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URANIUM DEPOSITS
IN
GRANITIC ROCKS

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A Report to the

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on

Uranium Deposits in Granitic Rocks

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INTRODUCTION AND SCOPE

This report is a review of published data bearing on the geology and origin of uranium deposits in granitic, pegmatitic and migmatitic rocks. The aim of this study is to assist geologists in developing predictive criteria which will aid them in their search for similar deposits in the United States. We concentrate our efforts on the so-called "porphyry" uranium deposits (Armstrong, 1974). This class of deposit is typified by the Rössing, Namibia, deposit which, though low grade, is the largest deposit of its kind known in igneous host rocks. Nonetheless, as the nation anticipates future deficits in the supply of uranium to serve as fuel for nuclear power plants, it is now prudent to search for uranium from new, perhaps lower grade, sources. As a result, uranium deposits in igneous rocks that have been studied in the past and considered of little consequence at that time must be examined more closely today.

Two types of uranium deposits are primarily considered in this report: deposits in pegmatites and alaskites in gneiss terrains; and disseminations of uranium in high-level granites. The former type of deposit is exemplified by the Bancroft, Canada, and Rössing, Namibia, deposits; and the latter by the Ross-Adams deposit at Bokan Mountain, Alaska.

We specifically have not included a detailed review of the uranium association in layered or zoned nepheline syenite bodies (such as those at Ilimaussaq, Greenland, and Pocos de Caldas, Brazil) or uranium deposits in carbonatites. Both types have already been the subject of intensive study by both igneous and ore petrologists because of their other ore metal associations and the unusual rock types associated with these complexes.

Although hydrothermal vein deposits are classified separately from uranium deposits in igneous rocks, there can be considerable overlap or gradation between vein-type deposits and deposits in granites, pegmatites and migmatites. Where this overlap occurs, we consider the vein deposits an ancillary feature of the igneous deposits. Vein-type uranium deposits are the subject of an exhaustive review by Rich et al. (1975), so our treatment of this type of deposit is minimal.

In Chapter 1 of this report, the general data on the distribution of uranium in igneous and metamorphic rocks are reviewed. Chapter 2 contains some comments on the classification of uranium deposits associated with igneous rocks and a summary of the main features of the geology of uranium deposits in granites. General concepts of the behavior of uranium in granites during crustal evolution are reviewed in Chapter 3. Also included is a discussion of the relationship of uranium mineralization in granites to the general evolution of mobile belts, plus the influence of magmatic and post-magmatic processes on the distribution of uranium in igneous rocks and related ore deposits. Chapter 4 relates the results of experimental studies on the crystallization of granites to some of the geologic features of uranium deposits in pegmatites and alaskites in high-grade metamorphic terrains. Potential or favorable areas for igneous uranium deposits in the U.S.A. are delineated in Chapter 5.

Data on the geology of specific uranium deposits in granitic rocks are contained in Appendix 1. A compilation of igneous rock formations containing greater than 10 ppm uranium is included in Appendix 2. Appendix 3 is a report by one of the authors (JJWR) on the results of a visit to the Rössing area in March, 1976. Appendix 4 is a report by two authors (RKN and JKG) on a field excursion to eastern Canada.

SUMMARY OF GENERAL FAVORABILITY CRITERIA

There apparently are certain geological features which characterize low-grade uranium deposits in granitic rocks. These features are discussed and developed extensively in the text, while the important characteristics of individual deposits are included in Appendix 1. They are summarized below:

1. Areas or provinces where the earth's crust has undergone extensive reworking appear to be a highly favorable environment for both vein and igneous uranium deposits. Remobilization and concentration of uranium can be triggered by the processes of granitization and anatexis.

2. Uranium deposits in pegmatites and aplites occur in uranium metallogenic provinces, i.e., areas where numerous other varieties of uranium deposits have been found. Good areas for future prospecting are those in which pre-existing deposits have been recognized or where there is known bedrock enrichment in uranium (for example, the Colorado Front Range).

3. Quartz monzonite, granite, alaskitic granite and syenite are favorable host rocks for deposits of the "porphyry" or pegmatite-alaskite-gneiss uranium association. The ore-bearing pegmatites are characteristically in or at the margins of these host granitic rock types and may inject the surrounding country rock in a migmatitic fashion.

4. Economic concentrations of uranium in pegmatites and alaskites are almost exclusively developed in and around granites which lie in upper-amphibolite- and amphibolite-grade metamorphic terranes. Thus, deeply eroded mobile belts are more favorable for this type of uranium mineralization than uneroded or slightly eroded terranes.

5. Ore localization generally clusters around structural traps, where the late-stage, uranium-rich differentiates may have migrated during the advanced stages of cooling of the magma. The crests of major anticlines or other folds are particularly favorable zones.

6. Metasomatized pegmatites are favored over unaltered varieties. Evidence at Bancroft and Rössing suggests that uranium mineralization was closely contemporaneous with metasomatism or metasomatic growth in the pegmatites.

7. If local faults or shear zones exist in the vicinity of uranium-mineralized pegmatites and aplites, these areas may be favorable areas to search for lenses or pods of uranium minerals which represent the residue of ore solutions that have migrated to zones of dilatancy.

8. The uranium deposits in pegmatites at Bancroft and Rössing are accompanied by nearby calcite-fluorite-apatite and quartz-fluorite veins. Vein uranium deposits of this type in the vicinity of granite bodies may indicate favorability for uranium mineralization in the granites and pegmatites.

9. In general, hydrothermally altered zones around uranium-rich granites are the most favorable areas to seek uranium mineralization.

10. In addition to the radioactive elements, uranium deposits in igneous rocks are associated with variable but small amounts of molybdenum and fluorine. Fluorine is believed to form mobile complexes of uranium under magmatic and hydrothermal conditions. Thus, fluorine-rich granites, pegmatites and veins may constitute higher-probability host rocks than fluorine-poor varieties. Much additional geochemical work is needed before any positive statements can be made on the characteristic elemental associations of uranium deposits in granites.

11. Archaean terranes are unfavorable areas to search for uranium deposits in igneous rocks. Aside from conglomerate deposits which may range in age up to 2.7 billion years, there are no known uranium deposits of Archaean age.

12. Abundant secondary enrichment of pegmatites and alaskites in uranium minerals, as in Rössing, may be due to the effects of unusual climatic conditions (such as found in the Namib desert).

CHAPTER 1

THE DISTRIBUTION OF URANIUM IN IGNEOUS ROCKS

AVERAGE CONCENTRATION DATA

Owing to the tremendous number of papers which report data on the concentration of uranium in the crustal rocks of the earth, no effort is made here to review all data on the crustal abundance of uranium. Several review papers report average concentration data for the more common igneous rock types (Kohman and Saito, 1954; Tilton and Reed, 1962; Adams et al., 1962; Vingradov, 1962; Wasserberg et al., 1964; MacDonald, 1964; Taylor, 1964; Clark et al., 1966; and Rogers and Adams, 1969a). Selected data are included in Table 1-1. The average crustal abundance of uranium is approximately 1.7 ppm. Mafic and ultramafic rock types have consistently low concentrations of uranium rarely exceeding 1 ppm. Of all the common igneous rock types, granites have the highest average concentration, approximately 3.5-4.5 ppm U. In general, most igneous rocks contain from 0.003 to 5 ppm U. Alkaline rocks tend to have higher concentrations of uranium than other rock associations listed on Table 1-1. This table also illustrates the general increase of uranium with degree of differentiation.

ENRICHMENT OF URANIUM IN COMMON AND UNCOMMON IGNEOUS ROCK TYPES

High concentrations of uranium (greater than 10 ppm) in igneous rocks are found in a variety of rock types. A compilation of igneous rock formations containing greater than 10 ppm U is included in Appendix 2,

TABLE 1-1, AVERAGE ABUNDANCES OF URANIUM, THORIUM AND POTASSIUM IN VARIOUS ROCKS

Author(s) and Types	U(ppm)	TH(ppm)	K(%)
Kohman and Saito (1954)			
Granite	4	15	3.5
Intermediate	2	7	2
Basalt	0.6	2	0.9
Ultramafic	0.05	0.2	0.001
Adams *et al*. (1959)			
Silicic intrusive	1-6	1-25	
Silicic extrusive	2-7	9-25	
Basic intrusive	0.3-2	0.5-5	
Basic extrusive	0.4-4	0.5-10	
Ultrabasic	0.001-0.03	low	
Alkaline	0.1-30	----	
Silicic pegmatite	1-4	1-2	
Vinogradov (1962)			
Granite	3.5	18	3.34
Intermediate	1.8	7.0	2.3
Basalt	0.5	3.0	0.83
Ultramafic	0.003	0.005	0.03
Tilton and Reed (1963)			
Granite	4.0	14.8	3.5
Intermediate	2.0	7.4	1.8'
Basalt	0.8	3.0	0.75
Eclogite	0.043	0.16	0.053
Peridotite	0.006	0.022	0.001
MacDonald (1964)			
Granite	4.75	18.5	3.79
Intermediate	2.0	----	1.8
Basalt	0.6	2.7	0.84
Eclogite (Low U)	0.048	0.18	0.036
Eclogite (High U)	0.25	0.45	0.26
Peridotite	0.006	----	0.0012
Dunite	0.001	----	0.0010
Wasserburg *et al*. (1964)			
Granite	4.75	18.5	3.79
Basalt	0.6	2.7	0.84
Taylor (1964)			
Crustal	1.7	9.6	2.09
Granite	4.8	17	3.34
Basalt	0.6	2.2	0.83
Shimazu (1966)			
Granite	4.75	18.5	3.79
Basalt	0.6	2.7	0.84
Peridotite	0.016	0.06	0.0012
Dunite	0.0041	0.012	0.0010

and data referred to in this chapter are appropriately referenced in this appendix. Five main families of igneous rocks account for most of the entries in Appendix 2:

1. Granites and alkali granites
2. Rhyolites
3. Peralkaline nepheline syenites
4. Alkaline volcanic rocks
5. Carbonatites

In general, the bulk uranium content of large igneous bodies rarely exceeds 20 ppm; however, the most differentiated components of the above rock families may show extreme enrichment of uranium with respect to the mean value for the entire body. Like all incompatible elements (elements not readily accommodated by any crystalline phase in magma systems), uranium tends to enter into the silicate melt and the late-stage magmatic fluid or gas phases rather than into the liquidus minerals. Thus, in granites, the highest uranium contents are often found in the pegmatitic or aplitic portions of plutons. In volcanic rock complexes, the highest uranium concentrations are generally recorded in the most highly differentiated member of the cogenetic magma series. Recent attention has focussed on the relationship between uranium and the volatile elements in magmas, particularly F and Cl (Shatkov, 1970; Rosholt *et al.*, 1971; Bhose *et al.*, 1974). Apparently, magmas that have retained their volatiles tend to retain uranium; thus, high uranium concentrations in late differentiates commonly correlate with a high bulk-rock content of volatiles.

Granites and Alkali Granites

In a series of granitic rocks, the highest uranium concentrations typically occur in the youngest, most highly differentiated rock unit.

While there are numerous examples (Appendix 2) of granites that contain a bulk concentration of over 10 ppm, examples of entire granite plutons with greater than 20 ppm U are rare. Pegmatites and aplites associated with granites can contain several thousand or greater ppm U. Perhaps the most outstanding examples of uranium-rich granites, in terms of volume of rock, are the Hercynian massifs of France (Table 1-2). Average uranium concentrations for granites are listed for comparison in Table 1-2.

The highest concentrations of uranium in granites occur in the Rössing, Namibia, area where uranium ore deposits in alaskites are associated with an alaskitic granite that contains from 30 to 1,000 ppm U (Appendix 3). Portions of the granites in the Johan Beetz area of Quebec contain an average of 70 ppm U (Little, 1970). Albite-riebeckite granites at Kaffo Valley, Nigeria, average approximately 100 ppm U. The peralkaline granites at Bokan Mtn., Alaska, range from 20 to 200 ppm U (MacKevett, 1963).

