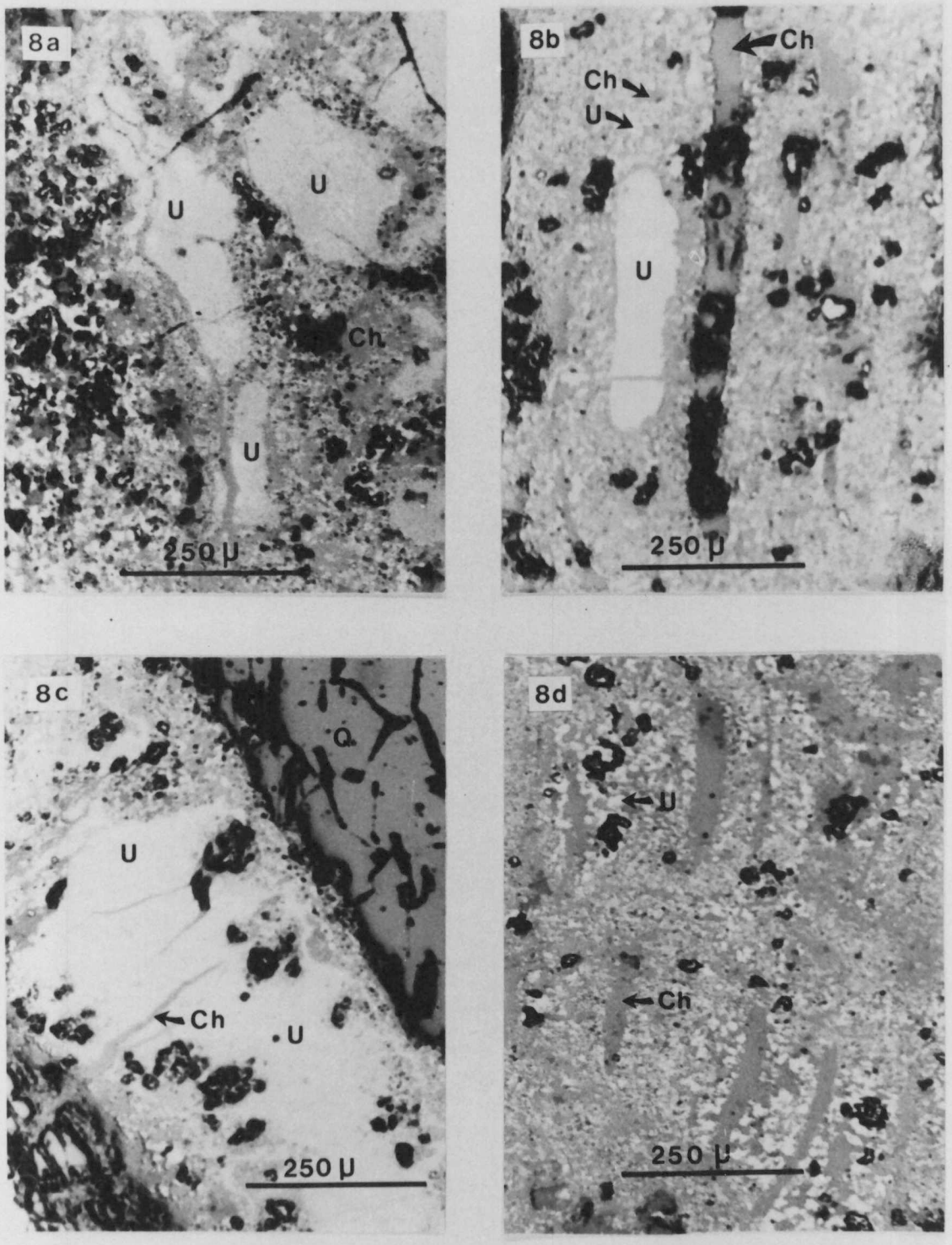
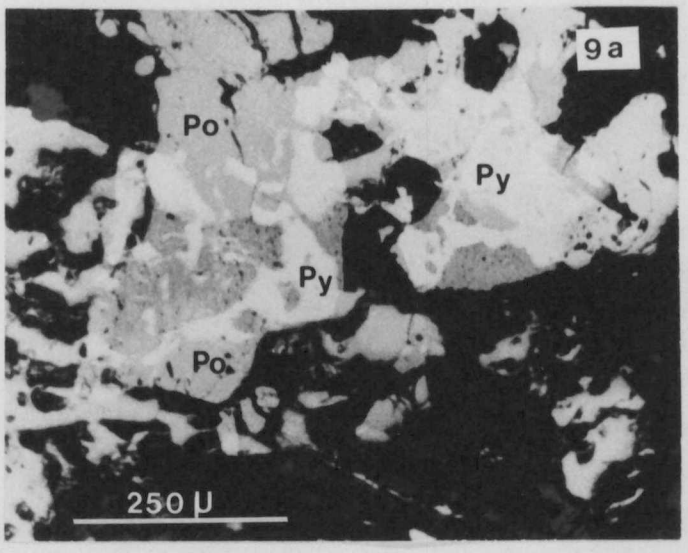


Figure 8.

Figure 9. Sulfides in uranium veins.

a. Photomicrograph of sample DDH2A-141.4 under reflected light showing pyrite and pyrrhotite on a complex vein wall.

b. Photomicrograph of sample DDH2A-141.4 under reflected light showing pyrite and pyrrhotite in the center of a complex vein.



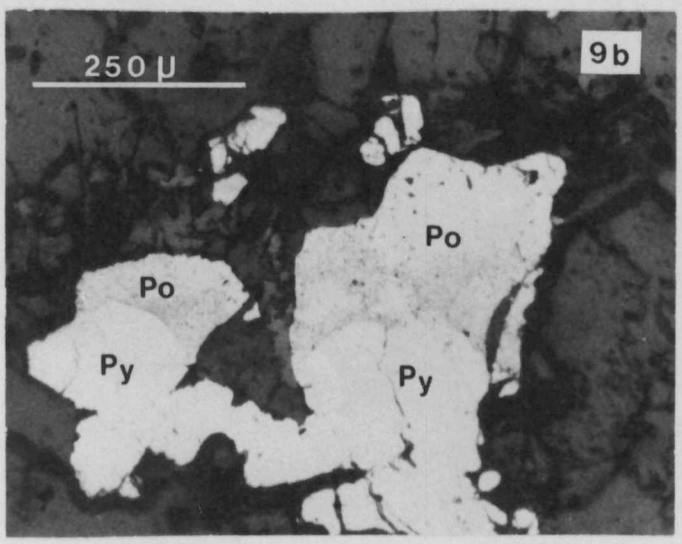


Figure 9.

The contact is clear and sharp denoting equilibrium between the uraninite and calcite.

Autoradiographs of veins were made by placing polished thin-sections in contact with X-ray film for periods up to eight days (Figures 10a and 10b). Only the uraninite bearing veins produced reasonable results. These autoradiographs clearly show the distribution of uranium minerals in the vein system.

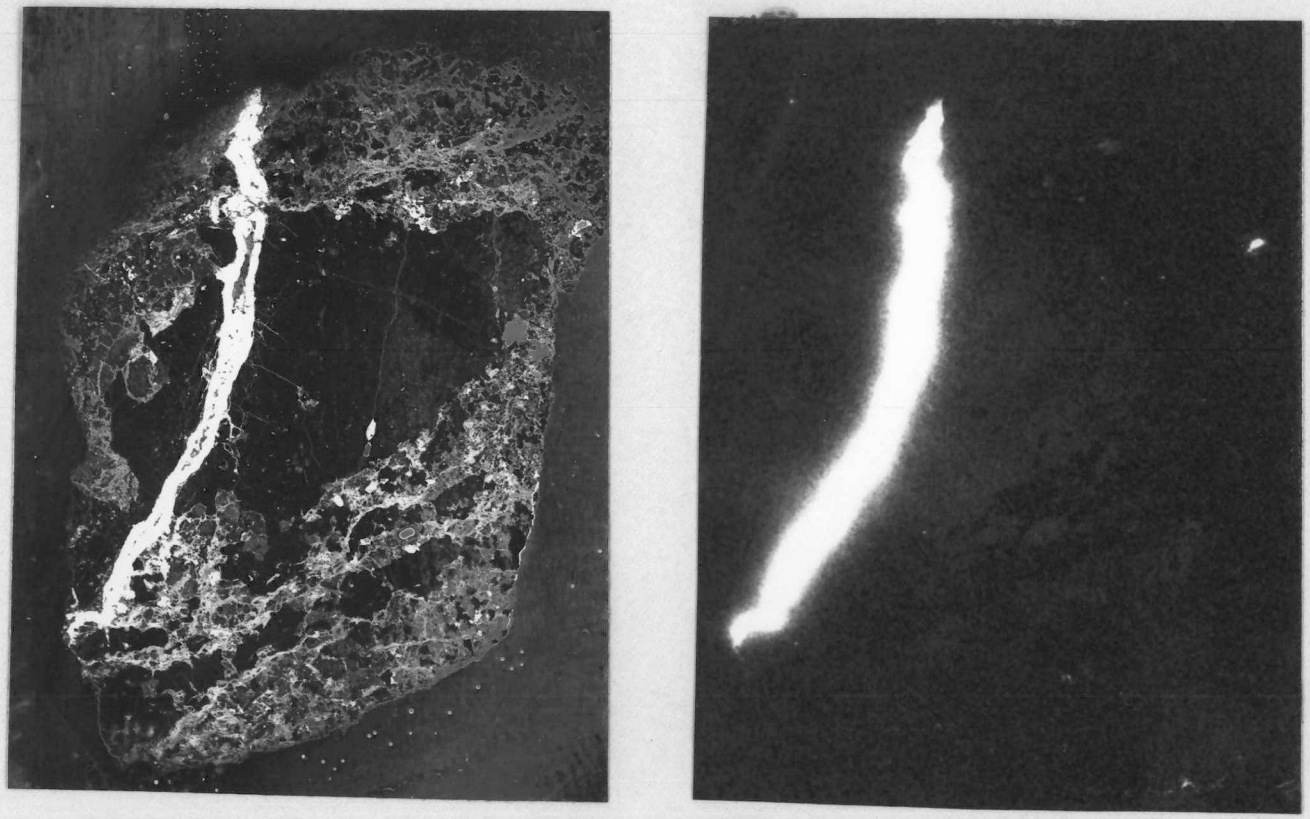
Paragenesis of veins. This assemblage contains most of the uranium found in the study area. Its mineralogy and paragenesis are complex (Figure 11).

Quartz, pyrrhotite, pyrite, and chalcopyrite do not appear to play an important role in the precipitation of uraninite. Recrystallized quartz occurs throughout the assemblage and is stable during the formation of the entire assemblage. Pyrrhotite, pyrite, and chalcopyrite occur very early and very late in the paragenesis. Uraninite is precipitated onto previously precipitated sulfides. Also, sulfides are found to form on older uraninite, but the two never precipitate at the same time. It is thus evident that the parameters that control the precipitation of these sulfides also prevent the concurrent precipitation of uraninite. Chlorite, calcite, sericite, and fluorite, on the other hand, are found in intimate association with uraninite. Chlorite and uraninite form together in the veins. It is impossible to determine if this chlorite is primary or retrograde after another micaceous mineral. Texturally, chlorite appears to replace sericitic muscovite and grade into the uraninite phase. If the chlorite that is

Figure 10. Autoradiograph of uranium bearing vein DDH2A-141.4.

a. Autoradiograph of DDH2A-141.4 showing radioactive zones. Magnification X2.5.

b. Negative print of DDH2A-141.4. Titanite in lower left is representative of disseminate mineralization. Vein type mineralization is shown at top of figure. Quartz crystal in center of figure is slightly radioactive. Magnification X2.5.



a b

Figure 10.