In the conterminous U.S., the Conway granite New Hampshire (Hurley, 1956; Rogers, 1965), Granite Mts., Wyoming (Malan, 1972), the quartz monzonites at Mt. Spokane, Washington (Nash and Lehrman, 1975), and the Silver Plume granites in the Colorado Front Range (Phair and Gottfried, 1964) are examples of unusual enrichment of uranium in large plutonic bodies. Granitic and alkalic rocks in the eastern Seward Peninsula, Alaska, (Miller and Bunker, 1976) comprise a plutonic belt over 300 km long displaying uranium enrichment.

Rhyolites

Concentrations of uranium of 10-20 ppm are also common in rhyolites (Appendix 2). Most of the uranium in this rock type, and

TABLE 1-2

URANIUM IN HERCYNIAN GRANITES FROM FRANCE

	Average U (ppm)	Range of U (ppm)	Reference
Hercynian granites	7.9	7-10	Burnol (1973)
Average granites	4	2-15	Rogers et al. (1969)

generally in most volcanic rock types, is contained in the glass rather than the phenocrysts (Rosholt et al., 1971), and there is a close coherence between the amount of F and Cl in the glass and the whole-rock uranium content. Although vein uranium mineralization is found closely associated with rhyolites, the concentrations of uranium found in this rock type are generally too low to consider them as a possible source of economically extractable disseminated uranium.

Peralkaline Nepheline Syenites

Among alkaline rocks* are three outstanding examples of uranium enrichment in igneous rocks: nepheline syenites of the Lovozero intrusion, Kola Peninsula, U.S.S.R.; the Ilimaussaq intrusion, west Greenland; and the Pocos de Caldas complex, Brazil. The Ilimaussaq intrusion contains an average of 62 ppm U, and a lujavritic unit of this intrusion contains approximately 360-400 ppm U (Sørenson, 1970; Bhose et al., 1974). Uraniferous zirconium deposits in parts of the Pocos de Caldas complex contain 1800-2000 ppm U (Ramos and Fraenkel, 1974). No uranium ore deposits have been reported in the Lovozero intrusion, but the entire complex averages 16 ppm U (Gerasimovsky et al., 1968).

A unifying feature of these three complexes is their chemical composition; all have a molecular ratio of $\frac{Na_2O + K_2O}{Al_2O_3}$ of greater than 1.3. Rocks with this characteristic are termed agpaitic by petrologists working in the field of alkaline rock systematics. Semenov (1974)

*Alkaline rocks are defined in this report as igneous rocks that contain feldspathoids; this is one of several recommended definitions of alkaline rocks in the AGI Glossary of Geology. Note that this definition excludes silica-oversaturated, alkali-rich rocks, i.e., alkali-rich granites.

generalizes that "agpaitic nepheline syenites (and corresponding lavas) are richer in disseminated uranium than other igneous rocks." However, non-agpaitic rocks may contain in excess of 10 ppm U (Appendix 2).

Alkaline volcanic rocks

Alkaline volcanic rocks are generally enriched in the incompatible elements, including uranium, compared to their less alkaline (tholeiitic or calc-alkaline) counterparts. The highest uranium concentrations in alkaline volcanic rocks occur in the ultra-potassic varieties (K_2O/Na_2O greater than 3). Perhaps the best examples of uranium enrichment in ultra-potassic lavas are the volcanic rocks of the East African Rift (Polyakov and Sobornov, 1971) and the volcanic fields of central and southern Italy (Locardi, 1967; Cheminee, 1973). In these areas, nephelinites and related alkaline and peralkaline rocks frequently show high concentrations of uranium but rarely exceed 50 ppm (Appendix 2). In central Italy, supergene uranium deposits derive their uranium from the exhalatives of ultra-potassic magmas (Mittempergher, 1970).

The term "bostonite" commonly refers to alkali-rich, fine-grained rocks that do not contain feldspathoids. Bostonite dikes in the Colorado Front Range (Phair and Jenkins, 1975) and in eastern Egypt (this report, Appendix 1) contain 100 ppm or more U. Other examples of uranium-rich bostonites occur in the eastern U.S. (Appendix 2).

Carbonatites

It is dubious to classify carbonatites completely separately from alkaline igneous rocks since carbonatite complexes typically contain an abundance of alkaline rock types. Nonetheless, the unusual composition of carbonatites has led petrologists to classify these rocks as a separate association. Carbonatites are characterized by an abundance of incompatible elements and, in some cases, by high uranium contents. Carbonatites in South Africa and Namibia, most notably the Phalaborwa complex (Verwoerd, 1967; Von Backstrom, 1974), and the Oka and Lake Nippising complexes (both contain uraniferous pyrochlore) in Canada (Rowe, 1958) are examples of uranium enrichment in this rock association (Appendix 2). Owing to the high concentrations of rare elements in carbonatites, it is feasible that some byproduct uranium could be recovered during the mining of other metals. Two other reported uranium deposits in the Minas Gerais district, Brazil, are found in alkaline-carbonatite intrusives, the Tapira intrusion (Sobrinha, 1974) and the Araxa intrusion (Maciel and Cruz, 1973). The Araxa deposit is primarily a source for Nb, principally found in the pyrochlore. Significant amounts of uranium occur in pyrochlore; phosphates, silicophosphates, monazite, and autunite are other minerals that contain trace to minor amounts of uranium.

Metamorphic rocks

Table 1-3, taken from Rogers and Adams (1969), summarizes data on the uranium content of various metamorphic rock types. Because metamorphic rocks form under a variety of physical and chemical conditions and from a wide spectrum of parental materials, uranium varies greatly in concentration. Granulite-facies rocks, however, tend to be uniformly low in uranium, implying a loss of this element during progressive metamorphism by the processes of dehydration or anatexis (for example, Heier and Adams, 1965; Lambert and Heier, 1967, 1968; Heier, 1973; Fahrig, 1967; Fahrig and Eade, 1968; Eade and Fahrig, 1971).

TABLE 1-3, CONTENTS OF URANIUM IN METAMORPHIC ROCKS

After Rogers and Adams (1969); from Handbook of Geochemistry, published by Springer Verlag.

Rock type	No. of Samples	U(ppm)	References
Gneiss, Japan	1	2.3	Evans and Goodman (1941)
Augen gneiss, Finland	1	2.1	Evans and Goodman (1941)
Eclogite, Switzerland	1	0.2	Evans and Goodman (1941)
Amphibolite(Schwarzwald, Germany)	3	3.5	Husmann(1956)
Biotite-hornbl. paragneiss (Schwarzwald, Germany)	2	2.0	Husmann(1956)
Paragneiss (Schwarzwald, Germany)	4	7.0	Husmann(1956)
Granulite(Schwarzwald, Germany)	2	4.9	Husmann(1956)
Orthogneiss(Schwarzwald, Germany)	4	3.6	Husmann(1956)
Metatectite(Schwarzwald, Germany)	4	4.8	Husmann(1956)
Diatectite(Schwarzwald, Germany)	4	11.2	Husmann(1956)
Cordierite gneiss (Schwarzwald, Germany)	1	5.8	Husmann(1956)
Orthoclase metacrysts (Schwarzwald, Germany)	1	45	Husmann(1956)
Marble	2	0.17	Pliler(1956)
Slate(mainly Michigan)	14	2.7	Pliler(1956)
Phyllite(mainly Arizona New Mexico)	7	1.9	Pliler(1956)
Schist(New Mexico)	4	2.5	Pliler(1956)
Mafic rocks (Terskei Ala Tau Mts.)	82 (comp)	3.2	Krylov(1958)
Idaho batholith gneisses	12	2.2	Larsen Jr. and Gottfried (1961)
(Almandine-amph. facies) Gneiss (Texas)	13	2.82	Billings(1962)
(Almandine-amph. facies) Amphibolite (Texas)	14	0.33	Billings(1962)
(Almandine-amph. facies) Graphite schist(Texas)	3	3.49	Billings(1962)
Marble (Grenville Province)	2	0.36	Doe(1962)
(Amphibolite facies) Light gneiss (Langoy, Norway)	<5	2.5	Heier(1962b)

TABLE 1-3, CONTENTS OF URANIUM IN METAMORPHIC ROCKS, (cont.)

Rock type	No. of Samples	U(ppm)	References
(Amphibolite facies) Amphibolite (Langøy)	7	<1.06	Heier(1962b)
(Retrograde gneiss) Monzonite(Langøy)	2	<1.25	Heier(1962b)
(Retrograde gneiss) Granite(Langøy)	8	<0.94	Heier(1962b)
Biotite schist (Front Range, Colorado)	9	4.7	Phair and Gottfried (1964)
Biotite hornblende schist and amphibolite(Front Range)	4	4.7	Phair and Gottfried (1964)
(High granulite facies) Monzonite(Langøy, Norway)	3	0.61	Heier and Adams (1965)
(High granulite facies) Banded gneiss(Langøy)	4	0.22	Heier and Adams (1965)
(Low granulite facies) Gneiss(Langøy)	5	0.88	Heier and Adams (1965)
(High amphibolite facies) Gneiss(Langøy)	3	1.22	Heier and Adams (1965)

CHAPTER 2

URANIUM DEPOSITS IN GRANITES

As of this writing, only two uranium deposits in granitic host rocks are currently being mined or brought into production: (1) the Madawaska mine (formerly the Faraday mine) in the Bancroft, Canada, district, which is being re-opened after a 12-year hiatus in operation; and (2) the Rössing deposit in Namibia, which went into production in late 1976. Numerous other uranium deposits occur in granites in other parts of Canada, the United States, Brazil, Spain, India, Africa, and Australia. Among deposits in non-granitic igneous rocks, only the deposits at Pocos de Caldas, Brazil, are a significant producer of uranium. These deposits are hosted by nepheline syenite.

CLASSIFICATION OF URANIUM DEPOSITS IN IGNEOUS ROCKS

Traditional classification schemes generally subdivide uranium deposits into sedimentary, vein, and igneous deposits. Further subdivision among these groups is based upon variations in the descriptive aspects of the deposits: host rock type, mineralogy, texture, general geology, and elemental associations. More recently, genetic classifications of uranium deposits have appeared in the literature (for example, Bigotte, 1964; Ruzicka, 1970; and Barnes and Ruzicka, 1972). They differ from the traditional, more descriptive classification schemes by emphasizing the geochemical and mechanical processes which introduce uranium into the geochemical cycle and concentrate it into ore deposits. Aspects of both types of classification schemes will be used here in a two-fold characterization of igneous-related uranium deposits. Uranium deposits in igneous rocks are subdivided by a very simple descriptive criterion, namely, host rock type. The various types of igneous uranium deposits in these host rocks are then classified with respect to the inferred stage of magmatic evolution during which the deposits formed.

Classification by Host Rock Type

Among the numerous varieties of intrusive igneous rock types, only four broad families of igneous rocks host uranium deposits:

1. Granites, alkali-rich granites, and affiliated syenites
2. Agpaitic nepheline syenites
3. Carbonatites
4. Rocks of the kimberlite-diatreme association

Here, the term "granite" is defined in the broadest sense, including all leucocratic plutonic rocks containing over 10% modal quartz.

Granites, alkali-rich granites and affiliated syenites are widespread igneous rock types. Rock suites 2 and 3 are volumetrically unimportant in the earth's crust but contain significant amounts of rare elements such as Nb, Ta, Zr, rare earth elements, etc. The volume of rock in the kimberlite-diatreme association is also miniscule.

Aside from the previously-mentioned bostonite dikes (Chapter 1), there are no reported volcanic or hypabyssal rocks that contain over 100 ppm uranium, so no classification of uranium deposits in volcanic rocks is given. The uraniferous bostonite dikes from Egypt and the Colorado Front Range, however, are reviewed in Appendix 1. Vein uranium deposits associated with volcanic rocks are described in Rich *et al*. (1975) and are not within the scope of this report.