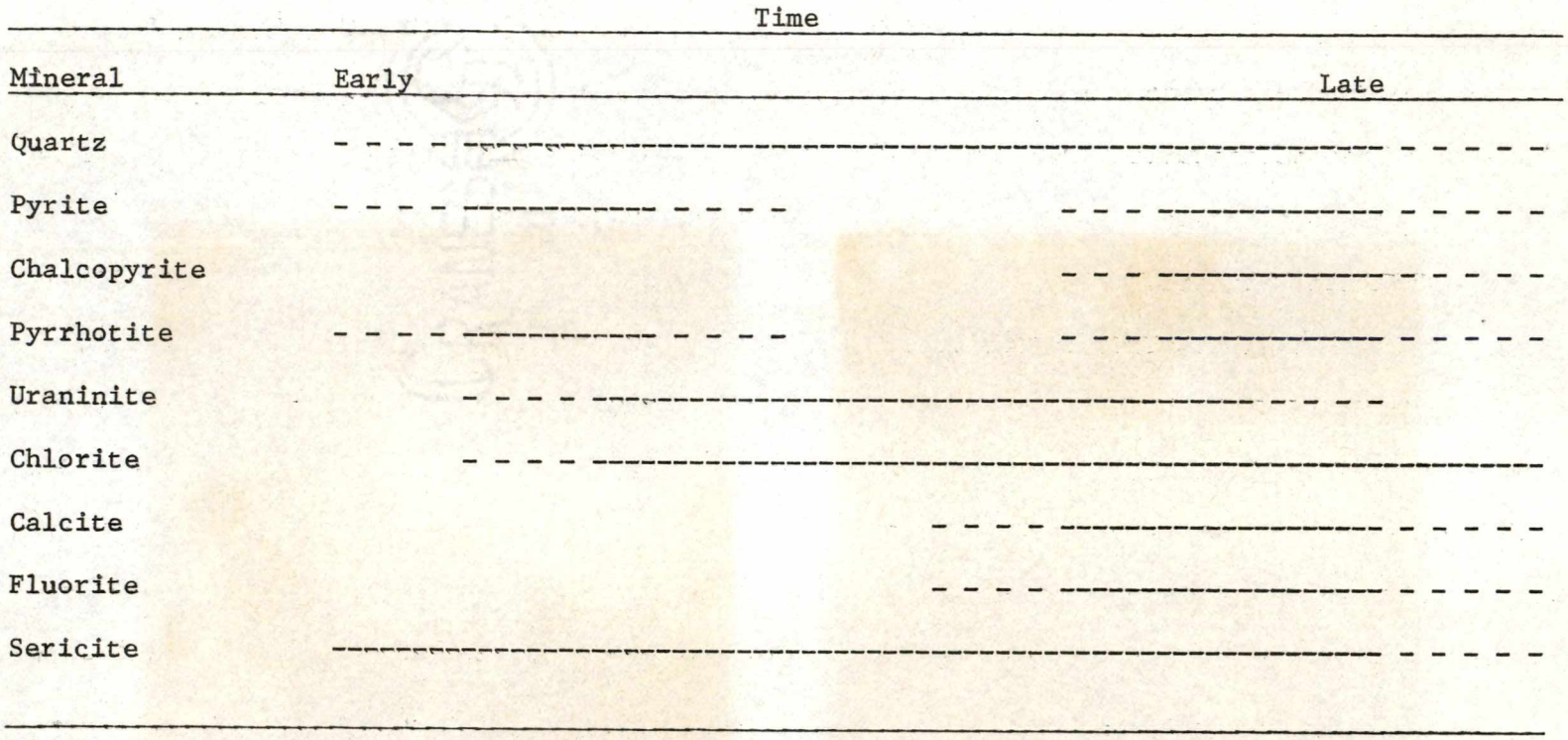


Figure 11. Paragenesis of the uranium bearing veins.

mixed with the uraninite is primary, then the depositional parameters are essentially the same. If the chlorite is retrograde, however, then the depositional parameters are the same for the uraninite and the predecessor of the chlorite. Calcite and fluorite occur exclusively after the formation of uraninite. It is possible that the formation of uraninite released ions from uranyl complexes which were subsequently free to combine with calcium to form calcite and fluorite.

Assemblage A5

The latest mineral assemblage in the Harper Creek section consists of supergene alteration products. This assemblage is restricted to the surface and upper ten to twenty meters of core section studied. Its presence is restricted to zones of secondary permeability in the shallow cover. Limonite and clays make up the materials in this assemblage. They fill recent fractures in the rocks and become most abundant near the surface.

III. LITHOLOGIES

Three rock types were encountered in the study; granofelsites, granofelsic cataclasites, and cataclastic gneisses (Figure 12). The granofelsites can be subdivided into granitic and quartz granodioritic subunits based on their composition. The cataclasites are demonstrably gradational from cataclasites to protomylonites to mylonitic gneisses. The stratigraphic columns (Appendix I) show the apparent random vertical distribution of these units. The correlation of mineralization to

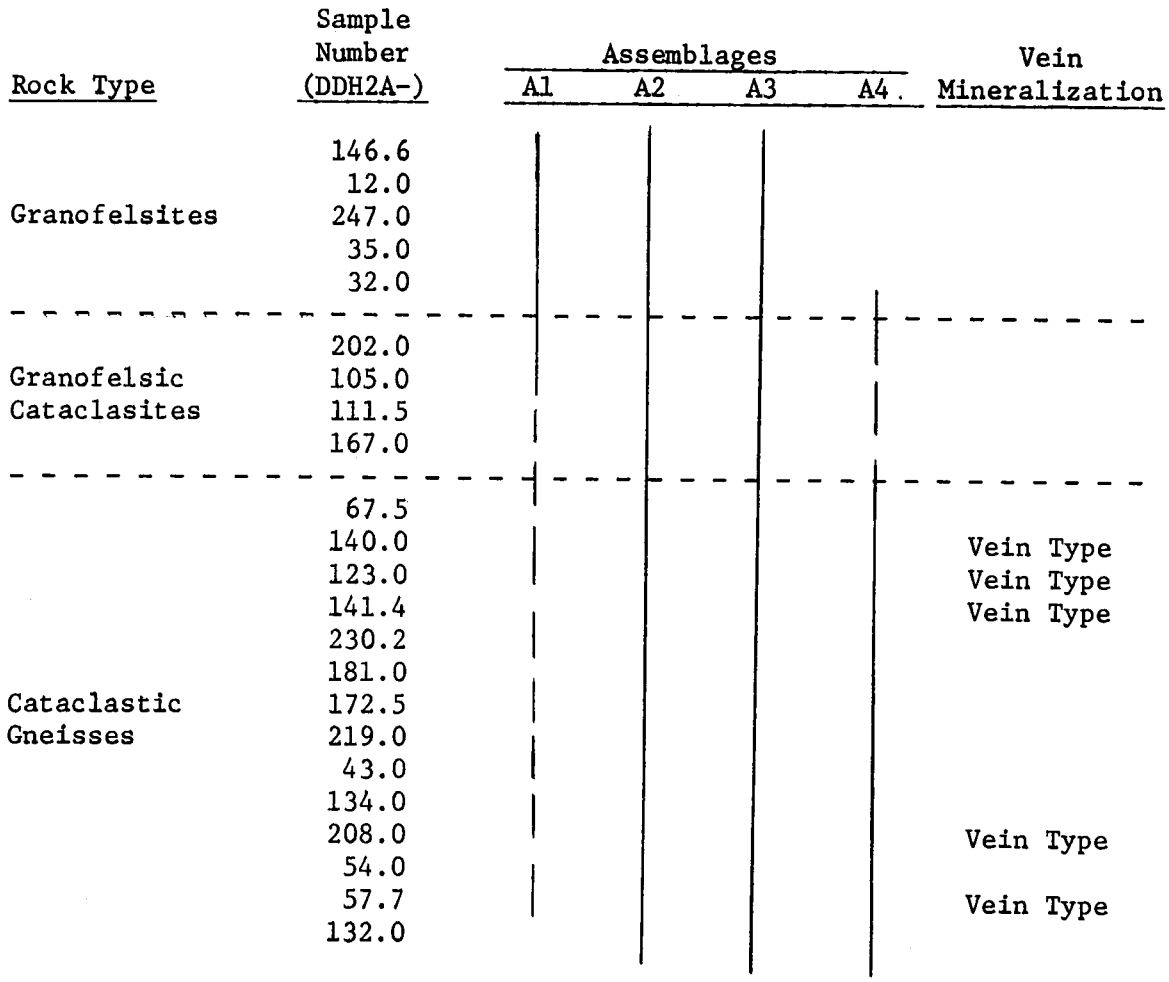


Figure 12. Correlation of uranium mineralization to increasing degree of cataclasis in drill hole DDH2A.

increasing cataclasis can be seen, however, by rearranging the samples of core DDH2A on the basis of increasing abundance of A4 assemblage (Figure 12). Point counts were used to derive modal compositions of 13 samples (Table 3 and Figure 13) taken from the study area.

Granofelsites

The composition of the granofelsites vary from granodiorite to granite and agrees favorably with the results of a similar study conducted by Bryant and Reed (1970a). The majority of the samples fall in the quartz rich granitic field. The relatively high quartz content (often 50 percent) indicates late stage fractionates of an intrusive magma. Such an interpretation is consistent with recent concepts of uranium ore genesis in igneous rocks (Rich et al., 1977).

As noted earlier, where the granofelsites have not suffered extensive cataclastic deformation, they often exhibit typical plutonic textures such as subhedral equigranular crystal development. These textures have been modified by the progressive metamorphic event that saussuritized the feldspars, strained the quartz and recrystallized muscovite, biotite, and quartz.

Granofelsic Cataclasites

Cataclastic deformation has modified the granofelsic rocks by increased saussuritization of plagioclase, recrystallization of quartz, straining of the plagioclase, orthoclase, and micas, and most significantly shearing the rock along zones of weakness. Minerals are generally strained, crushed, and sheared. Granofelsic cataclasites do

Table 3. Results of Point Counts of 13 Samples Expressed as Percent of Total Rock

Mineral	Sample 12	22	35	43	54	67.5	123	140	167	181	202	208	247
Qtz	36.17	36.73	41.5	21.16	38.21	40.87	44.29	59.12	42.96	38.94	54.01	54.53	53.06
Plag	36.24	15.27	26.8	2.74	2.21	6.43	34.10	9.21	-	27.82	31.50	30.56	33.89
K-Spar	17.25	32.62	8.4	13.79	0.21	29.33	1.33	10.35	6.75	3.66	10.35	8.21	8.72
Musc	8.03	13.13	21.4	5.41	1.20	21.31	18.76	14.38	-	24.83	2.07	2.43	3.84
Epid	-	-	-	-	8.32	1.08	-	0.13	50.30	4.75	2.07	4.27	2.43
Cc	-	2.25	1.9	-	-	-	1.52	0.69	-	-	-	-	-
Gar	2.30	-	-	0.24	-	-	-	0.06	-	-	-	-	-
Opq	-	-	-	2.43	0.20	-	-	6.06	-	-	-	-	-
Ser	-	-	-	24.22	18.86	-	-	-	-	-	-	-	-
Biot	-	-	-	30.02	0.60	-	-	-	-	-	-	-	-
Chl	-	-	-	-	29.59	-	-	-	-	-	-	-	-
Total %	99.99	100	100	100.01	100	100	100	100	100.01	100	100	100	100
Counts	1432	2521	2266	1276	997	1300	1050	1585	845	737	943	1000	1977
Qtz*	40.34	43.41	54.11	56.14	78.06	52.59	55.56	75.12	42.96	51.80	55.15	55.87	55.18
Plag + Epid	40.42	18.05	34.94	7.27	21.51	9.66	42.77	11.85	50.30	43.33	34.28	35.70	37.76
K-Spar	19.24	38.55	10.95	36.59	0.43	37.74	1.67	13.13	6.75	4.87	10.57	8.41	7.05
Total %	89.61	84.62	76.70	37.69	48.95	77.71	79.72	78.81	100	75.17	97.93	97.59	96.16

*Normalized to 100% for the quartz-plagioclase K-feldspar components.

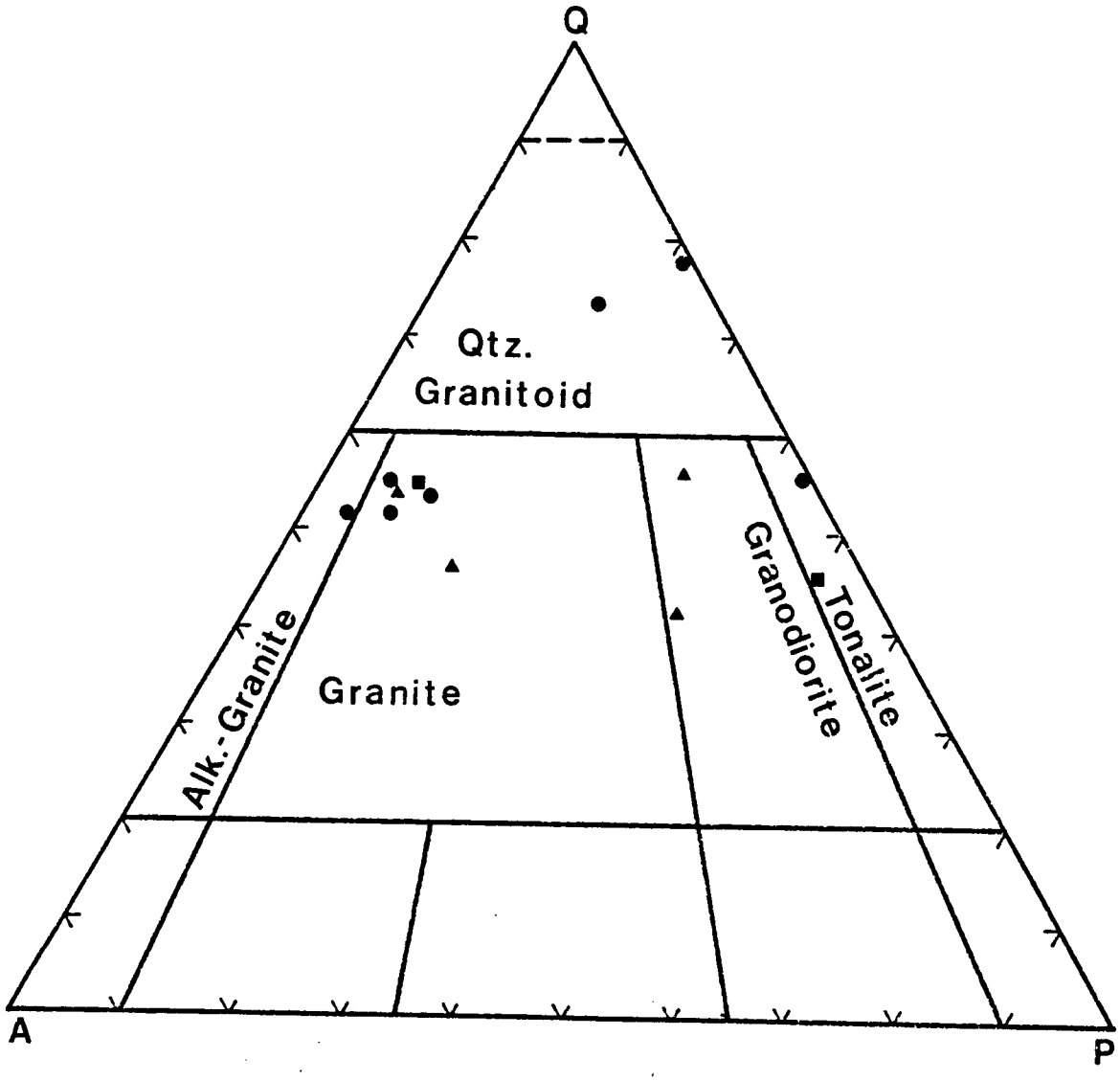


Figure 13. Modal compositions (Table 3) of samples normalized to 100%. Triangles represent granofelsites, squares represent granofelsic cataclasites, and circles represent cataclastic gneisses. Q = quartz, A = alkali feldspar, and P = plagioclase.

not exhibit segregation banding, however, the porphyroclasts are surrounded by a ground mass of sericitic muscovite which is often partially retrograded to chlorite. Occasionally, stringers of calcite and epidote are well developed.

Cataclastic Gneisses

Cataclastic gneisses are differentiated from granofelsic cataclasites by well developed segregation bands of recrystalline quartz and sericitic muscovite. Porphyroclasts of all A1 minerals as well as early A2 assemblage minerals are present in the cataclastic gneisses but their grain size is usually reduced due to intense crushing. All quartz is recrystalline and often forms augens. Extreme saussuritization of the plagioclase is apparent. Retrograde chlorite often replaces sericitic muscovite.

IV. ORIGIN OF THE ROCK SEQUENCE

As noted in Chapter I, Bryant and Reed (1970a) consider the Wilson Creek Gneiss to be orthogneissic while Wagener (1978) considers the Wilson Creek Gneiss in the Harper Creek Locality to be paragneissic. Conclusive evidence for either of these two possible interpretations has to await a more systematic investigation of the Wilson Creek Gneiss. However, the petrologic data obtained in the course of this study suggests that at least at the North Harper Creek prospect the Wilson Creek Gneiss is of plutonic origin. This conclusion is based on the following data:

1. feldspar textures and compositions;
2. absence of phyllitic textures described by Wagener (1978); and
3. uniform modal composition of cataclasites and granofelsites.

As noted earlier, the plagioclase composition varies from Ab_{95} to Ab_{98}. The cores have been saussuritized while the rims are usually pristine indicating normal zonation during growth and subsequent metamorphic homogenization. Smith (1974) summarizes the observations of several investigators by noting that any type of zoning in feldspars implies an igneous source. Furthermore, he states that normal zonation is most likely to occur in igneous rather than metamorphic rocks. Smith considers that the absence of zoning and twinning suggest a metamorphic origin for feldspars. Thus, as the plagioclase found in the Harper Creek suite was originally normally zoned and subsequently homogenized by a metamorphic event, this author considers that an igneous origin for the Al asemblage most likely.

The growth of myrmekite has been suggested by several authors (e.g., Williams et al., 1954; Hyndman, 1972; and Smith, 1974) to be formed by late stage magmatic or early post-magmatic replacement processes. Several myrmekitic zones have been identified in the granofelsites at North Harper Creek.

Perthites have been recognized in the Harper Creek suite. Hyndman (1972) discusses experimentally determined stability limits of common minerals in quartz-bearing noncalcareous rocks. He shows the reaction of homogeneous alkali feldspar producing perthite to occur well

within the andalusite, sillimanite, and anatectic fields for metamorphic rocks. No evidence has been collected that would indicate such high metamorphic conditions existed in the Harper Creek suite. Thus, if the perthite grew during metamorphism, then one must expect to see higher temperature assemblages than those observed in the suite. These perthites must, therefore, be of igneous origin.

Wagener (1978) states that the phyllonites described by Bryant and Reed (1970a) are really phyllites. He concludes that the phyllites must be produced from sediments and volcanics. This study agrees with Bryant and Reed. The fine grained schists are not phyllites, but rather phyllonites and protomylonites. The textural evidence in support of this conclusion is presented above.

Additional support of this conclusion is given by the results of the modal compositions of the cataclastic and not-cataclastic zones. If the cataclastic zones were in reality phyllites, then one would expect to see a compositional variation between the phyllite and granofelsites. This compositional variation would result from original compositional variations of the parent materials that formed the granofelsites and "Phyllites." As seen in Figure 13, page 48, the compositions of the two rock types are essentially the same indicative of a common source.

V. EVOLUTION OF THE ROCK SEQUENCES

Prograde metamorphism reached a maximum of almandine grade which is equivalent to the highest temperatures (500° to 550°C) of Winkler's

(1976) low grade metamorphism. Hyndman (1972) noted that the muscovite-biotite-quartz-oligoclase-carbonate-almandine assemblage is typical of this grade. The A2 assemblage discussed in this chapter is a result of the prograde metamorphic event. As noted earlier, the almandine formed at a different time than the biotite with which it is in contact. It is important to note that this textural interpretation does not imply that no biotite formed prior to the garnet. It does suggest, however, that cataclastic deformation continued during and after the maximum metamorphic temperatures were reached and that this cataclastic action also controlled the formation of biotite. Winkler (1978) notes that petrographic data suggest the following reaction may control the formation of almandine:

Chlorite + anorthite compounent of oligoclase = almandine + chlorite + quartz + H_2O (3.1)

Minute chlorite and quartz grains were found in contact with the garnets in the suite. It is possible that this reaction is responsible for the formation of almandine in the study area. The absence of staurolite, and the small grain size of the unzoned almandine indicate that a maximum temperature of about 500°C was reached in the prospect area.

The saussuritization of plagioclase is associated with the progradation. Bryant (1966) presents evidence that the saussuritization was controlled, in part, by the shearing intensity. Data collected during this research agree with the interpretation of Bryant. The plagioclase porphyroclasts within the cataclastic zones are usually

more altered than the plagioclase in the granofelsic zones. Bryant suggests that if epidote minerals are present, the following reaction expresses the saussuritization characteristic of the rock suite:

$$2An_{20} + 3K\text{-spar} + K^{+} + 7H^{+} + H_2O = Epid + 4Musc + 22Quartz + 8Na^{+} \quad (3.2)$$

Bryant (1966) also gives a reaction for the alteration of potassium feldspar sometimes seen in this suite:

$$3K\text{-spar} + 2H^{+} = 1Musc + 6Quartz + 2K^{+} \quad (3.3)$$

Both reactions (3.2) and (3.3) are consistent with the petrographic data collected in this study.

After temperatures reached a maximum, they began decreasing resulting in the formation of the A3 retrograde assemblage. This assemblage is characterized primarily by the continued formation of biotite and the subsequent alteration of the micas to chlorite. Hyndman (1972) notes that retrograde metamorphism may result from water driven off by prograde metamorphism at depth. Bryant and Reed (1970a) conclude that the metamorphic event climaxed 350 m.y. ago but may have continued to 250 m.y. ago. If such is the case, and if cataclasis continued after the end of prograde metamorphism, then solutions could have ascended both to aid in retrogradation and to transport materials from depth.

Dynamic (cataclastic) metamorphism produced the A4 assemblage during the thermal event that produced the A2 and A3 assemblages. Fluids appear to have played an important role in the development of the cataclastic textures now seen.

The granofelsic cataclasites are visualized to have formed from the granofelsites in the following manner. During Paleozoic thrusting, a directed stress field operated on the Precambrian crystalline rocks in the lower block (e.g., the Wilson Creek Gneiss and the Blowing Rock Gneiss). This stress was relieved in two ways. First, where strain rates exceeded the rock strength, the crystalline rock deformed cataclastically. Several of the samples studied showed fluid injection textures attendant to the phyllonitization. This fluid probably was formed from mineral dehydration and acted both as a lubricant and as a circulation system for the transport of ions and complexes. If the granofelsic rock was homogeneous, then the cataclastic deformation probably started along random planes of weakness such as rock cleavage and joint systems. Such a mechanism would explain the apparent random manner in which the cataclastic deformation took place. The second manner in which the directed stress was relieved is by plastic deformation of the host granofelsites. Plastic deformation would be expected where the stress field did not exceed the strength of the rock. Textural evidence indicates that both mechanisms were active in the deformation of the North Harper Creek suite. The precursor to the Wilson Creek Gneiss was first cataclastically deformed. As sericitic assemblages were produced in cataclastic zones the rock strength was significantly reduced. Continued thrusting then plastically deformed the cataclastic zones. This interpretation is supported by the following petrographic evidence:

1. a systematic decrease in Al porphyroclasts with increasing deformation,

2. kink folds recognized in the Cataclasites but not in the Granofelsites,
3. fluid injection textures seen in both A1 and A2 assemblages,
4. increased alteration of plagioclase and microcline with increasing cataclastic deformation,
5. increased recrystallization of muscovite and biotite with increasing cataclastic deformation, and
6. contortions of vein systems that were formed early in the metamorphic cycle.