Genetic Classification of Uranium Deposits in Intrusive Igneous Rocks

Among these four broad host rock types, magmatic processes have operated to concentrate uranium into deposits. Table 2-1 is a genetic classification of igneous-related uranium deposits that classifies uranium deposits by the stage of magmatic evolution at which uranium was fixed into its host rocks.

Syngenetic uranium deposits in igneous rocks (type 1) form during the orthomagmatic stage of crystallization of magmas, the stage during which approximately 90% of the magma crystallizes. Uranium-bearing minerals crystallized at or about the same time as the other mineral components of the host rock and are distributed in a disseminated fashion. Uranium commonly resides in uraninite, zircon, sphene, allanite, monazite, pyrochlore or other accessory minerals.

Table 2-1 subdivides uranium deposits formed from late magmatic differentiates and associated fluids and vapors into four genetic types. Deposits formed during the pegmatite stage of crystallization (2A) comprise deposits in pegmatites, alaskitic pegmatites or aplites that occur at the margins of igneous intrusions and apparently crystallize after the main body of magma from late-stage, volatile-rich differentiates.

Metasomatic deposits of uranium (type 2B), associated with intrusive igneous rocks, are most likely formed by the action of ore-carrying fluids or vapors emanating from magmas. Used here, the term "metasomatic uranium deposit" applies mainly to carbonate or pyroxenite country rocks that have undergone metasomatic replacement during ore deposition. The deposit at Mary Kathleen, Australia, is the most important example of this type of deposit and is currently being brought back into production. Other examples

TABLE 2-1

GENETIC CLASSIFICATION OF URANIUM DEPOSITS
IN INTRUSIVE IGNEOUS ROCKS

1. Syngenetic disseminations of uranium in igneous rocks formed during the orthomagmatic stage of crystallization

   CHARACTERISTICS: Primary uranium-bearing minerals such as uraninite, sphene, zircon, monazite, allanite, and pyrochlore disseminated through unaltered, non-pegmatitic igneous rocks.

   EXAMPLES: Uranium-rich granites, alkaline rocks and carbonatites discussed in Chapter 1. Uranium-rich rocks in diatremes (Shoemaker, 1955; Appendix 2)

2. Late-stage, high-temperature deposits formed from late magmatic differentiates and associated fluids and vapors

   2A. Deposits formed during the pegmatite stage of crystallization

   CHARACTERISTICS: Pegmatites, aplites, alaskitic pegmatites at or in the margins of plutons. Range in texture from pegmatitic to aplitic; may show evidence of replacement (metasomatism) due to attack by late-stage magmatic fluids and vapors. Primary uranium minerals such as uraninite, davidite, uranothorianite, or brannerite (granitic pegmatites) disseminated through host rock. Uraniferous Zr, Ta, Nb, etc., minerals in alkaline pegmatites.

   EXAMPLES: Granitic host rocks: Many pegmatites contain minor amounts of uranium; however, important economic deposits include Rössing, Bancroft, and Crocker Well (Appendix 1). Pegmatites at Bokan Mtn., Alaska (Appendix 1). Other examples in Appendix 1. Alkaline: Nepheline syenite pegmatites at Ilimaussaq, Greenland (Sørenson, 1970); non-pegmatitic but "gas-rich" lujavrites at Ilimaussaq (Bhose *et al.*, 1974)

   2B. Contact metasomatic deposits in country rocks adjacent to igneous intrusions

   CHARACTERISTICS: Mineral replacement apparently caused by the reaction of magmatic fluids with country rock. Deposits occur most commonly in calcareous rocks at igneous contacts (skarns).

   EXAMPLES: Granitic host rocks: Deposits in pyroxenites and skarns at Bancroft, Ontario; skarn deposits at Rössing, Namibia; economic deposits at Mary Kathleen, Australia, in zones of garnetization.

2C. High-temperature vein deposits gradational into metasomatic and pegmatite uranium deposits

CHARACTERISTICS: Distinguished from pegmatite uranium deposits by a lack of some or all minerals commonly found in igneous pegmatites. Distinguished from metasomatic deposits by vein morphology.

EXAMPLES: Granitic host rocks: quartz-fluorite veins at Rössing; calcite-fluorite-apatite veins at Bancroft; brannerite-rich quartz veins at Crocker Well; carbonate-hematite-fluorite veins at Bokan Mtn., Alaska. Carbonatite: Carbonate-fluorite veins at the Oka carbonatite complex (Rowe, 1958); Alkaline: Hydrothermal vein deposits at Ilimaussaq (Sørenson, 1970; Bhose *et al.*, 1974)

2D. Autometasomatic deposits

CHARACTERISTICS: Disseminations of primary uranium minerals in non-pegmatitic igneous host rocks; crystallization of uranium minerals is speculated to be approximately contemporanoous with autometasomatic alteration by magmatic vapors or fluids

EXAMPLES: Granitic host rocks: Ross-Adams deposit, Bokan Mtn., Alaska; albite-riebeckite granite, Kaffo Valley, Nigeria (Appendix 1); Carbonatite: Fenite zone of the Newman carbonatite deposit (Rowe, 1958); Alkaline: Metasomatically-altered roof zone in the lujavritic phase of the Ilimaussaq intrusion, Greenland (Sorenson, 1970).

3. Pegmatite deposits formed by local, *in situ* partial melting of uraniferous country rock.

CHARACTERISTICS: No associated comagmatic pluton; apparently, pegmatites formed by partial melting of layers of biotite gneisses (e.g., Mt. Laurier)

EXAMPLE: Mt. Laurier, Canada (Appendix 1), granitic pegmatites of contact metasomatic deposits are the uranium-rich skarns at Bancroft and Rössing.

Some pegmatite uranium deposits have undergone mineral replacement or growth due to alteration by magmatic fluids or vapors and are metasomatic deposits in the strictest sense (see, for example, descriptions in Berning et al (1976) of the Rössing alaskitic pegmatites). However, since these "metasomatic pegmatite" deposits generally retain the mineralogy and texture of pegmatites, they are arbitrarily classed as pegmatite deposits in this classification scheme.

Although closely related to igneous rocks, metasomatic uranium deposits at or near igneous intrusions are generally categorized as hydrothermal or vein-type uranium deposits rather than igneous uranium deposits.

High-temperature vein deposits (2C) gradational into pegmatitic and metasomatic uranium deposits are distinguished from pegmatitic deposits on the basis of mineralogy. Pegmatite deposits are mineralogically very similar to their associated intrusive mass, while vein-type deposits lack some or all of the rock-forming minerals of the associated igneous intrusive. For example, pegmatite uranium deposits at Crocker Well, Australia, grade into quartz vein deposits as feldspar decreases in the pegmatite assemblage.

Autometasomatic deposits (2D) form during the alteration of igneous intrusives by their own uranium-rich fluids and vapors. Albitization or silicification often accompanies this type of deposit.

"Metamorphic" pegmatites formed by local, in-situ melting of crustal rocks (type 3) evolve when uraniferous metamorphic rocks suffer partial melting and form small pockets of uraniferous magma. This type of mineralization occurs specifically at Mt. Laurier, Canada (Allen, 1971; Kish, 1975; Appendix 1).

Uranium deposits composed entirely of secondary uranium minerals at the contact of igneous intrusives, such as at Austin, Nevada (Sharp and Hetland, 1954), and Midnite mine, Washington (Nash and Lehrman, 1975), are a variety of low-temperature hydrothermal uranium mineralization and are not considered to be igneous uranium deposits. The source of uranium in the secondary minerals may, however, ultimately be the igenous rocks.

URANIUM DEPOSITS IN GRANITES, ALKALI-RICH GRANITES AND AFFILIATED SYENITES

The remaining segments of this chapter concentrate on non-vein occurrences of uranium in granites, alkali-rich granites and affiliated syenites. Metasomatic and vein uranium deposits are considered only in cases where they are affiliated with disseminated uranium mineralization in granitic rock types. All of the genetic types of uranium deposits listed in Table 2-1 are known to occur in association with granitic rocks, but two types of uranium deposits appear to have comparatively greater potential as future low-grade sources of uranium from granitic rocks. They are: (1) the deposits formed during the pegmatite stage of crystallization (2A), represented primarily by the Rössing and Bancroft "porphyry" deposits; and (2) autometasomatic deposits (2D) exemplified by the Bokan Mtn. deposit.

The Pegmatite-Alaskite-Gneiss Uranium Association

Large, low-grade (as low as 300-400 ppm U) deposits of uranium in pegmatites, aplites and alaskites represent newly-considered potential sources of uranium for the near future. The large, proven reserves at Rössing, Namibia, and the rising price of uranium have caused a great deal of interest in the exploration for similar types of deposits.

Likewise, the great demand for uranium has caused renewed exploration in the Bancroft district as well as the re-opening of the Faraday mine.

This ore association can include metasomatic and vein deposits of an ancillary nature in addition to mineralization in pegmatites and alaskites. Granites and syenites associated with the uranium deposits may have above-average concentrations of uranium, which are thus syngenetic deposits in large granitic masses.

Distribution

In addition to the Bancroft and Rössing deposits, there are several other important, but non-producing deposits in pegmatites and alaskites in gneiss terranes. Numerous pegmatite uranium deposits form a broad, 240 - 310 km-wide belt along the Grenville province of Quebec and Ontario; most of these deposits are small and uneconomical. However, the deposits at Sept Iles and Johan Beetz, Quebec, have been the subject of investigation as possible economic, but low-grade, uranium deposits. Several pegmatite deposits occur in northern Saskatchewan in the Churchill province. One of these, at Charlebois Lake, is cited by Armstrong (1974) as a possible "porphyry" uranium deposit. Other deposits occur in the Olary province, South Australia; the Broken Hill district (Thackaringa davidite belt), New South Wales; Wheeler Basin, Colorado; Currais Novos, Brazil; and possibly several minor deposits in Spain. The principal occurrences are denoted on Table 2-2 and described individually in Appendix 1.

A conspicuous feature of the distribution of these deposits is their location in areas where either numerous uranium deposits of sedimentary and/or vein and/or igneous affiliation occur or where there is known

TABLE 2-2

PRINCIPAL OCCURRENCES OF THE PEGMATITE-ALASKITE-GNEISS URANIUM ASSOCIATION

Location	Grade	Major U Mineral	Age	Host Rock Type	Associated Plutonic Rocks	Reference
Wheeler Basin, Colorado	.05 % U up to .73 %	uraninite	1450 my	alaskitic pegmatite, migmatite	quartz monzonite	Young and Hauff (1975)
Rössing, Namibia	.05 % U up to .6 % U	uraninite + secondary minerals	510 my	alaskite, migmatite	alaskite	Von Backstrom (1970)
Bancroft, Ontario	.11 % U	uraninite, uranothorianite	∿1000 my	granitic and syenitic pegmatite, migmatite	granite, syenite	
Charlebois Lake, Saskatchewan	.004 up to 1.5 % U	uraninite	∿1800 my?	pegmatite, migmatite	quartz monzonite	Mawdsley (1952)
Johan Beetz, Canada	.007 % U and up	uraninite	Grenville	granite, pegmatite	granite	Baldwin (1970)
Crocker Well, S. Australia	.4 % U	brannerite var. "absite"	560 my	alaskite, aplite	quartz monzonite	Campana and King (1958)
Broken Hill Dist Australia (Thackaringa)	?	davidite		alaskite		Rayner (1960)
Currais Novos, Brazil	.015-0.15% U	uraninite, uranothorianite, secondary minerals	Precambrian	pegmatoid granite,	granite	Ramos and Fraenkel (1974)

bedrock enrichment in uranium. Such areas have been called "uranium provinces", and Table 2-3 lists several of these provinces and their distinguishing features. As indicated in this table, there is considerable latitude in the definition of "uranium province". The Olary province and Broken Hill district are included in the "Australian Uranic Arc", which also includes uranium deposits at Mt. Isa-Cloncurry and Rum Jungle-South Alligator River (Rayner, 1960). Numerous vein, sedimentary and pegmatite uranium deposits reside in the Grenville province of Canada in addition to the Bancroft deposits. The uranium deposit at Wheeler Basin, Colorado, is peripheral to Silver Plume-type granite, a component of Phair and Gottfried's (1964) Colorado Front Range uranium province. Pegmatite uranium deposits at Currais Novos, Brazil, are located within an eastern Brazil uranium province that embraces uranium deposits in granites, conglomerates, carbonatites, and other alkaline rock complexes (Heinrich, 1958). Vein deposits (the Beaverlodge district), as well as several minor pegmatite deposits, are found in the Athabasca region in addition to the "porphyry" uranium occurrence at Charlebois Lake (Beck, 1969, 1970; Armstrong, 1974). The Iberian Peninsula is a component of an extensive Hercynian-age uranium province that extends discontinuously through parts of southern England, France, Spain, Portugal, and Germany (Heinrich, 1958; Brinck, 1974); this province is characterized mainly by vein-type uranium mineralization. Southern Africa has also been termed a uranium province by Heinrich (1958); besides the Rössing alaskite ores, there are numerous vein, sedimentary and igneous uranium deposits discontinuously distributed through this extended province.