Points 1, 4, and 5 indicate the granofelsite was systematically broken down due to mechanical deformation. The alteration and recrystallization of porphyroclasts results from both the stress and increased fluid pressure as evidenced by point 3. Points 2 and 6 indicate that early formed assemblages were themselves deformed plastically due to a reduced rock strength.

CHAPTER IV

ORIGIN OF URANIUM-BEARING VEINS

I. INTRODUCTION

Any model that describes the source, transport, and deposition of uranium at North Harper Creek must also account for the features observed in the host rocks of the prospect. This study presents evidence that, at North Harper Creek, the Wilson Creek Gneiss is probably an igneous body that suffered dynamic and thermal metamorphism. This event produced prograde, retrograde, and cataclastic assemblages. Uraninite is found as fine disseminations within granofelsites and cataclasites. Mineralogically complex veins containing uraninite are found primarily in cataclastic zones and occasionally crosscutting granofelsites. Evidence has been presented showing the time correlation of vein deposition to the cataclastic event which overlaps the prograde and retrograde thermal events in time. The model proposed here for the origin of uranium-bearing veins in the North Harper Creek prospect adequately conforms to the origin and evolution of the Wilson Creek Gneiss in the prospect area.

II. SOURCE OF URANIUM

The Wilson Creek Gneiss in the prospect area is primarily a quartz-rich granitic to quartz-rich alkali granitic rock. The uranium content of granites (2.1-21.0 ppm U) and alkalic intrusives (0.04-140.0

ppm U) is generally significantly higher than the crustal abundance (about 2 ppm) of uranium (Clark et al., 1966; Rogers and Adams, 1967). This relatively high concentration of uranium in granitic rocks is attributed to enrichment of uranium in the late stage fractionates in a differentiating magma (Sorensen, 1970; Rich et al., 1977). The same is also true for granitic magmas produced by partial melting because uranium and other incompatible elements are strongly fractionated into the early melts (Cox et al., 1979).

The uranium in the granitic rocks occurs as: (a) disseminated, minor, accessory minerals such as uraninite; (b) isomorphous substitutions for Th^{+4}, Zr^{+4}, and Ca^{+2} in accessory minerals such as monazite, zircon, apatite, titanite, and allanite, and (c) mulecular-ionic disseminations in the rock forming minerals such as feldspars, biotite, muscovite, and hornblende (Rogers and Adams, 1967; Larsen and Gottfried, 1961). Uranium occurring in the rock-forming minerals seems to have weaker bonding. Leaching experiments conducted by Larsen et al. (1956) showed that a significant part of the uranium in the rock forming minerals of the Southern California batholith was leachable without removing much of the silicate material (Table 4).

The bulk of the loosely bonded uranium held in the rock-forming minerals is likely to be removed during progressive metamorphism of granitic rocks. This is largely because of desorption from surfaces as the specific surface area of minerals is significantly reduced during metamorphic recrystallization. Studies of Precambrian metamorphic terrain in Norway (Heier and Adams, 1965) and the USSR (Yermoloyev,

Table 4. Leachable Uranium Content, Southern California Batholith[a]

Mineral	Original Uranium Content (ppm)	Unleached Uranium Content (ppm)	Percent Uranium Leached	Percent Sample Leached
Quartz	1.1	0	0	2.2
Microcline	1.1	0.3	70	3.1
Plagioclase	5.1	0.2	98	2.0
Biotite	5.1	1.8	64	30.0
Hornblende	10.0	2.3	77	11.5
Hypersthene	5.2	1.7	68	10.8
Accessory Minerals	50-5000		0-30	
Average	2.5	1.0	60	

[a]Larsen, E. S., Jr., and Gottfried, D., 1961, Distribution of uranium in rocks and minerals of mesozoic batholiths in western United States: U.S.G.S. Bull. 1070-C, pp. 63-103.

1971) have shown a systematic loss of uranium from rocks as grade of progressive metamorphism increases (Table 5). The released uranium (along with other trace elements) would be concentrated in the fluid phase generated during metamorphism. This fluid would be expelled upward through lower grade metamorphic regimes along fracture and shear zones as metamorphic-hydrothermal fluids (Boyle, 1961).

The hydrothermal fluid responsible for the vein-type uranium mineralization at Harper Creek is believed to be of metamorphic derivation. By using autoradiographic techniques Galipeau and Ragland (1977) found uranium rich areas in feldspars, muscovite and biotite. No systematic study has been undertaken to check if there is a laterial variation in the uranium contents of these minerals in a direction away from the uraninite bearing veins. However, the rather low (garnet) grade metamorphism of the near surface rocks in the area suggests that these rock-forming minerals probably did not lose much of their disseminated uranium during metamorphism. It seems more likely that the bulk of the uranium was obtained from a deeper source of higher grade metamorphic rocks and was carried in hydrothermal fluids down a pressure gradient to a lower grade metamorphic regime. The localization of uranium bearing veins in cataclastic zones and the persistence of disseminated uranium mineralization in the upper level rocks are compatible with this hypothesis.

III. TRANSPORT OF URANIUM

The route used by the transporting fluids is far easier to describe than the mechanism of transport. A strong correlation exists

Table 5. Uranium and Thorium in Regional Metamorphic Grades, Precambrian, Northern Norway[a]

	U (ppm)	Th (ppm)	Th/U (ppm)
Epidote-amphibolite facies	3.45	26.48	7.1/1
Amphibolite facies	1.22	9.39	7.8/1
Low-grade granulite facies	0.88	4.09	4.6/1
High-grade granulite facies	0.39	0.93	2.4/1

[a]Heier, K. S., and Adams, J. A., 1965, Concentration of radioactive elements in deep crustal material: Geochim. et Cosmochim. Acta, v. 29, no. 1, pp. 5-37.

between uraniferous veins and cataclastic deformation. Cataclasis occurred during both prograde and retrograde metamorphism. Penetration textures in the A4 assemblage produced in the cataclastic zones indicate that fluids were actively circulating during the precipitation of uraninite (Figure 7c, page 28). Cataclasis increased the permeability of the host rocks and allowed transporting fluids to migrate towards regions of lower pressure and temperature.

It is well established from experimental studies (e.g., Miller, 1958; Trung and Poty, 1972; and Langmuir, 1978) that uranium can form a large number of uranous (U^{+4}) and uranyl (U^{+6}) complexes in aqueous systems. The relative importance of these complexes in a given system is determined by the parameters of the system such as activities of various complex forming ions, pH, and temperature, as illustrated for some of the uranyl species in Figures 14a and 14b. The important uranous species include fluoride, hydroxide, and phosphate complexes, but the solubility of uranium in quadrivalent form under reasonable geologic conditions is very small. On the other hand, experimental data suggest that enough uranium can be transported as U^{+6} complexes, especially as O^{-2}, OH^{-1}, and CO_3^{-2} complexes in oxidizing to slightly reducing conditions to account for the formation of hydrothermal uranium deposits. The chemistry of uranium transport in hydrothermal fluids is not yet fully understood, particularly at higher temperatures (Kimberly, 1978). However, on the basis of available data, Rich et al. (1977) concluded that the major complexes for hydrothermal transport of uranium are as follows: $UO_2(OH)^+$ and UO_2^{+2} in acid

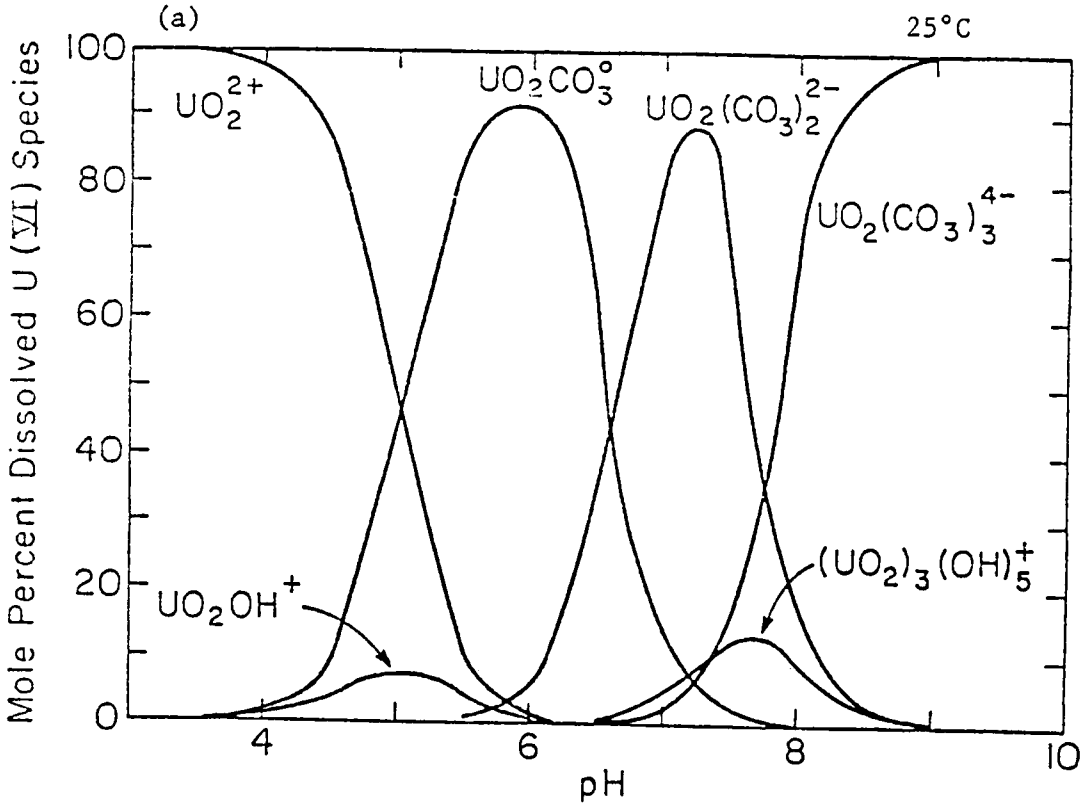


Figure 14. Solubility of uranyl-hydroxide and uranyl-carbonate complexes as a function of pH for $PCO_2 = 10^{-2}$ atm and $U = 10^{-8}$ M (2.4 ppb) at 25°C and 100°C. (After Langmuir, 1978)

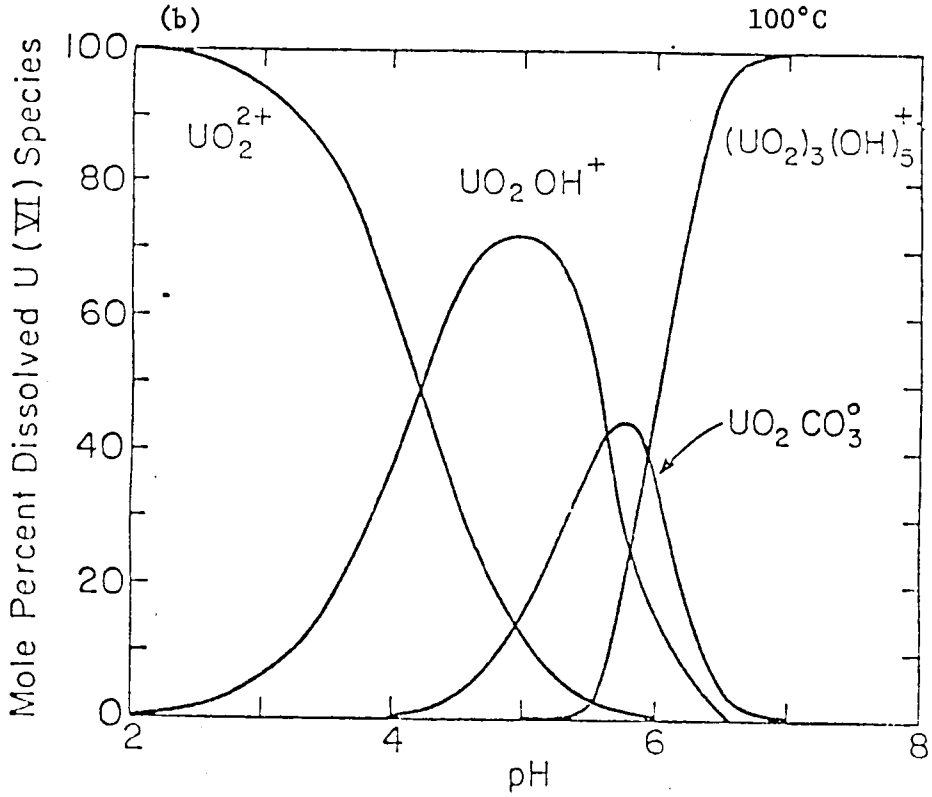


Figure 14. (Cont'd)

solutions, $UO_2OH_2^0$ and $UO_2CO_3^0$ in near neutral solutions, and $UO_2(CO_3)_2^{-2}$ and $UO_2(CO_3)_3^{-4}$ in alkaline solutions. Although the stabilities of uranyl-carbonate complexes decrease above 25°C (Langmuir, 1978), the presence of rather large CO_2 concentrations (up to about three mole percent CO_2) in fluid inclusions from some hydrothermal uranium deposits (Poty et al., 1974) attest to the importance of carbonate complexes in uranium transport.