TABLE 2-3

AREAS SPECIFIED AS URANIUM PROVINCES

Area	Distinguishing Features
Colorado Plateau and Wyoming Area (Brinck, 1974)	Contains 30% of world's uranium reserves
Colorado Front Range (Phair and Gottfried, 1964)	Bedrock enrichment in thorium and uranium
Colorado Plateau and surrounding areas, including the Front Range, parts of New Mexico, Arizona, and eastern Washington, western Idaho (Heinrich, 1958)	Deposits in veins, sandstones, coals, carbonatites, granites and contact zones
Northern Territory, Australia (Brinck, 1964)	Contains 8% of world's uranium reserves
The Australian Uranic Arc (Rayner, 1960)	Discontinuous belt of uranium deposits from South Australia to Northern Terr.
Rum Jungle, Waterhouse; Northern Territory (Heier and Rhodes, 1965)	Uranium-rich granites
Fennoscandian Shield, Southern Norway (Kileen and Heier, 1975)	Uranium-rich alkaline igneous rocks
"Hercynian area", Europe (Brinck, 1974)	Contains 6% of world's uranium reserves
Broad belt, E-W across Europe, including parts of Germany, France, England and Portugal (Heinrich, 1958)	Numerous epithermal vein deposits
Iberian Peninsula (Arribas, 1974)	Numerous uranium deposits in pegmatites, veins, sediments, migmatites
Niger, Gabon, Central African Republic (Brinck, 1974)	Contains 8% of world's uranium reserves
Broad, discontinuous belt across southern Africa (Heinrich, 1958)	Numerous deposits in pegmatites, migmatites, veins, conglomerates; pyro-metasomatic deposits

Area	Distinguishing Features
Witwatersrand Basin, South Africa (Brinck, 1974)	Conglomerates contain 23% of world's uranium reserves
Eastern Brazil, including Rio Grande do Norte, Paraiba, Bahia, Minas Gerais, Espirito Santo and Sao Paulo	Numerous uranium deposits; granitic pegmatites, carbonatites, and conglomerates
Precambrian Shield Area, Canada (Brinck, 1974)	Contains 21% of world's known uranium reserves
Southern and western margins of the Canadian Shield, (Heinrich, 1958)	Numerous pègmatite, vein and sedimentary uranium deposits
Athabasca Region (Beck, 1969; 1970)	Numerous uranium deposits in veins, pegmatites, migmatites and sediments
Ferghana-Kara, Tau Region, U.S.S.R. (Heinrich, 1958)	Disseminations of uranium in sandstones and veins

Age

Most of the deposits are of Proterozoic age; however, the Rössing and Crocker Well, Olary province, Australia, deposits are younger than Precambrian (510 and 560 m.y., respectively).

Form and Setting

Certain broad patterns in the form and setting of these deposits exist; however, the details of each occurrence vary somewhat with respect to mineralogy, texture and structure.

The most obvious feature of the regional setting is that these deposits occur in mobile belts in the interior of continents, either in intracratonic mobile belts or in orogenic zones separating or adjacent to cratons. Deposits in Canada occur largely in areas affected by the Hudsonian (1800 m.y.) and Grenville (1000 m.y.) orogenies. The Pan-African-age Damaran orogenic belt, which lies adjacent to two cratonic masses in Africa, hosts the Rössing uranium deposit. Deposits in Spain, Brazil and Colorado are all in orogenic zones that have undergone repeated tectonic activity for a long period of geologic time.

Within these mobile belts, the uranium deposits and host granites lie in moderate- to high-grade metamorphic terranes, mainly of the amphibolite and upper amphibolite facies. Deposits in granulite terrains are conspicuously absent. The granitic rock types apparently consanguineous with the mineralized alaskites and pegmatites are syn- or late-tectonic with respect to the regional development of the orogenic belt.

The mineralized pegmatites are the youngest components of closely associated granitic rocks and intrude the granitic rocks and/or surrounding metasediments. Injection of the pegmatites into surrounding country rock results in the formation of migmatites, as seen, for example, at Bancroft and Rössing.

The host rock types of the mineralized pegmatites vary in their composition. At Bancroft, the ores are associated with both hybrid granitic and syenitic plutons; the Rössing deposits occur in an alaskitic granite. Intermediate igneous rocks, referred to as adamellite at Crocker Well, Australia, and quartz monzonite at Charlebois Lake, Saskatchewan, are also host rocks for uraniferous pegmatites.

The uranium ores comprise a variety of compositional and textural types, including albitic pegmatites, alaskitic pegmatites, syenitic pegmatites and aplites. Textures of the host rocks vary from massive pegmatitic to fine-grained aplitic to heavily brecciated and cataclastic. Ore localization often centers in structural traps such as the limbs of major anticlines or other large folds. Sheared or brecciated zones also constitute favorable structures for ore localization.

Mineralogy

At the Rössing deposit, the primary uranium mineral is uraninite; however, the high abundance of secondary uranium minerals (45% of the ore) is unique among ores of the pegmatite-alaskite-gneiss association. Uraniferous pegmatites at the Currais Novos, Brazil, deposit are reported to contain significant amounts of secondary uranium minerals in addition to primary uraninite (Favali, 1973) and are similar to Rössing in this respect. Canadian deposits of uranium in pegmatites are dominated by uraninite and uranothorianite, with only minor development of secondary uranium minerals. Titanium-rich uranium minerals, davidite and brannerite ("absite"), are characteristic of pegmatite uranium deposits in Australia. Table 2-4 lists some of the more common minerals in known pegmatite-alaskite-gneiss deposits of uranium.

A salient feature of both the Bancroft and Rössing deposits is that geologists who developed them have emphasized the extensive role metasomatism played in the origin of the ore-bearing pegmatites. The principal effects of metasomatism include:

1. Growth of the alaskite dikes by metasomatism such that country rock was replaced by alaskite (Berning et al., 1976) at Rössing;
2. Formation of metasomatic skarns in carbonate and pyroxenite country rocks at both Bancroft and Rössing;
3. Metasomatic alteration of the intruded gneiss, resulting in the replacement of biotite, hornblende, and pyroxene by muscovite and chlorite. Addition of fluorite, calcite, apatite, sphene, zircon, sulfides and radioactive minerals occurred in the pegmatites in the Bancroft deposit (Cunningham-Dunlop, 1967).

Origin

Literature on the origin of these deposits is somewhat confusing because of the repeated use of the term "granitization", which is rarely defined with precision and, in fact, has a disputed definition according to the AGI Glossary. Nonetheless, theories on the origin of these deposits can be subdivided into speculations on the source, transport and deposition of the uranium. The following discussion again draws mainly from studies on the economic deposits at Bancroft, Rössing, and the Olary province.

TABLE 2-4, MINERALOGY OF PEGMATITES, ALASKITES AND APLITES OF THE PEGMATITE-ALASKITE-GNEISS URANIUM ASSOCIATION

Quartz	Ubiquitous, commonly smoky due to radiation damage
Potassium feldspar	Ubiquitous, microcline or orthoclase
Plagioclase feldspar	Minor (alaskites) to abundant, ranges from albite to oligoclase when present
Biotite	Ubiquitous; uraninite, davidite, or absite mineralization is frequently found in the biotite-rich portions of the pegmatites
Muscovite	Rare to absent
Pyroxene	Uncommon; however, pyroxenes occur in the mineralized pegmatites at Bancroft, Ont.
Magnetite	Very common, particularly in the absence of abundant hematite
Hematite	Very common; red alteration of pegmatites due to hematite stains is considered an ore guide at Bancroft and Rössing
Sulfides	Ubiquitous; common varieties encountered include pyrite, pyrrhotite, chalcopyrite, and molybdenite; accessory amounts only
Fluorite	Common; an accessory mineral
Zircon	Common; an accessory mineral; can be metamict
Other Accessory Minerals	Sphene, apatite, calcite, ilmenorutile, monazite, tourmaline, allanite, thorite, rare earth phosphates
Uranium minerals	Mainly uraninite, uranothorianite, davidite, and brannerite ("absite"); secondary uranium minerals may be abundant (Rössing)

Source. Three sources are proposed for the uranium-rich differentiates:

1. The host granitic rocks and pegmatites crystallized from melts produced by anatexis of uranium-rich metasediments. The basal Proterozoic sedimentary unit overlying Archaean-age rocks is proposed to be the source of uraniferous melts for the Grenville deposits in Canada (Allen, 1971), while the Nosib group sediments in the Damaraland orogen are speculated to be the source of the anatectic granites at Rössing (Berning et al., 1971)

2. Von Backström (in press) speculates that the uranium in the alaskitic granites at Rössing may have been ultimately derived by the anatexis of ash beds.

3. Robinson (1958) and Evans (1964) propose that granite magmas were not the source of uranium in the pegmatites at Bancroft. They believe that the heat from the intruding granitic magmas caused uranium to migrate from the surrounding sediments into the pegmatites.

Available evidence leads to the tentative conclusion that the immediate source of uranium in these deposits was uraniferous sediments which were fused to form anatectic melts of approximately granite composition.

Transport and Deposition. If the deposits were derived from granitic melts, it is likely that two successive magmatic processes operated to concentrate uranium into economic deposits: (1) magmatic differentiation (crystal fractionation); and (2) "second boiling" of the magma.

Magmatic differentiation increases the concentration of uranium in the residual melt (e.g., Larsen et al., 1956; Bhose, 1974; Armstrong, 1974). With increasing crystallization of granitic melts, however, water and other volatiles are built up in the residual liquid to the point of supersaturation. This supersaturation results in the "second boiling" of the magma when water and volatiles separate from the silicate melt along with metal ions and dissolved silicate solids. It is generally believed that the second boiling of magmas produces the metal-rich solutions which are the source of many hydrothermal ore deposits (Holland, 1972). Uranium would be partitioned into the aqueous vapor or fluid phase evolved during second boiling, probably in the form of fluorine complexes (Shatkov et al., 1970). At pressures equivalent to those expected in the lower crust, this aqueous vapor phase contains up to 10% of dissolved granitic or pegmatitic solids (Luth and Tuttle, 1968), accounting for the affiliation of uranium mineralization with pegmatites.

If the uranium in pegmatite-alaskite-gneiss deposits is derived from an aqueous, vapor phase rich in volatiles, silicates, alkalis, and metal ions, then the following features of the deposits can be accounted for:

1. Metasomatic skarn deposits (the result of reaction of the aqueous vapor phase with carbonate country rock);

2. The apparent metasomatic origin of pegmatites and alaskites--while capable of acting as a metasomatic fluid, the aqueous vapor phase also contains granitic or pegmatitic solids;

3. Vein uranium deposits which are gradational to metasomatic and pegmatitic deposits--after removal of the dissolved granitic solids, the remaining material constitutes a hydrothermal solution which can cool to form hydrothermal vein assemblages.