In the Harper Creek prospect, the apparent lack of wall rock alterations at the contact of uranium-bearing veins suggest that the ore-forming solutions may have been close to neutral in pH. It is therefore reasonable to postulate that the uranium was present in the ore forming solution as $UO_2OH_2^0$ and $UO_2CO_3^0$ complexes. The presence of abundant calcite in the uranium bearing veins supports this conclusion. Sulfate and fluoride complexes are not likely to have been quantitatively important in the near neutral ore solutions (Langmuir, 1978); this is compatible with the very minor amounts of sulfides and fluorite in the veins.

IV. PRECIPITATION OF URANIUM

Three possible mechanisms may be important in the precipitation of uranyl-carbonate complexes. They are: (1) change of Eh of the solution, (2) change in pH of the solution, and (3) loss of CO_2 from the solution. Each of these three parameters (Eh, pH, and CO_2 content of the fluid) control the stability of uranyl-hydroxide and uranyl-carbonate complex stability in solution. Thus, by changing one or more of these parameters, it should be possible to precipitate uranite.

As mentioned before, there are too few systematic data to define the effect of pH on the solubility of uranium compounds at high temperatures and therefore to evaluate the effect of pH changes on the development of hydrothermal uranium deposits. According to Rich et al. (1977), from the available data, it seems likely that the effects of changes in solution pH are not as important as those of redox reactions for precipitation of uraninite.

Langmuir (1978) has shown the phase relations of various uranyl-complexes and uraninite in Eh-pH space in the uranium-oxygen-carbon dioxide-water system at 25°C (Figure 15). Although this diagram does not represent temperatures typical of hydrothermal conditions, it does show the relative positions of the uranyl-complexes and uraninite. It is evident from this diagram that a reduction of the Eh of the solution would result in the precipitation of uraninite.

Rich et al. (1977) have discussed the evidence for reduction as a viable mechanism of uranium precipitation in many hydrothermal deposits. Evidence for the reduction-deposition model such as concommitant oxidation of Fe^{+2} to Fe^{+3} in the form of hematite, presence of graphite or organic matter, and preferential localization of uranium bearing veins in more reduced rock units have not been found in the Harper Creek prospect. The Harper Creek uranium bearing veins do not contain any hematite but X-ray diffraction analysis of chlorite associated with uraninite suggest a relatively Fe^{+3}-rich composition for the chlorites. Moreover, the presence of sulfides in association with uraninite in the veins provide some evidence that relatively reducing conditions prevailed during the precipitation of uraninite.

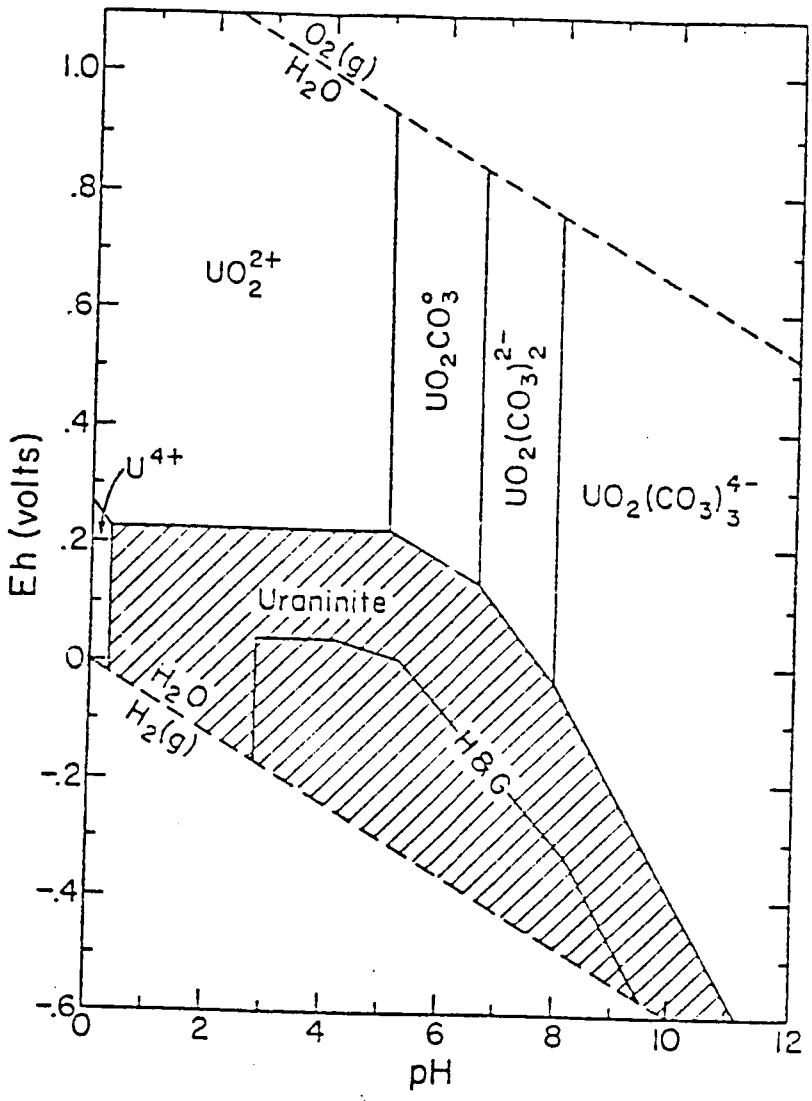


Figure 15. Eh-pH diagram in the U-O_2-CO_2-H_2O system at 25°C for $P_{CO_2} = 10^{-2}$ atm. Uraninite, UO_2(c), solution boundaries are drawn at 10^{-6} M (0.24 ppm) dissolved uranium species.

If uranium was transported as carbonate complexes, it may have been precipitated by a loss of CO_2 on boiling as suggested by Poty et al. (1974). This possibility has been discussed by Rich et al. (1977) with respect to the $UO_2(CO_3)_2^{-2}$ complex. The equilibrium between the hydrothermal fluid and UO_2 may be expressed by the general reaction:

$$UO_2 + 1/2O_2 + 2CO_2 + H_2O \rightleftharpoons UO_2(CO_3)_2^{-2} + 2H^+ \quad (4.1)$$

However, since HCO_3^- is the dominant carbonate solute species at intermediate pH (Stumm and Morgan, 1970), Rich et al. (1977) recast reaction 4.1 as:

$$UO_2 + 1/2O_2 + 2HCO_3^- \rightleftharpoons UO_2(CO_3)_2^{-2} + H_2O \quad (4.2)$$

According to reaction 4.2, the activity of $UO_2(CO_3)_2^{-2}$ in the solution saturated with UO_2 is proportional to $f_{O_2}^{1/2}$ and $a_{HCO_3^-}$. At constant or decreasing f_{O_2}, continued precipitation of UO_2 can be achieved by a decrease in the $a_{HCO_3^-}$ via the reaction:

$$Ca^{+2} + 2HCO_3^- \rightleftharpoons CaCO_3 + CO_2 + H_2O \quad (4.3)$$

Reaction 4.3 implies that the precipitation of UO_2 due to loss of CO_2 should result in the coprecipitation of calcium carbonate. Rich et al. (1977) argued against this mechanism because hydrothermal uranium deposits generally lack evidence for simultaneous precipitation of UO_2 with calcium and other carbonate minerals. However, in the Harper Creek prospect, the broadly contemporaneous precipitation of calcite and uraninite suggests that uraninite may have been precipitated through

loss of CO_2 from the fluid. It has been argued before that $UO_2CO_3^0$ and not $UO_2(CO_3)_2^{-2}$ was probably the dominant carbonate complex at the site of uranium deposition at Harper Creek, but a similar set of reactions and arguments can be written for the $UO_2CO_3^0$ complex.

V. SUMMARY

Two possible sources of the uranium found in the veins are: (a) from the disseminations found locally, and (b) from a deeper metamorphic-hydrothermal source. On the basis of available data, the latter source appears to be more likely. Uranium was transported along zones of secondary permeability produced by cataclastic deformation as complex ions. Due to the paucity of thermodynamic data at elevated temperatures and pressures of uranium complexes, it is presently impossible to determine which complexes are responsible for uranium transport, however, uranyl-hydroxide and uranyl-carbonate complexes appear to be favored. The precipitation of uraninite in veins can be accomplished by changing Eh or a_{CO_2} while pH changes do not seem to aid precipitation. As calcite is found in the uraninite bearing veins, boiling of CO_2 is favored as a mechanism for precipitating uraninite from the ore solutions.

CHAPTER V

SUMMARY AND CONCLUSIONS

The objectives of this study were: (1) to study the nature and distribution of the uranium mineralization, and (2) to interpret its genesis in the North Harper Creek prospect, Avery county, North Carolina. The results of this research are based on samples collected from limited outcrops and three drill cores taken at the prospect.

In order to understand the uranium petrogenesis, it was necessary to study the host rock petrology in detail. Host rock petrologic studies rendered the following results:

1. The Wilson Creek Gneiss protolith in the prospect area was probably a quartz-rich alkaline granite;
2. Primary disseminated uranium was emplaced as inclusions in late stage minerals in the granite;
3. A dynamothermal metamorphic event produced three assemblages corresponding to prograde, retrograde, and cataclastic events;
4. Complex uraninite-bearing veins were emplaced during the cataclastic event;
5. The source of uranium-bearing veins was possibly from a deeper, higher grade metamorphic region;
6. Uranium was transported along zones of increased permeability (due to cataclasis) to the site of precipitation, possibly as complex ions;

7. Precipitation of uraninite was probably accomplished by boiling of CO_2 and O_2 due to a lowering of fluid pressure;
8. Subsequent erosion produced a supergene enrichment zone through saprolitic alteration of the exposed rocks.

The Wilson Creek Gneiss protolith is represented by an assemblage consisting of quartz, normally zoned plagioclase, orthoclase, muscovite, and biotite. Myrmekite, perthite, zoned plagioclase, and equigranular randomly oriented minerals indicate that the protolith in the region of Harper Creek was an intrusive body. Modal analyses show that it was a quartz-rich alkaline granite to quartz granodiorite. Previous workers have shown that this plutonic rock was emplaced about 1.1 b.y. ago.

Galipeau and Ragland (1976) have shown through autoradiography that disseminated uranium was located primarily in zircon, biotite, muscovite, and feldspars. Background values of radioactivity appear to be elevated throughout the Wilson Creek Gneiss. This high background radiation indicated that no appreciable decrease in disseminated uranium occurred near the prospect.

The dynamothermal event that produced the metamorphic and cataclastic mineral assemblages in the prospect area probably occurred during Taconic time. This event prograded the rocks to the upper limit of Winkler's (1976) low grade metamorphic facies producing almandine garnet. Subsequent lowering of heat retrograded much of the micas produced by prograde and cataclastic action to chlorite. The cataclastic event started after the onset of thermal prograde metamorphism

and stopped before the end of the retrogradation of the previously formed assemblages. This dynamic action produced straining in the granofelsites (metamorphosed granite), granofelsic cataclasites, and cataclastic gneisses.

During cataclasis zones of permeability were created along which complex uraninite bearing veins were deposited. The source of these veins was probably from a deeper, higher grade metamorphic region where significant dewatering of the rocks occurred and where uranyl complexes were stable in solution. This dewatering produced a hydrologic gradient. Fluids containing uranyl complexes moved upward towards lower pressure regions.

The partial pressure of CO_2 and O_2 reached the boiling point due to a decrease of total fluid pressure. As these gases were boiled off, uranyl complexes became unstable and uraninite was subsequently precipitated. These fluids were also rich in other metals that were incorporated in minerals coevil to the uraninite.

Erosion of the rocks produced the supergene zones described by previous authors. This supergene environment altered the rocks and percolated minor uranium downward along zones of secondary permeability to depths of twenty meters.

I. RECOMMENDATIONS FOR FURTHER RESEARCH

Three specific studies are recommended in the Harper Creek area. They are:

1. Confirmation of the origin of the Wilson Creek Gneiss;

2. Dating of the prograde and cataclastic assemblages;
3. Description of the nature of the supergene alteration found at the surface.

The first study could be approached in two ways. Isotopic studies of the premetamorphic minerals might yield an answer to the question of whether the Wilson Creek Gneiss is an ortho or paragneiss. Furthermore, rare earth element studies of fresh rocks might support the isotopic research. This study is not only essential in confirming or refuting the model proposed for the uranium petrogenesis of the area, but also to better understand the regional evolution of the rocks in the Grandfather Mountain window.

The second study could possibly be accomplished by fission track or isotopic methods. By dating the cataclastic assemblage and the prograde assemblage, one essentially dates the timing of precipitation of uraninite. Furthermore, such data would provide an approximate date for the metamorphic event that produced the mineralization at Harper Creek and elsewhere in the window.

The last study would enhance the exploration ability of similar prospects elsewhere in the Grandfather Mountain window. By adequately understanding the nature of the supergene enrichment processes one could possibly find index minerals directly related to the alteration of uranium bearing assemblages.

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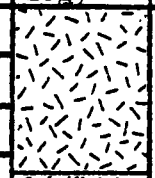
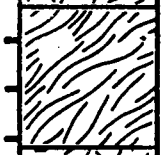
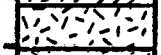
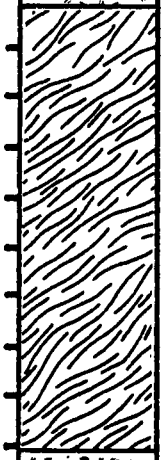
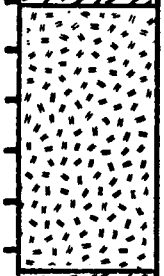
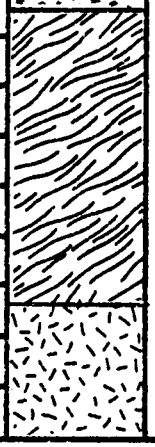
APPENDIX

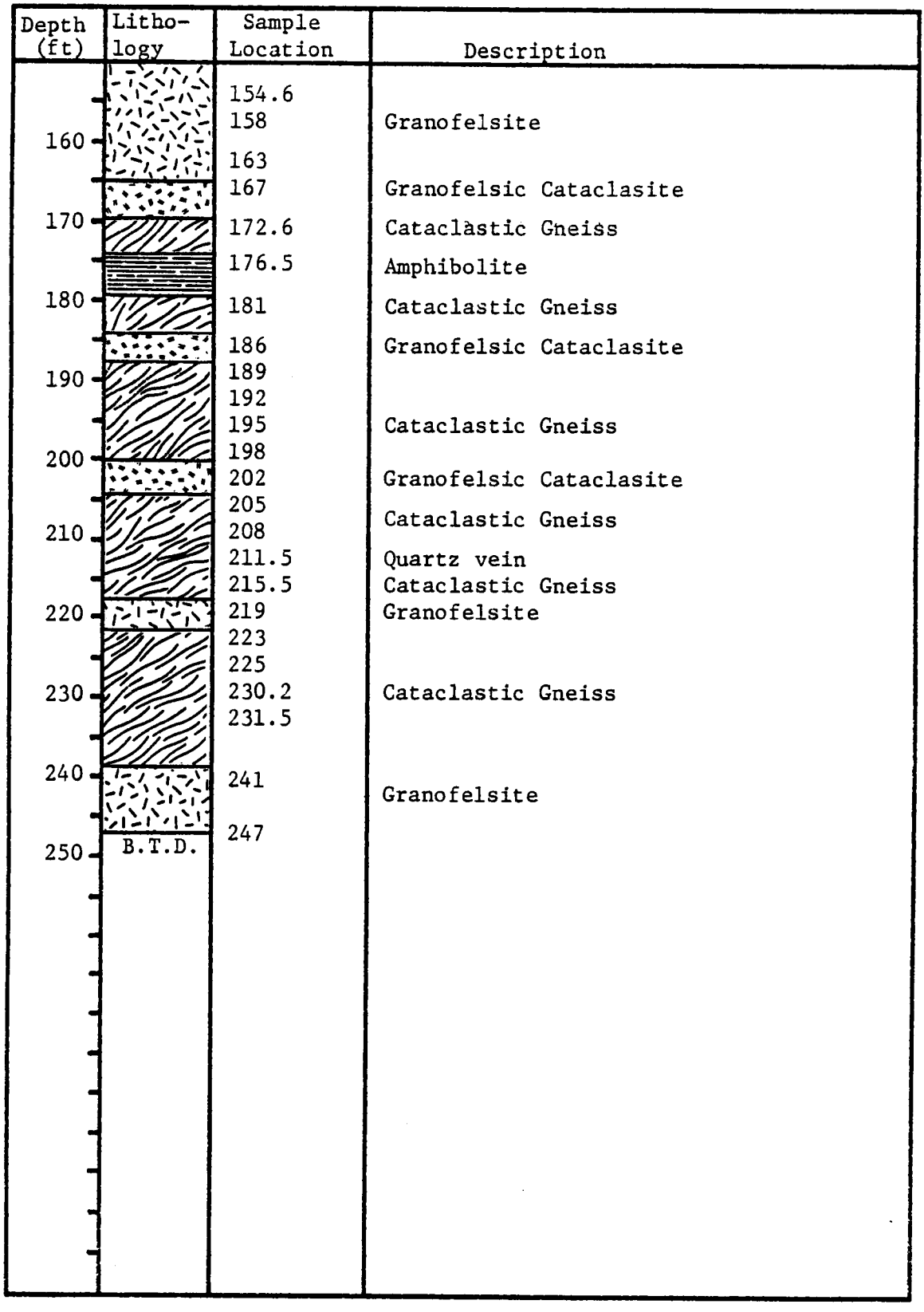
APPENDIX I

LOGS OF CORES STUDIED

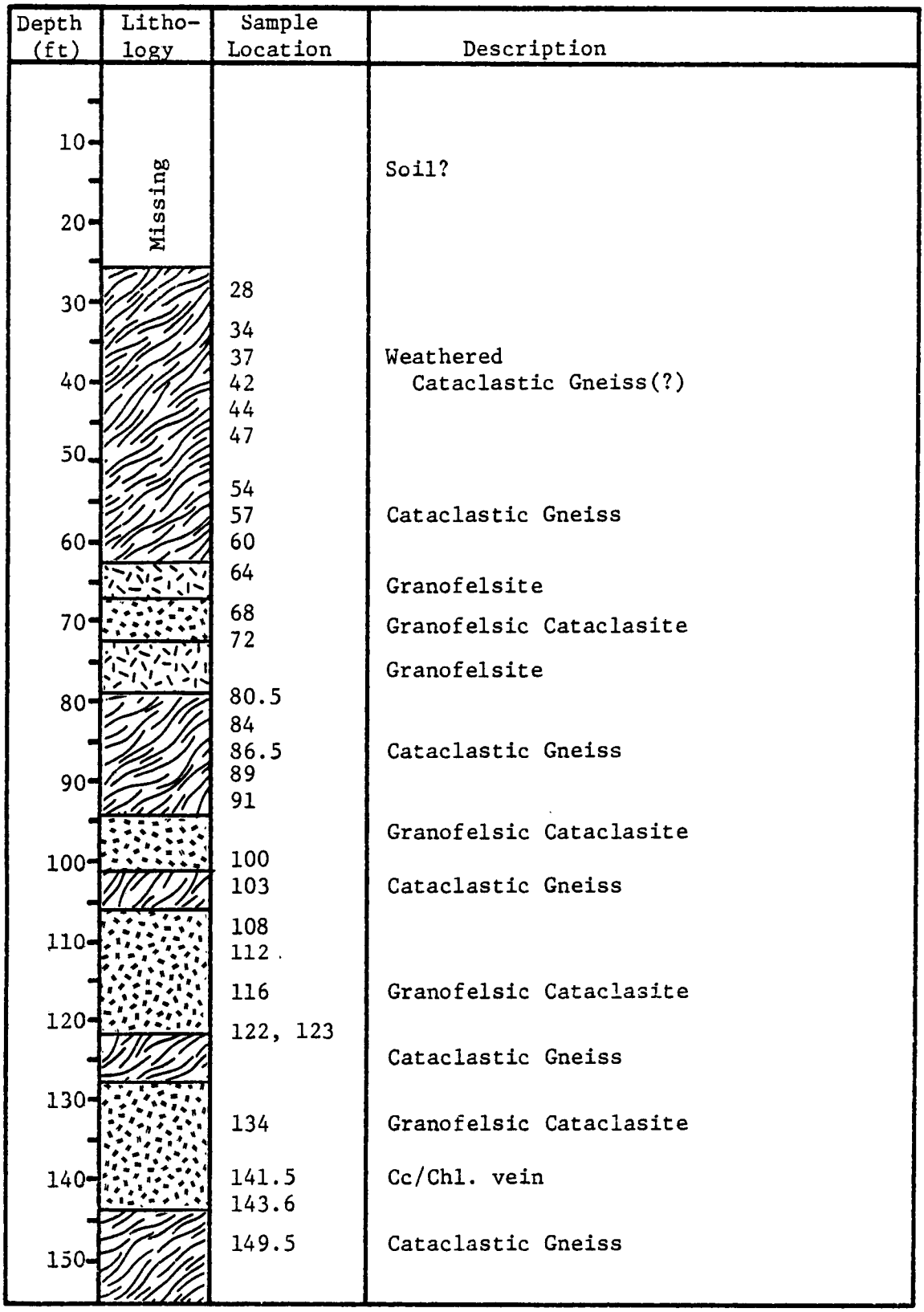
LOG OF CORE DDH2A

Depth (ft)	Litho-logy	Sample Location	Description
		5	
10		10	Granofelsite
			
20		24.5	Cataclastic Gneiss
		26	
30		30	
		32	Granofelsite
		35	
40		40	Granofelsic Cataclasite
		43	
50			
		54	
		59.7	U_3O_8
60		60.2	Cataclastic Gneiss
		67.5	
70			
		72.6	
80			
		81.5	
		86	
90			
		94	Granofelsic Cataclasite with A4 assem-
		97	blage veins
100		100, 101	
		105.5	
		108	
110		111.5	
		115.5	
		119, 120	Uraninite
120		123, 124.5	Cataclastic Gneiss
		125, 127	
130		132	
		134	
		137, 138	
140		140, 141.4	Uraninite veins
		146.5	
		148.6	Granofelsite
150		154	