The competency, reactivity and structure of country rock partly determines the mode of uranium mineralization, such as pegmatitic, metasomatic or vein deposits. Quartzo-feldspathic and pelitic metamorphic country rock constitute favorable host rocks for pegmatite uranium mineralization.

In contrast, pyroxenite or carbonate-rich country rocks are apparently reactive to ore solutions and are amenable to metasomatic uranium mineralization in the form of metasomatic pyroxenite deposits (Bancroft) or skarn deposits (Bancroft and Rössing). Structural traps such as anticlines or other major folds appear to be favorable sites for pegmatite ore localization (Bicroft mine, Bancroft; Rössing; Currais Novos), while local faults or shear zones may accommodate vein lodes (Crocker Well; Currais Novos).

Geochemistry

There is very little specific information on the major and trace element geochemistry of these ore deposits and their associated granitic rocks. The mineralogy of the ores, however, suggests that certain elements are positively correlated with uranium:

1. Sulfur, copper, and molybdenum: Pyrite, pyrrhotite, chalcopyrite and molybdenite are common, but minor, accessory minerals in the ore bodies.

2. Fluorine: The ancillary quartz-fluorite veins in the Rössing area and the calcite-fluorite-apatite veins at Bancroft suggest that fluorine might be positively correlated with uranium mineralization. Fluorite, however, is a common, but not ubiquitous, accessory mineral in the pegmatites and alaskites. Significant amounts of fluorine may be substituted for OH^- in the biotites, but no data are available to support or deny this.

3. Zirconium: Zircon is a common accessory mineral in the ores; however, zirconium is not as concentrated in these deposits as in the Ilimaussaq and Pocos de Caldas uranium deposits, where uranium is contained in complex oxides of zirconium.

4. Uranium in the associated granitic bodies: Uranium enrichment in the granitic and syenitic rocks associated with the uranium-rich pegmatites and alaskites appears to be an important geochemical feature. Radiometric surveys may be useful in delineating favorable areas for this type of mineralization.

5. Potassium: Quartz monzonites, granites, and syenites which host these deposits are richer in K_2O than the more mafic, plagioclase-rich granitic rocks, diorite, quartz diorite and granodiorite.

6. Other elements commonly associated with vein or stratabound uranium deposits: Little data exist on the elemental concentrations of Ni, Bi, Co, V, P, Nb, Ta, Cl, and the rare earth elements. Favali (1974) suggests that Ni and Co are elements found in association with uranium at the Currais Novos, Brazil, deposits in pegmatites.

Uranium Dissemination in Porphyritic, Peralkaline Granites

Two uranium deposits in epizonal granites, the albite-riebeckite granite of the Liruei complex of the Kaffo Valley, Nigeria, and the peralkaline granite of Bokan Mtn., Alaska, comprise a type of uranium deposit that shows some similarities in form, texture and setting to the porphyry copper deposits. Table 2-5 compares the features of the Bokan Mtn. uranium deposit to a general set of characteristics of porphyry copper deposits (after Stanton, 1972).

Form and Setting

Although both the Kaffo Valley (Liruei) and Bokan Mtn. deposits have similar petrological features, there are some differences in their location with respect to major tectonic features. The Kaffo Valley deposit is one of the Younger Granite ring complexes in northern Nigeria, and the uranium deposits are associated with Early Jurassic plutons intruded into an older, Precambrian crystalline terrane. The Younger Granite ring complexes may be related to incipient rifting along the Benue trough, which extends northeastward through Nigeria and formed at the same time as the major rifting that created the South Atlantic Ocean. The Bokan Mtn. deposit occurs in the highly deformed eugeosynclinal belt that developed along the western margin of North America during the Mesozoic, possibly coincident with earlier Paleozoic geosynclinal trends. It is uncertain whether a crystalline basement underlay the marginal eugeosynclinal trend at the time of the deformational activity.

Despite these differences in regional setting, however, broad similarities do exist, including:

1. Both deposits are hosted by epizonal albite-riebeckite granites.

TABLE 2-5

COMPARISON OF SOME OF THE GEOLOGICAL FEATURES OF
BOKAN MOUNTAIN, ALASKA, URANIUM DEPOSITS AND PORPHYRY COPPER DEPOSITS

Porphyry copper deposits (Stanton, 1972)	Bokan Mt. U-Th deposit (MacKevett, 1963)
1. The ore bearing intrusions are in stocks or bosses.	1. The uranium deposit is in "a boss 3 miles in areal extent".
2. At least one member of the intrusion is porphyritic .	2. "Porphyritic and cataclastic textures prevail" in the host peralkaline granite.
3. Within orogenic belts, these intrusions show a marked affinity for eugeosynclinal zones.	3. "Meta-sedimentary and metavolcanic rocks underly about 5% of the area" "They may be relict eugeosynclinal rocks".
4. Porphyry coppers involve shallow intrusions.	4. Hypabyssal rocks are widespread throughout the area".
5. Extensive hydrothermal alteration is an outstanding and characteristic feature.	5. "Albitization that affected many of the rocks near the peralkaline boss is probably related temporally and spatially to hydrothermal activity" Hydrothermal deposits and hydrothermally altered dikes are present.
6. Contact or pyrometasomatic or pneumatolytic mineralization develops as partial or complete halos about the source rocks.	6. "A roughly concentric aureole approximately 1½ miles wide surrounding the peralkaline boss" "...uranium-thorium deposits...occur within an (albitized) altered aureole as much as 1½ miles wide..."
7. The ore occurs as constituents of small irregular veinlets following a variety of cooling and deformational features or as disseminations through the body of rock concerned.	7. "The ore (at the Ross-Adams deposit) consists of numerous ore bearing veinlets between 0.1 and 0.8 mm thick and uranium and thorium minerals scattered through the peralkaline granite host. . ."

2. Both intrusions are not synchronous with the main orogenic events of their respective regions. The Bokan Mtn. albite-riebeckite granite was intruded some 260 million years after the intrusion of the regional calc-alkaline magma series (Lanphere et al., 1964). The ring complexes in Nigeria, including the Kaffo Valley (Liruei) complex, are anorogenic intrusions located in Precambrian terrane in, and north of, the Jos Plateau region. The Bokan Mtn. peralkaline granite is 180 million years old, while the Kaffo Valley complex is also Jurassic in age.

3. Albitization is an outstanding characteristic of both plutons.

At Bokan Mtn., the peralkaline granite forms a boss which intrudes a diorite-quartz diorite-granodiorite calc-alkaline rock series and a eugeosynclinal assemblage of volcanic and metasedimentary rocks. The peralkaline granites do not fall on the major-element differentiation trend of the surrounding plutonic suite. While unusual, this relationship is not unique and is observed at the Golden Horn batholith in the state of Washington, where albite-riebeckite granites intrude a typical calc-alkaline batholith (Barksdale, 1975). A similar situation is also apparent in the uranium-rich alkaline plutonic belt in the eastern Seward Peninsula, Alaska. Here, granitic and alkaline plutonic rocks intrude an older, Late Cretaceous to Jurassic eugeosynclinal assemblage of andesite and graywackes.

In contrast, the albite-riebeckite granites at Kaffo Valley occur in an alkaline ring complex composed of several varieties of alkaline granite and rhyolite. McKay and Beer (1952) and Greenwood (1961) have commented on the similarity between the Nigerian ring complexes and the White Mtn. magma series in New Hampshire, which contains the Conway granite, an important U.S. example of uranium enrichment in granite.

Constitution

The Ross-Adams deposit at Bokan Mtn. contains as much as 0.45% U, while the uranium content of albite-riebeckite granites of the Liruei complex at Kaffo Valley is only 100 ppm U.

A salient characteristic of both deposits is that the uranium-rich zones occur in the albitized portions of the riebeckite granites, and in the case of Bokan Mtn., the albitized zones of the surrounding country rocks. While MacKevett (1963) has commented on the general similarities in mineralogy and texture of the Bokan Mtn. peralkaline granite and peralkaline granites of Nigeria, there are differences in the composition of uranium minerals in the two deposits. Uranothorianite and uraninite are the main uranium minerals at Bokan Mtn., while uraniferous pyrochlore accounts for most of the uranium at Kaffo Valley (MacKay and Beer, 1952). Both veins and disseminations of uranium are scattered through the peralkaline granite at the Ross-Adams deposit at Bokan Mtn., while uraniferous pyrochlore is disseminated through the albite-riebeckite granites at Kaffo Valley.

Hydrothermal alteration is much more extensive at Bokan Mtn., where an albitized aureole approximately 2.5 km wide surrounds the peralkaline granite boss. This aureole contains higher concentrations of uranium than the unalbitized country rocks as well as numerous low-grade deposits of uranium. Hydrothermal alteration at Kaffo Valley is limited to the albite-riebeckite granites where deuteric solutions caused albitization of this rock type.

Origin

Both deposits appear to have formed in response to the addition of late-stage hydrothermal fluids. The Bokan Mtn. deposit, in particular, shows features which suggest that it formed in a manner analogous to porphyry coppers, which evolve during second boiling of magmas at fairly low pressures. Minor amounts of uranium in the form of uraninite occur early in the paragenetic sequence at the Bisbee, Arizona, porphyry copper deposit (Bain, 1951), so it is not unreasonable to suggest that uranium mineralization could form in a similar manner as the copper ores.

While these two deposits do not make a general ore association, they serve to indicate that uranium deposits in granitic rocks may occur in terrains younger than Precambrian and in post- or anorogenic settings. Exploration for this variety of uranium mineralization should emphasize the albitized or otherwise hydrothermally altered portions of alkali granites.

CHAPTER 3

BEHAVIOR OF URANIUM DURING CRUSTAL PROCESSES

This discussion on the relationship of uranium, granite formation and crustal evolution is arbitrarily subdivided into four categories. We will first review some studies that broadly relate both the behavior of uranium and the occurrence of uranium ore deposits in geologic time and space to current concepts on crustal evolution. Such studies are necessarily highly speculative but, nonetheless, suggest some conclusions as to favorable geologic environments for uranium deposits. Next, we review models of the geologic history of areas that have been loosely termed "uranium provinces"; these are geologic provinces that contain numerous uranium deposits, generally in a variety of different settings. The third general topic embraces studies on magma-forming, magmatic, and post-magmatic processes that lead to the concentration of uranium into ore-grade deposits in igneous rocks. The fourth topic is a brief discussion of variations in the Th/U ratio in uranium deposits and the significance of this ratio with respect to relating uranium deposits to processes of crustal evolution.

URANIUM, GRANITES AND CRUSTAL EVOLUTION

Most simplified models of early crustal evolution propose an initial geochemical fractionation of the earth leading to the concentration of lithophile elements, including uranium, in the upper mantle and proto-continental crust. Major uncertainty exists, however, with respect to later, particularly post-Archaean, processes of crustal evolution. For example, many writers consider that most segregation of continental material had taken place by the end of the Archaean, with Proterozoic and later events acting largely upon this earlier-formed material (e.g., Watson, 1973; Engel et al., 1974); a contrary view, however, envisions fairly constant evolution of continental crust throughout much of geologic time (e.g., Glikson, 1972; Rogers and McKay, 1972; Rogers et al., 1974).