LOG OF CORE DDH2A (Cont'd)



LOG OF CORE DDH3



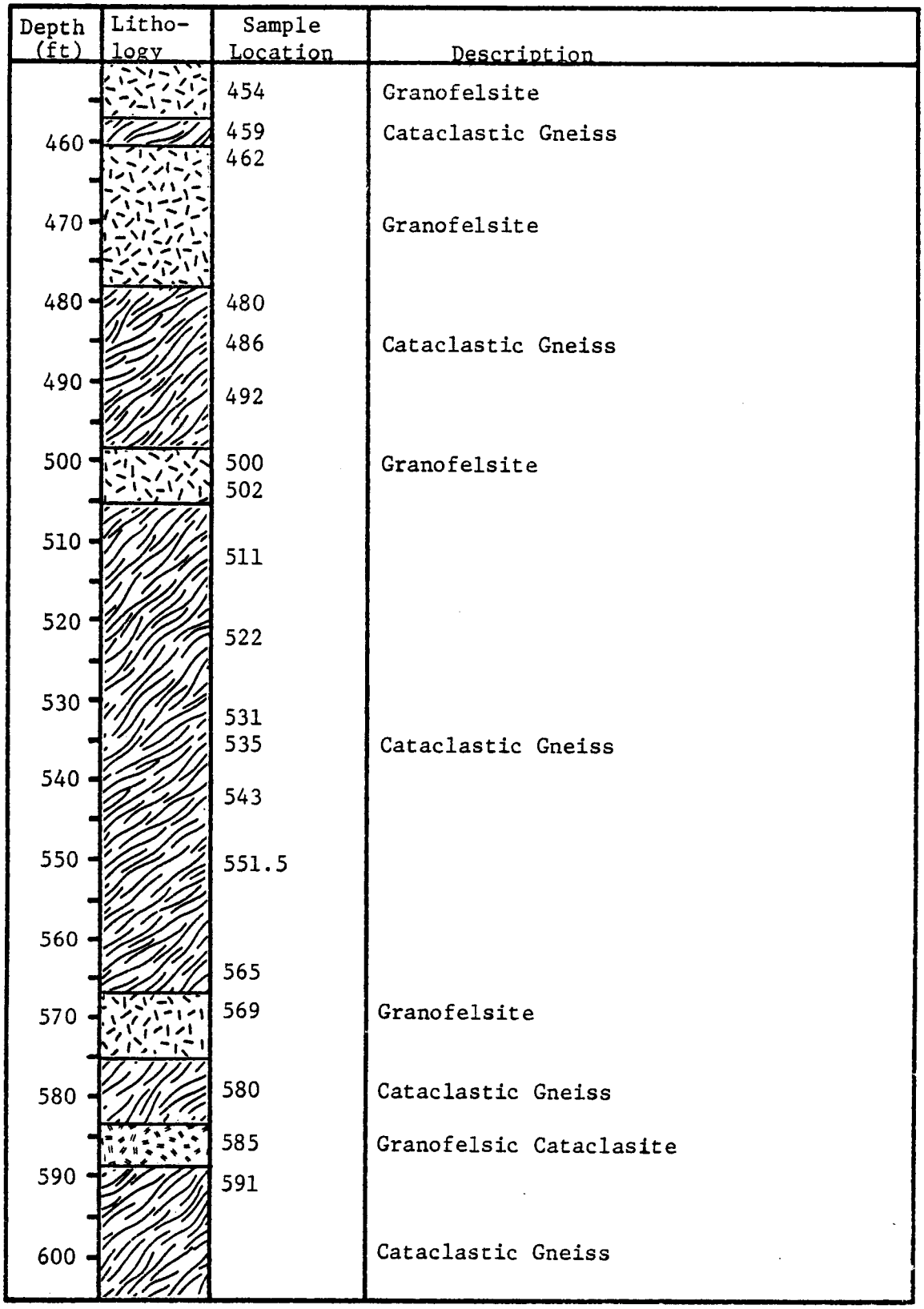
LOG OF CORE DDH3 (Cont'd)

Depth (ft)	Litho-logy	Sample Location	Description
			Cataclastic Gneiss
		155	Granofelsic Cataclasite w/pyrite
		157	Quartz vein
160		162.5	
		166.5	
170		170	Cataclastic Gneiss
		175	
180			
		184	
		188	
190		190.5	Granofelsic Cataclasite zone
		195	
200		200	Cataclastic Gneiss
		205	
		208	Granofelsic Cataclasite
210		214.5	
220			Cataclastic Gneiss
		224	
230		231	Granofelsic Cataclasite
240		240	
		244.6	Qtz/Chl vein
250		250	Cataclastic Gneiss
		255	
260		263.5	
			Granofelsic Cataclasite
270		270	
		275	Cataclastic Gneiss
280		281	Quartz vein
		288, 289	
290			
		297.5	Cataclastic Gneiss
300			

LOG OF CORE DDH3 (Cont'd)

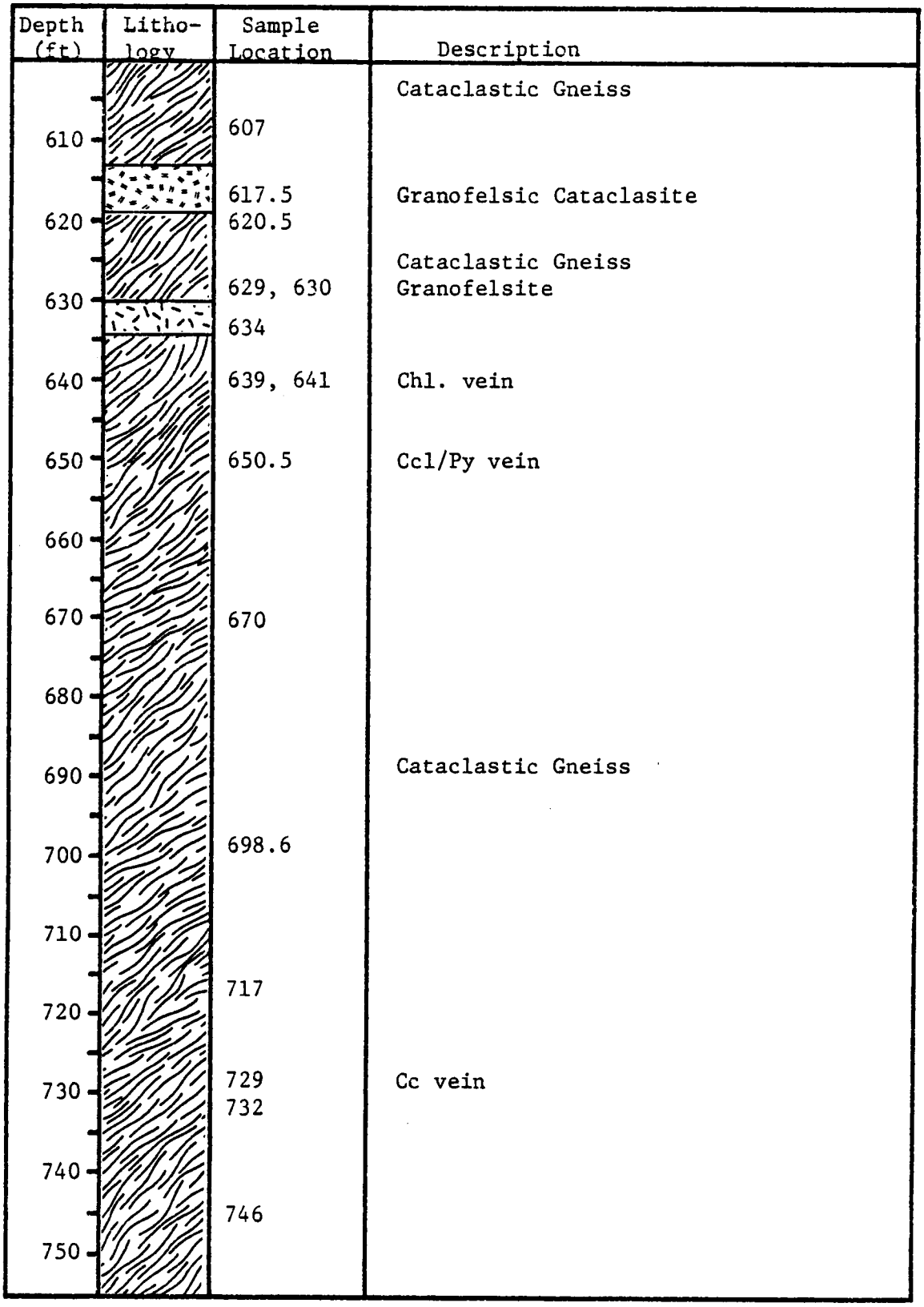
Depth (ft)	Litho-logy	Sample Location	Description
		305	
		309	
310			
320			
		324	
		328	
330			
		335	Qtz/Chl. vein
340		341	Cataclastic Gneiss
350			
		353	Qtz/Chl. vein
360			
		364.5	
370			
		376	
380			
390		392.6	Granofelsic Cataclasite
400		404	Cataclastic Gneiss
		408	
410		413	Cc/Chl. vein
420			Granofelsic Cataclasite
430		429	
440		441	Cataclastic Gneiss
450		454	Granofelsite

LOG OF CORE DDH3 (Cont'd)

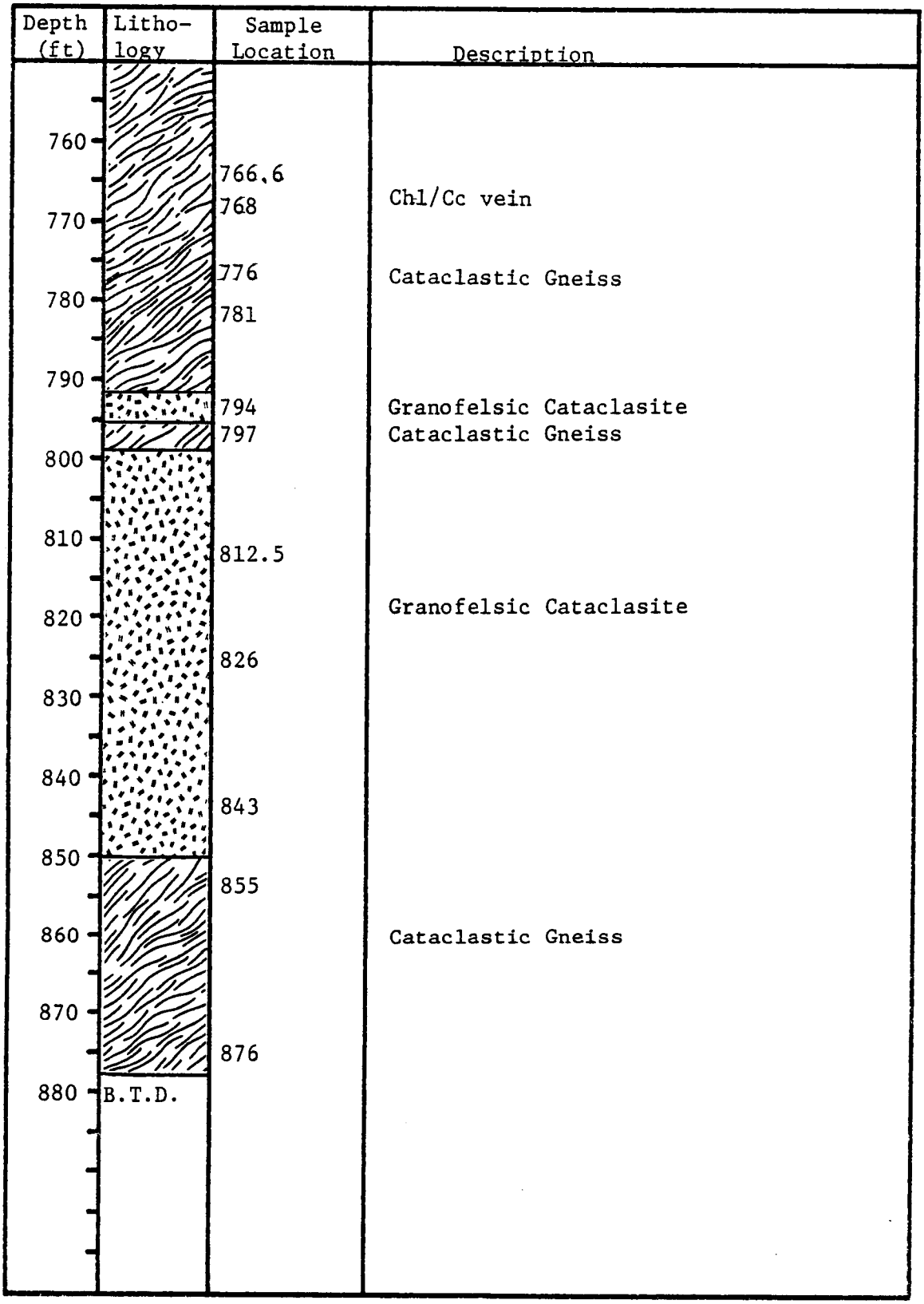


Depth (ft)	Litho-logy	Sample Location	Description
		454	Granofelsite
		459	Cataclastic Gneiss
460		462	
470			Granofelsite
480		480	
		486	Cataclastic Gneiss
490		492	
500		500	Granofelsite
		502	
510		511	
520		522	
530		531	
		535	Cataclastic Gneiss
540		543	
550		551.5	
560		565	
570		569	Granofelsite
580		580	Cataclastic Gneiss
		585	Granofelsic Cataclasite
590		591	
600			Cataclastic Gneiss