Petrologic features of rocks dating from approximately the first billion years of recorded earth history (the Archaean, approximately 3.8 to 2.5 billion years ago) are interpreted to indicate a period during which the earth's crust was hot, weak and unstable. No known economic uranium deposits are older than 2.7 billion years, and most ore deposits older than 2.7 billion years derived their material directly from, or through a single stage of fractionation of, the mantle. During the Archaean, high heat flow and steep geothermal gradients caused the extrusion and intrusion of an inordinate amount of ultramafic to mafic rock types. These high-temperature igneous rocks formed greenstone belts and are associated with high-grade tonalite-gneiss terranes, resulting in the well-known bimodal spatial association of greenstone belts and tonalite gneiss. Engel et al. (1974) and Watson (1973) view Archaean magmatism as primarily dominated by rocks derived from the mantle, in contrast to the Proterozoic and Early Phanerozoic periods, during which segments of the crust of the earth underwent "ensialic refractionation". This refractionation is a process of remobilization of pre-existing continental crust which may have enriched Proterozoic and Phanerozoic granites in uranium and other LIL ("large ionic lithophile") cations. Perhaps the lack of silicic, potassic, uranium-rich granitic source rocks of Archaean age may account, in part, for the paucity of uranium ore deposits of this age.

The oldest uranium ore deposits, which are in fact the first important concentrations of mobile elements in the earth's crust (Watson, 1973), are uranium-bearing conglomerates that occur in latest Archaean and basal Proterozoic (2.7-2.2 billion-year-old) beds. The best-known occurrence of this type of deposit is in the Eliot Lake, Ontario, region; however, other deposits are found at Witwatersrand, S. Africa, several other localities in Canada, several in Brazil, and in the Nullagine area of Western Australia. Roscoe (1973) and Robertson (1974) have emphasized the limited age range of these syngenetic, stratabound uranium deposits and suggest that they formed during a period after the development of extensive acidic crust but prior to the development of an oxidizing atmosphere. Biogeologic evidence cited by Cloud (1968) implies the development of an oxygen-rich atmosphere during the period between 2.0 and 1.8 billion years before present. The upper age range of these conglomerates (2.7 billion years) correlates with an increase in variety of ore deposits and the evolution of the first stable and relatively cool crustal units at about this time (Watson, 1973). Watson (1973) notes that these uranium deposits "represent the first major suite of ore deposits to derive their substance from material recycled at the surface of the earth. . ." More importantly, basal Proterozoic sediments formed after the Archaean may be the source of uranium for many younger vein, igneous or sedimentary uranium deposits; numerous economic deposits of uranium and other metals are spatially related to this sedimentary horizon (Derry, 1961).

The bulk of known pegmatite-alaskite-gneiss uranium deposits evolved during the Proterozoic-Early Phanerozoic stage of crustal evolution. Included in this age range are the Bancroft, Rössing, Currais Novos, Crocker Well, Charlebois Lake, and Thackaringa deposits. All of these deposits are hosted by massive or gneissic quartz monzonites, pegmatitic granites or alkali-granite complexes which lack abundant cogenetic mafic components (tonalites and diorites). Although the details of petrology, tectonics, and geochemistry of these deposits may vary considerably, they are nonetheless allied by common origin to remobilization or modification of crustal materials. Each of these deposits is hosted by granitic or syenitic rocks believed to have been formed by granitization or anatexis of local or underlying sediments and metasediments. Some of these deposits occur in areas where crustal evolution has been a complex, multistage phenomenon involving repeated deformation and reworking of the local crust. We have already noted that these deposits occur mainly in deeply eroded segments of the earth's crust and in mobile zones within or between cratons.

Several of the aforementioned features of the style and composition of Proterozoic-Early Phanerozoic magmatism may favor the evolution of pegmatite-alaskite-gneiss deposits in the Proterozoic rather than the Archaean:

1. Early Archaean granites are generally low in uranium.
2. Quartz monzonites and "granites", host rocks for these deposits, are more abundant in Proterozoic terranes.
3. Although Proterozoic magmatism was certainly not entirely the result of "ensialic refractionation", the overall high mobility of the sialic crust during the Proterozoic was amenable to the remobilization of incompatible elements into new, possibly ore-forming, environments.

As discussed in a later section, the very low Th/U ratio that characterizes deposits in these reactivated belts is a further indication of multistage crustal reprocessing. The extreme excess of uranium over thorium may most readily be explained by at least one stage of sedimentary cycling in the complex history of uranium ores in such belts.

Uranium ore deposits containing Th/U ratios in the normal crustal range (2.5-4) appear to be common only in the later part of the Phanerozoic (the last 0.4 to 0.3 billion years). This age range contains large quantities of mafic, mantle-derived igneous rocks and sediments that commonly form continental-margin eugeosynclinal belts. Characteristic rock types are tonalites, andesites, ophiolites and blueschists, all characteristic of modern plate-tectonic processes. There are no known pegmatite-alaskite-gneiss-migmatite deposits in this age range; however, Hercynian anatectic granites are the locus of abundant vein uranium mineralization in parts of western and central Europe. The rarity of pegmatite-alaskite-gneiss uranium deposits is not easily explained, but it can be noted that erosion to the catazone, where most examples of this type of deposit reside, is rare in these younger terranes (Buddington, 1959). Exposure may thus be a factor, as may be the different thermal and tectonic regimes manifested by the plate tectonic processes during this stage of earth history.

Some relatively young deposits, such as those of the Kaffo Valley of Nigeria, are difficult to explain by any particular system of crustal evolution. Kaffo Valley, for example, is formed in association with young intrusive rock emplaced into Precambrian crystalline terrane; the plutonic activity may be connected with rifting and eugeosynclinal activity in the Benue trough, immediately to the south. Thus, the area seems to be a hybrid of several mechanisms of crustal evolution.

Age relationships of uranium deposits are particularly interesting in connection with the tendency of some areas to undergo repeated mineralization at different times. In the western U.S., for example, the oldest igneous uranium enrichment occurs in Late Archaean (~2.5 b.y.) potassic granites of the Wyoming igneous province. Metasediments of the Colorado Rockies (Idaho Springs Fm.) formed at 1.7 b.y. ago show promise as a source of disseminated uranium; the original source of this uranium may have been detritus from the Archaean basement. A very widespread plutonic episode 1.4 b.y. ago formed: 1) the uranium-enriched Silver Plume granites in the central Rockies; 2) Elsonian-age granite plutons in Missouri (Graniteville) and Wisconsin (Big Falls); and 3) granites and quartz monzonites in the southwestern U.S. (Black Mts., Arizona; Marble Mountains, California; McCullough Range, Nevada). An equally widespread intrusive period occurred in Late Mesozoic to Middle Tertiary time, forming vein-type uranium deposits around quartz monzonites in such places as: the Owl Mountains, California; near Austin, Nevada; the Midnite and Mt. Spokane districts, Washington; and various bodies in western Canada and southern and western Alaska. Late Mesozoic and Tertiary alkaline granites and syenites are also important sources of uranium in the Colorado Front Range, west Texas, west-central Montana, and Alaska.

HISTORY OF SELECTED URANIUM PROVINCES

Studies which relate crustal evolution to ore formation suggest that ores are a part of their geologic environment and that certain ore types are closely related to changes in the composition, structure, and behavior of the earth's crust over geologic time. Relationships between the form, setting, and distribution of uranium deposits and the regional patterns of evolution of specific geologic provinces which host uranium deposits may provide useful guides for prospecting. At the outset, several general observations on the occurrence of uranium deposits with respect to regional settings should be mentioned:

1. As previously mentioned, Derry (1961) notes the grouping of many ore deposits (including uranium deposits) at the litholigical interface between the Archaean and Proterozoic, particularly at sites of major faulting and granitization.

2. Bowie (1971) states that the most favorable environments for uranium deposits are intracratonic and miogeosynclinal sediments and more recent sediments in intermontane regions.

3. In a review of Canadian and East European uranium deposits, Ruzicka (1971) concluded that uranium deposits are closely associated with orogenetic and tectonic events in uranium-rich provinces and that granitization is an important factor in the evolution of certain uranium deposits.

The Canadian Shield

The following regularities in the distribution of uranium deposits in pegmatites and granites within the Canadian Shield have been reported:

1. Most of the uranium deposits in pegmatites of eastern Canada occur in a belt that is parallel to the Grenville Front or nearly so. This belt lies approximately 250-300 km southeast of the Front (Little, 1970).

2. There is a close association of uranium deposits, including vein, stratabound, and pegmatite deposits, to basal Proterozoic units

which occur just above unconformable contacts with Archaean horizons. This feature has been specifically noted for conglomerate uranium deposits (Roscoe, 1969; Robertson, 1974), pegmatite uranium deposits in Saskatchewan (Beck, 1970), and all types of uranium deposits in eastern Canada (Allen, 1971).

3. Radiometric surveys by Darnley et al., (1971) indicate that the regional contact of the Grenville group and underlying granitic basement is the locus of radioelement enrichment over more than 500 km.

4. Most deposits of uranium in veins, pegmatites and sediments occur in geosynclinal belts surrounding provinces and subprovinces of the shield (Smith, 1974).

5. Pegmatite uranium deposits are restricted to granites in amphibolite to upper amphibolite metamorphic terranes (Allen, 1971; Beck, 1969).

Assuming the above generalizations are valid, it is clear that uranium deposits in pegmatites and granites occur in very specific geologic environments in the Canadian Shield. They are lithologically controlled by the Archaean-Proterozoic basal unit and are restricted to the amphibolite facies portions of geosynclinal belts. Most of the eastern Canadian pegmatite uranium deposits are restricted to units of the Grenville province, while deposits in northern Saskatchewan correlate with granitic rocks produced during the local Hudsonian orogenic event.

The occurrences in eastern Canada are closely related to the development of the Grenville Province and should be considered separately from the Saskatchewan occurrences. Wynne-Edwards (1969) provides an excellent summary of the development of a segment of the Grenville province, the Mt. Laurier-Kempt Lake area. This area contains pegmatite uranium deposits (Allen, 1971; Kish, 1975) and affords a representative view of the geological evolution of the Grenville. Figure 3-1, taken from Wynne-Edwards (1969), summarizes the tectonic evolution of the Grenville province in this area. Plutonic and metamorphic rocks are subdivided into five tectonic categories:

I A pretectonic basement complex

II A pretectonic metasedimentary complex, the Grenville Group

III A pretectonic plutonic intrusive group

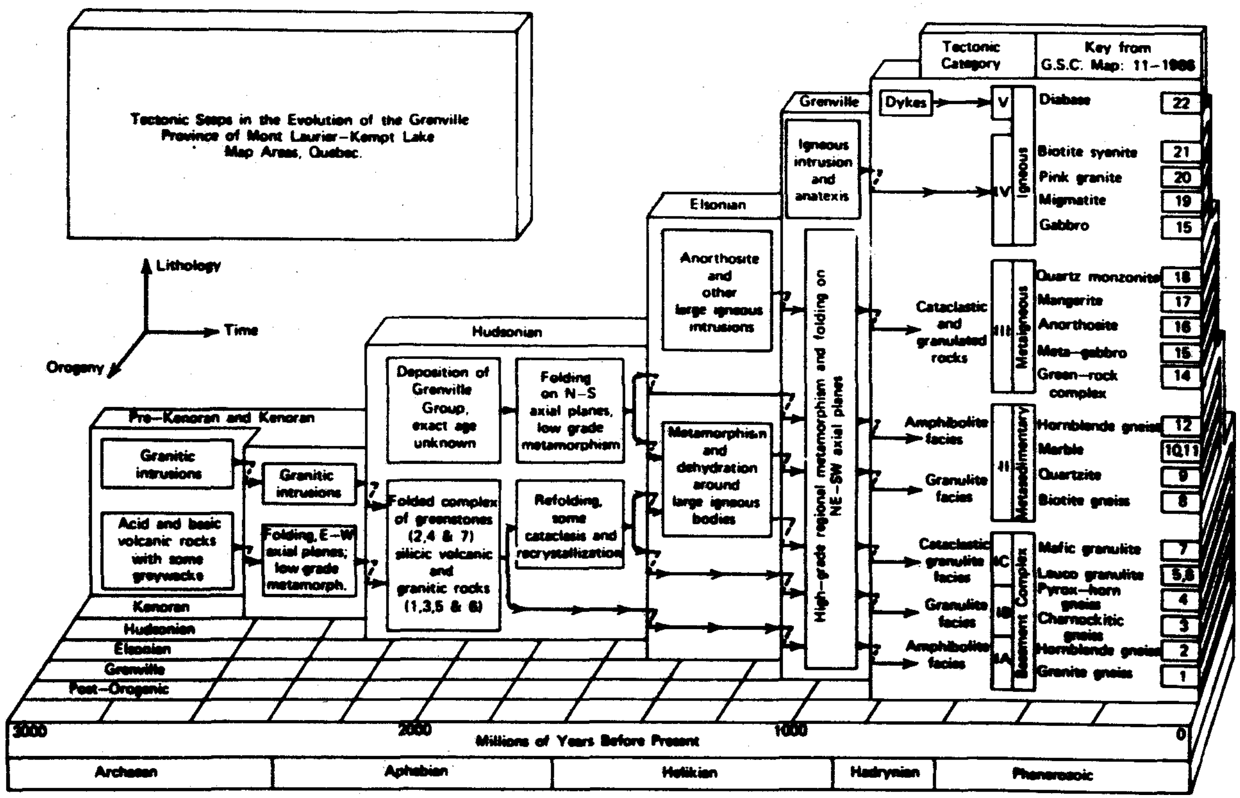
IV A syntectonic plutonic intrusive group

V A posttectonic family of diabase dikes.

The first three categories were deformed and recrystallized during the Grenville orogeny. Uranium deposits in pegmatites are found in category IV and are represented by rock types 19-21 (Figure 3-1), anatectic granites and migmatites that formed after the area had undergone nearly 2 billion years of crustal reworking.

Figure 3-2, also taken from Wynne-Edwards (1969), is a theoretical time-depth curve for the basement-supracrustal contact of the Grenville orogenic belt. According to this diagram, the Grenville area was subjected to a protracted period of burial from the Aphebian to late Helikian. Burial to the catazone is speculated to have been passive and unaccompanied by strong folding. Anatexis, high-grade metamorphism and folding then took place during the Grenville orogeny. The main folding events were probably a consequence of non-uniform viscous flow of the deeply-buried rocks as they ascended towards the surface during isostatic recovery. Clearly, the Wynne-Edwards model of the Grenville implies that anatexis, caused by burial of supercrustal rocks to the high-temperature regimes of the catazone, was responsible for the origin of Grenville-age granites,

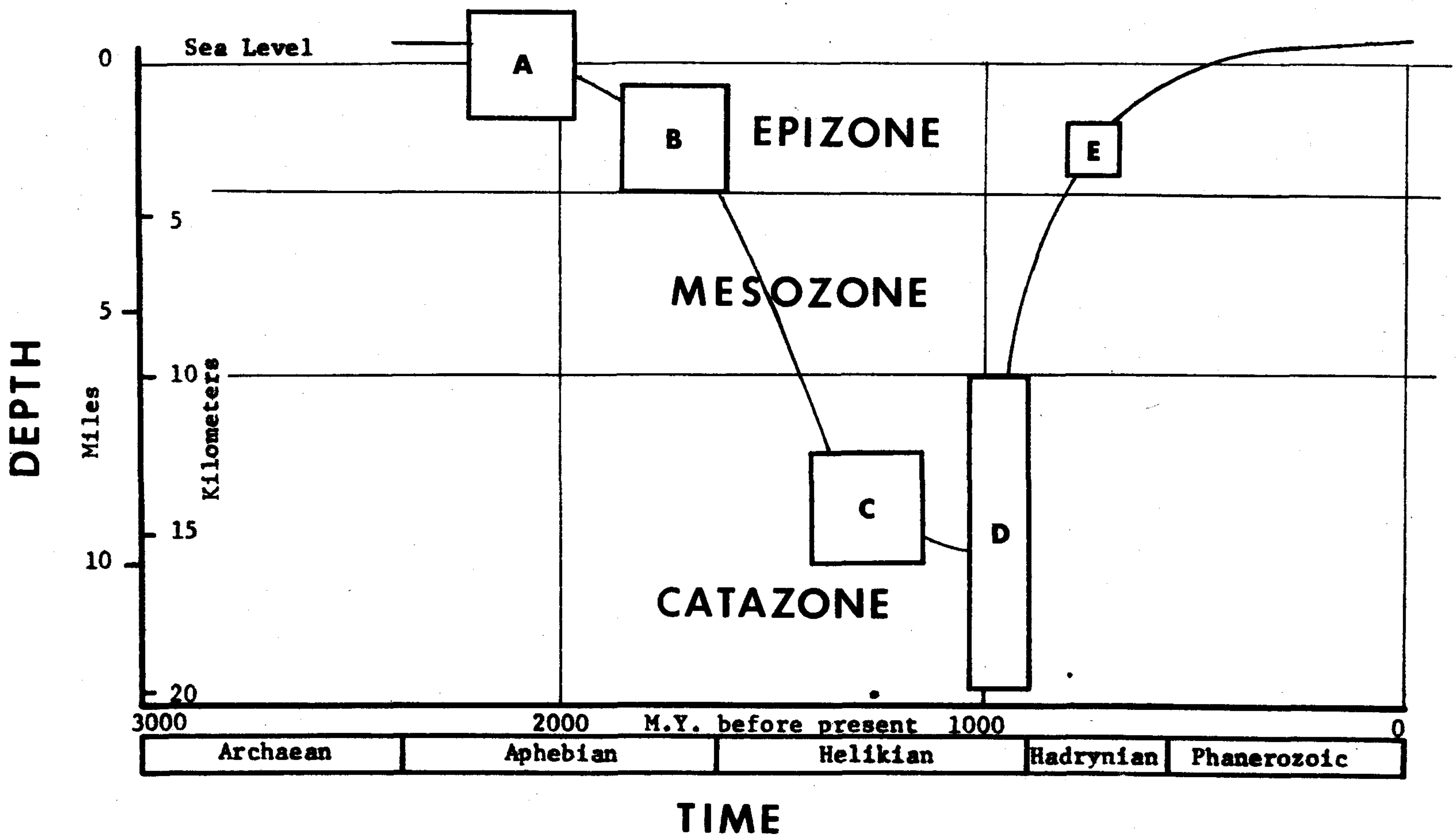
FIGURE 3-1



After Wynne-Edwards (1969); Geological Assoication of Canada Special Paper 5.

FIGURE 3-2

After Wynne-Edwards (1969); Geological Association of Canada Special Paper 5.



A-Deposition of Grenville group
B-Folding on N-S axial planes - low grade metamorphism
C-Anorthosite and other large igneous intrusions
D-High-grade regional metamorphism and folding
E-Diabase dikes

syenites and migmatites. It is these rock types and granitized and hybrid rocks that are the host rocks for the uranium deposits in pegmatites. The source of uranium for the anatectic granites was probably the Grenville group metasediments, owing to their known radioelement enrichment (Darnley *et al.*, 1971) and their close association to uranium deposits of all types in the Grenville province.

Following burial of supracrustals to the catazone and anatexis, the original floor of the geosyncline was re-exposed by extensive erosion over a period of approximately 200-300 million years.

The relationship between uranium mineralization and the tectonic evolution of a part of the Churchill province in northern Saskatchewan has been reviewed by Beck (1969, 1970). This area contains the Charlebois Lake uranium deposit, an example of a potential "porphyry" uranium deposit (Armstrong, 1974); other minor deposits of uranium in pegmatites are scattered throughout this area (Mawdsley, 1958).

Table 3-1, taken from Beck (1969), summarizes the rock formations in the Athabasca area of Northern Saskatchewan, and Table 3-2, also taken from Beck (1969), is a postulated sequence of geologic events and their duration as evaluated from available radiometric age studies. Beck subdivides this region into two structural types of environments:

1. linear belts consisting of a diverse assemblage of metasedimentary and metavolcanic rock types, paragneisses, basic intrusive rocks and granites. This type of terrane is usually heavily faulted, mylonitized and brecciated. The grade of metamorphism is typically low to medium;

2. stable blocks which consist of granite, paragneiss and migmatite. Granites are subdivided into two genetic types: (1) type 0, or older, granites typically have radiometric ages of approximately 2200 million years and occur in the stable-block structural areas--these granites have low

TABLE 3-1

SUMMARY OF FORMATIONS, ATHABASCA REGION

After Beck (1969)

		Stable Blocks	Linear Belts
Cenozoic		Glacial Drift	
		Great Unconformity	
Proterozoic	Cover Rocks		Diabase dykes and gabbro sills
			Intrusive contacts
			Athabasca Formation
			Unconformity (?)
			Martin Formation
			Unconformity (?)
			Hale's Lower Athabasca
			Unconformity
Archean or Aphebian	Basement Complex	Pegmatites	Plugs and sills of granites of varying composition including alkali granites and pegmatites (Type Y granites).
		Intrusive Contact	Norite, gabbro, amphibolite
			Intrusive contact
		Pre- and syn-tectonic granodiorite-adamellite in batholiths (Type O granites).	Small bodies of pre- and syn-tectonic granodiorite-adamellite (Type O granites).
		Gradational contact	
		Biotite-and biotite-hornblende gneisses, garnetiferous gneisses, hornblende-pyroxene gneiss and granulite.	Quartz-feldspar-biotite-hornblende gneisses of variable mafic content; locally garnetiferous.
		Gradational and faulted contacts	
		Marble, diopside-serpentine rocks.	Volcanic flows and tuffs, chlorite-epidote rocks, conglomerate, quartzite, meta-greywacke, meta-argillite, limestone, iron formation.

TABLE 3-2

POSTULATED SEQUENCE OF EVENTS, ATHABASCA REGION,

After Beck (1969); Saskatchewan Dept. Min. Res. Rept. 126.

	EVENT	ISOTOPIC EVIDENCE		Regional Metamorphism. Syntectonic granites	Syngenetic Uranium emplacement	Late- and Post-Tectonic Granites	Early faulting and Mylonitization	Normal or Block faulting	Pitchblende Mineralization	Diabase Intrusion
	12. Further fault movements and erosion. Glaciation and subsequent isostatic response. Supergene alteration of deposits by groundwater	0-100	U-Pb data						▌	
	11. Uplift. Fault movements. Erosion of Phanerozoic sediments. Rejuvenation of pitchblende	270	U-Pb data					▌	▌	
	10. Peneplanation. Subsidence and partial covering by Phanerozoic sediments.									
	9. Tectono-thermal events in Shield. Rejuvenation of pitchblende	1110	U-Pb data. Episodic lead loss					▌	▌	
	8. Deposition of cover rocks and intrusion of diabase	1410-1490 1630	K-Ar on gabbro and diabase. K-Ar on basalt							▌
	7. Erosion of Hudsonian orogen and formation of basins of deposition							▌	▌	
Hudsonian Orogeny	6. End stages of orogeny. Retrograde metamorphism, hydrothermal alteration, emplacement of pitchblende	1780 1740-1795	U-Pb concordia on pitchblende. K-Ar on gneisses	▌	▌	▌	▌	▌	▌	
Hudsonian Orogeny	5. Emplacement of late- and post-tectonic granites. Crystallization of uraninite	1815 1820	K-Ar on muscovite, Gunnar mine. Rb-Sr isochron, Athabasca	▌	▌	▌	▌			

TABLE 3-2
POSTULATED SEQUENCE OF EVENTS, ATHABASCA REGION (cont.)