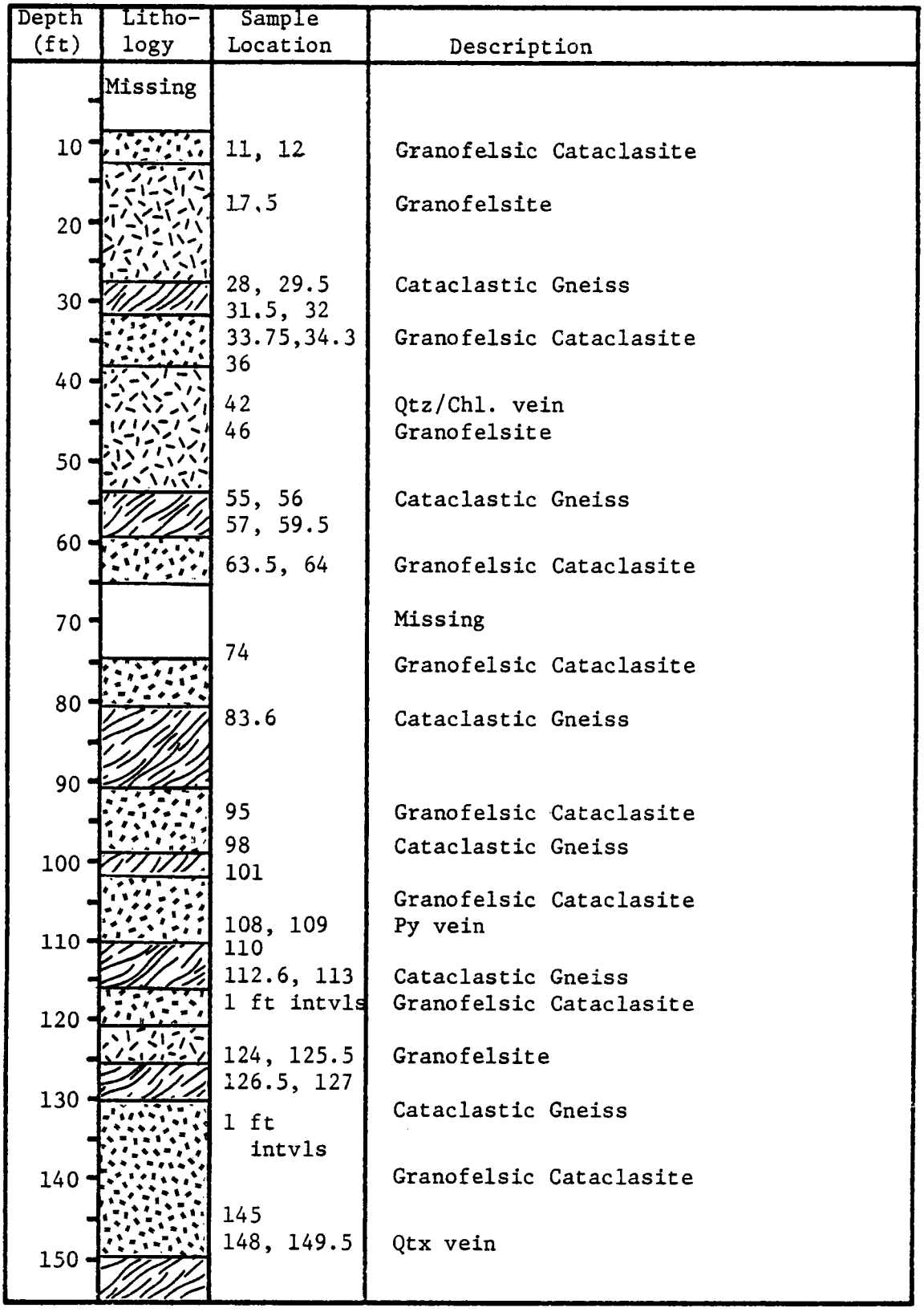
LOG OF CORE DDH3 (Cont'd)



LOG OF CORE DDH3 (Cont'd)

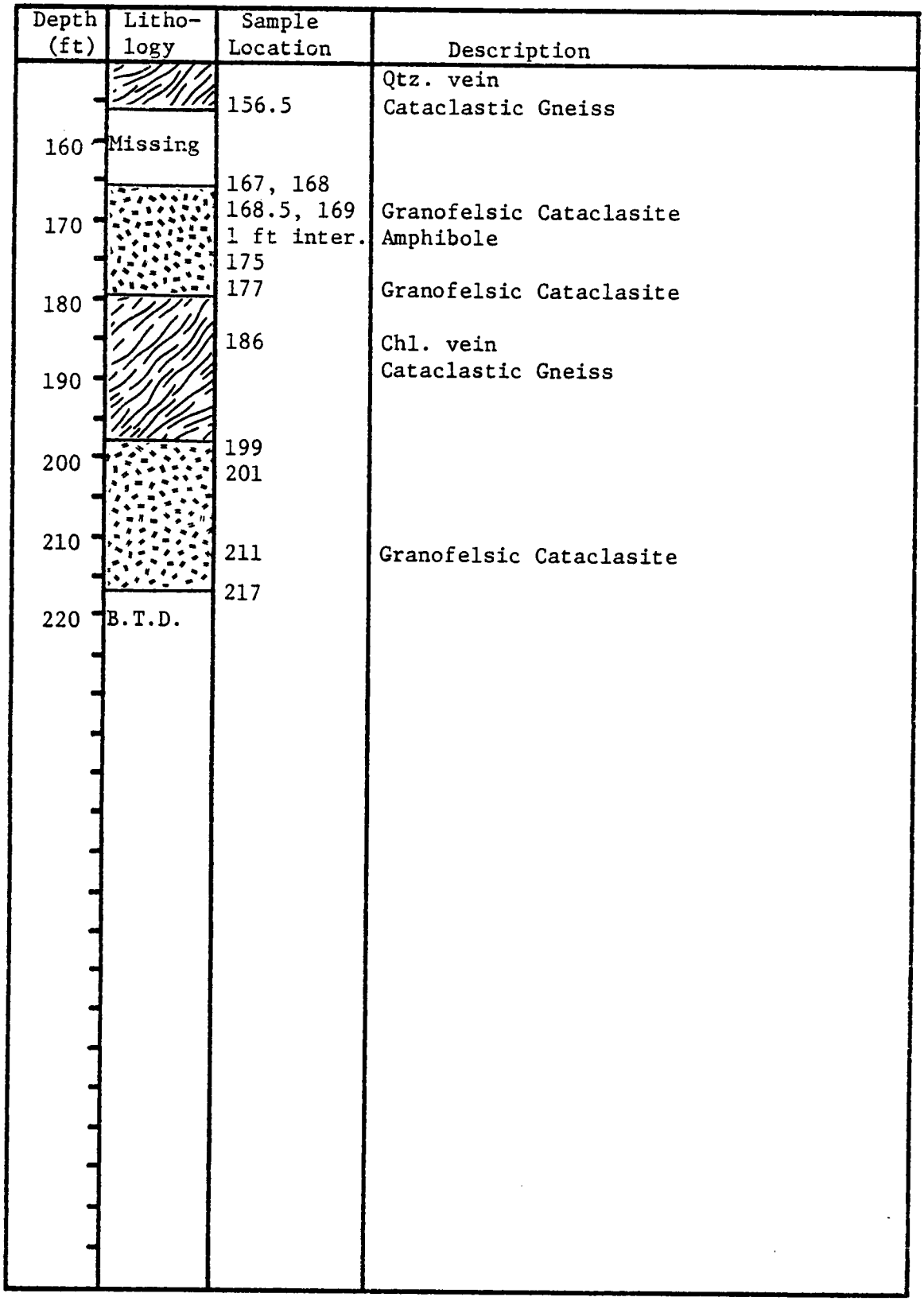


LOG OF CORE DDH3B



Depth (ft)	Lithology	Sample Location	Description
	Missing		
10		11, 12	Granofelsic Cataclasite
		17.5	Granofelsite
20			
		28, 29.5	Cataclastic Gneiss
30		31.5, 32	
		33.75,34.3	Granofelsic Cataclasite
		36	
40		42	Qtz/Chl. vein
		46	Granofelsite
50			
		55, 56	Cataclastic Gneiss
		57, 59.5	
60		63.5, 64	Granofelsic Cataclasite
			Missing
70		74	
			Granofelsic Cataclasite
80		83.6	Cataclastic Gneiss
90			
		95	Granofelsic Cataclasite
		98	Cataclastic Gneiss
100		101	
			Granofelsic Cataclasite
		108, 109	Py vein
110		110	
		112.6, 113	Cataclastic Gneiss
		1 ft intvls	Granofelsic Cataclasite
120			
		124, 125.5	Granofelsite
		126.5, 127	
130			Cataclastic Gneiss
		1 ft intvls	
140			Granofelsic Cataclasite
		145	
		148, 149.5	Qtx vein
150			

LOG OF CORE DDH3B (Cont'd)



VITA

Allen Kem Fronabarger was born on February 2, 1948, in Las Vegas, New Mexico. He traveled extensively during his younger years, attending grade school and secondary school in Europe and the United States and was graduated from Oak Park High School, Kansas City, Missouri in June 1967.

Mr. Fronabarger received his Bachelor of Science degree in Geology from the Missouri School of Mines at Rolla, Missouri where he studied from 1967 to 1972.

Mr. Fronabarger was employed by the Peace Corps as an exploration geochemist from 1972 to 1974 in Upper Volta, West Africa, where he was responsible for gold, diamond and mercury exploration. After returning to Europe, he married Chantal (Rousselin) Fronabarger and moved to Washington, D.C. where he worked as staff geologist for the Federal Power Commission, auditing natural gas reserves on federally leased properties. In 1976, Mr. Fronabarger moved to Oak Ridge, Tennessee where he was employed as Exploration Geologist for Union Carbide Corporation, conducting orientation surveys for the National Uranium Resource Evaluation project.

He entered graduate school at The University of Tennessee, Knoxville in September 1977. While at The University of Tennessee, Knoxville, Kem represented the geology student body to the faculty from March 1978 to March 1979. He supported his studies as consultant with Science Applications, Inc., and as a Graduate Assistant at the Geology Department.

Following the conclusion of his studies toward the Master of Science degree, Mr. Fronabarger will begin research towards his Doctor of Philosophy degree in Geology at The University of Tennessee