EVENT	ISOTOPIC EVIDENCE		Regional Metamorphism. Syntectonic granites	Syngenetic Uranium emplacement	Late- and Post-Tectonic Granites	Early faulting and Mylonitization	Normal or Block faulting	Pitchblende Mineralization	Diabase Intrusion
Widespread mylonitization and formation of thrust and tear faults									
Regional metamorphism, formation of gneisses and syntectonic granites. Crystallization of uraninite	1900 1930	U-Pb concordia, and Rb-Sr isochron, Alberta U-Pb concordia, Athabasca							
One or more orogenic periods	2200 2250 2350 2440	Rb-Sr isochron, Athabasca Rb-Sr isochron and U-Pb concordia, Alberta K-Ar on hornblende K-Ar on hornblende							
Sedimentation and volcanic activity		Probably > 2500 m.y. ago							

Note: Events 3-6 would be probably transitional and overlapping and would not necessarily be of equal duration or extent in all parts of the orogen.

initial strontium isotope ratios (0.700) and may represent mantle-derived magmas; (2) Type Y, or younger, granites are restricted to linear belts and are largely of metasomatic or replacement origin. Most of the uraninite-bearing pegmatite and pegmatite granites are type Y. High (0.736) initial strontium isotope ratios of type Y granites suggests that they originated from crustal rocks enriched in radiogenic strontium.

Most of the uranium deposits in pegmatites in this region formed during the Hudsonian orogeny, when regional metamorphism and the formation of gneisses and syntectonic granites were the dominant processes. Formation of the ore deposits was preceded by an early period of sedimentation and volcanic activity followed by one or more regional orogenic events. As in the Grenville province, uranium deposits in the Athabasca region are closely related to basal Proterozoic beds unconformably overlying the Archaean (Beck, 1969). The relationship of pegmatite uranium deposits to anatectic granite melts, however, is less clear in the Athabasca region; Beck (1963) states that many of the pegmatite deposits were formed by granitization rather than anatexis. However, the Charlebois Lake deposits, as described by Mawdsley (1951,1952, 1958) occur in pegmatites that formed by the injection of magma, and closely associated granitic rocks are apparently also magmatic.

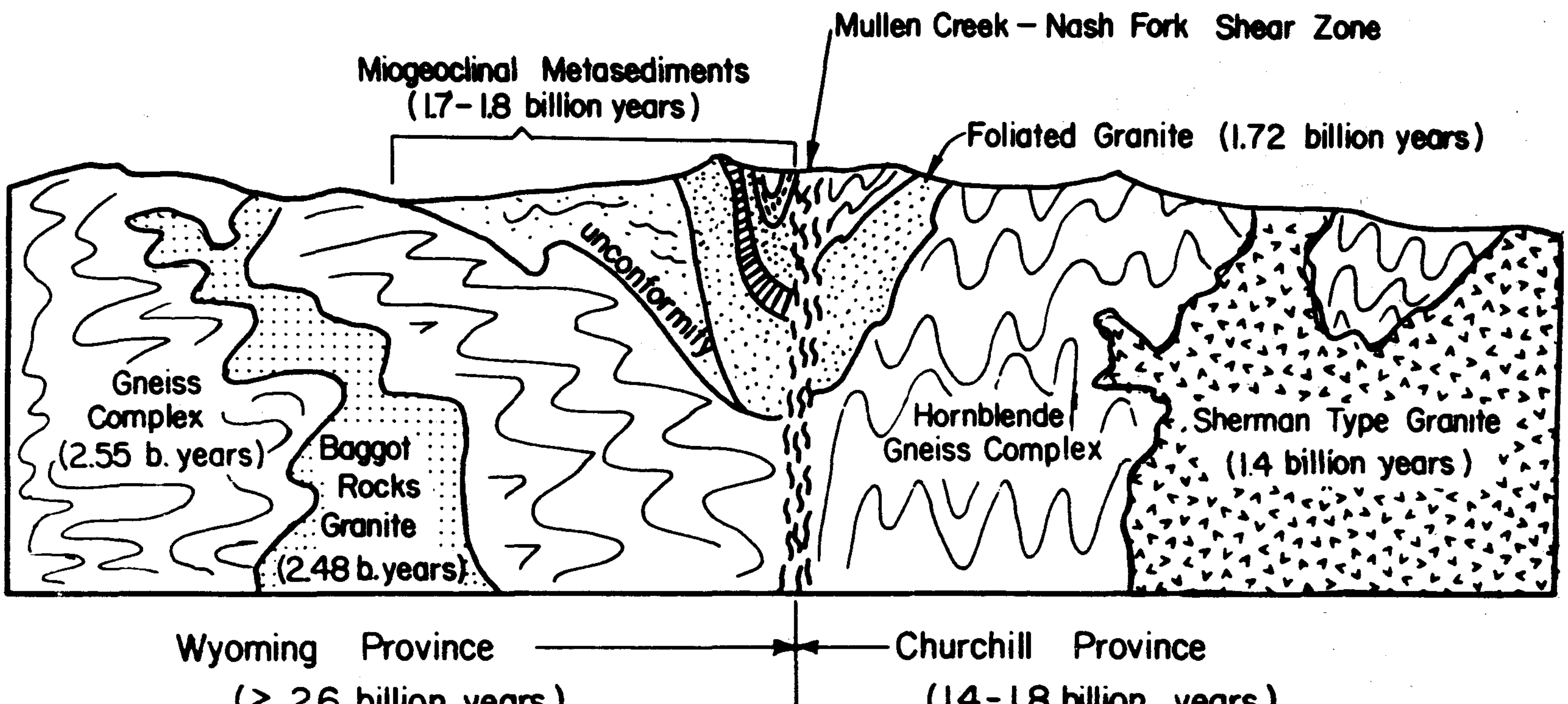
Thus, Canadian uranium deposits in pegmatites, although widely separated in both time (Hudsonian vs. Grenville) and space, appear to have evolved during somewhat parallel stages of two different regional mobile belts. That stage would be characterized by the burial of supracrustal rocks to catazonal depths and subsequent granitization and anatexis.

Parallels to the Canadian mobile belts that contain uranium are apparent in the Wyoming and Churchill provinces of the U.S. (Figure 3-3,

FIGURE 3-3,

Generalized cross section of the Wyoming and Churchill provinces, Wyoming and northern Colorado,

After Condie (1975)



after Condie, 1975). Reworked, miogeosynclinal sediments of Proterozoic age occur in Colorado and Wyoming and unconformably overlie the Archaean in some areas. Numerous sedimentary and vein uranium deposits characterize this area as a uranium province. Furthermore, it has been established that at least some of the granites in this area formed by crustal anatexis (Divis, 1974). Although uranium deposits in pegmatites and alaskites are rare here, it might be reasonable to prospect for uranium in these rock types at the margins of quartz monzonites, granites and syenites in amphibolite or upper amphibolite terranes. Recently, Young and Hauff (1975) reported an occurrence of uranium mineralization in alaskites in Proterozoic migmatites at Wheeler Basin, Colorado; this deposit is, in some ways, similar to Rössing. Though small, it is the first deposit of its kind to have been found in the United States.

The Damaran Orogen

A description of the relationship between tectonic evolution of the Damaran orogen and the origin of the G_4 granites, which contain the uranium ore deposits, is included in Appendix 3.

The Olary Province

Sections 3.2.2 and 3.2.3, Appendix 1, contain a review of the relationship between crustal evolution and uranium deposits in the Olary province.

URANIUM AS RELATED TO MAGMATIC AND POSTMAGMATIC PROCESSES

Several igneous and metamorphic rock-forming processes may have an important effect on the mobilization and concentration of uranium into ore deposits in pegmatites and alaskites. These processes are:

1. Progressive metamorphism
2. Granitization
3. Ultrametamorphism and anatexis
4. Magmatic differentiation
5. Separation of aqueous fluids or vapors during the latest stages of magmatic crystallization, including the pegmatite stage of crystallization.

Pressure, temperature, water pressure and the activity of certain chemical species are parameters which control the behavior of uranium during these processes and thus determine whether uranium is dispersed or concentrated.

Progressive Metamorphism

Little direct evidence is available on the effects of progressive metamorphism on the distribution of uranium in metamorphic rocks. Uranium mineralization in pelitic schists in the Kulu Himalayas is stated by Narayan Das (1968) to be the result of the metamorphic process whereby uranium, originally fixed by adsorption on argillaceous clays, was concentrated and mobilized in the early stages of metamorphism. With further metamorphism, continued mobilization, concentration and crystallization of uranium result in the segregation of uraninite along foliation planes in the schist. Generally, uranium is mobilized and lost from rocks at low grades of regional metamorphism (Yermolayev, 1971, 1973) and solutions formed by rock dehydration and decarbonization provide a medium of uranium transport away from their host minerals.

Circumstantial evidence that uranium is lost during metamorphism is provided by data that indicate a depletion of uranium in granulite-facies metamorphic rocks compared to lower-grade metamorphic equivalents (for example, Heier and Adams, 1965; Lambert and Heier, 1967, 1968; Heier, 1973; Fahrig and Eade, 1971). Lambert and Heier (1967) concluded that metamorphic processes involving movement of a vapor phase and partial melting contribute towards an upwards migration of uranium.

Granitization

A definition of granitization (AGI Glossary of Geology) is: "An essentially metamorphic process by which solid rock is converted or transformed into granitic rock by the entry or exit of material and without passing through a magmatic stage. Some authors include in this term all granitic rocks formed from sediments by any process, regardless of the amount of melting or any evidence of movement. The precise mechanism, frequency and magnitude of the processes are still in dispute."

The strict definition of granitization implies that metasomatism, the addition or subtraction of chemical species to the rock material in question, causes granitization. Granitization is believed to have played an important role in the evolution of at least two major uranium deposits (the Beaverlodge vein deposits of Canada and the Singhbum vein deposits in Bihar, India) by the geologists who studied them.

Tremblay (1972) states that all granites in the Beaverlodge region formed by a metasomatic rather than magmatic process. These granites are allegedly the source of the uranium in local vein deposits. Uranium was initially mobilized and concentrated from uraniferous sediments during the formation of granitic rocks by metasomatic granitization. Ultimately, vein deposits formed when uranium was again remobilized from the granites during mylonitization and late fracturing.

In the Singhbum shear zone in India, vein uranium deposits appear to be related to a combination of cross folding, migmatization and shearing. According to Banjeri (1962), the ultimate source of uranium in the Singhbum vein deposits is the migmatized sedimentary and volcanic rocks plus emanations from some deep-seated magma at the base of the sedimentary pile. Migmatized rocks in this region are described as augen gneiss, a term implying that metamorphic or metasomatic processes were involved.

A few minor pegmatite deposits occur in granites formed solely by metasomatic replacement in rocks of the Athabasca region (Beck, 1969, 1970); however, these uranium deposits are in no way comparable in size to Bancroft or Rössing.

Granitization may thus mobilize and concentrate uranium from sediments and be the first step in the evolution of certain vein and pegmatite uranium deposits.

Ultrametamorphism (Anatexis)

Ultrametamorphism and anatexis are the processes of melting of rock and the creation of magma _in situ_. It is probable that the temperatures high enough to cause partial fusion of hydrous sediments and igneous rocks are reached during the higher grades of regional metamorphism. According to the experimental studies of Tuttle and Bowen (1958), Winkler (1965) and Winkler and Von Platen (1960), temperatures as low as 650^{o} C are sufficient to cause partial melting of crustal rocks. The first liquids produced will approximate granite in composition. Temperatures allowing the formation of anatectic granites are likely to be reached at upper amphibolite and higher metamorphic grades. Data collected on suites of metamorphic and ultrametamorphic rocks indicate that ultrametamorphism is accompanied by mobilization of uranium and thorium into the magma (Yermolayev, 1971, 1973).

The ability of the ultrametamorphic process to concentrate uranium is also demonstrated in the Mt. Laurier area, Canada, where uraniferous sediments were partially melted to form granitic melts highly enriched in uranium (up to 2,000 ppm), which crystallized into uraninite-bearing pegmatites (Allen, 1971; Kish, 1975).

Theoretically, anatexis may also serve to disperse rather than concentrate uranium. Anatectic melting of a uranium deposit, along with its surrounding country rock, would result in the destruction of the deposit by the mobilization and dissemination of uranium into the newly-created magma. Dissemination of uranium from pre-existing deposits in this manner is said to have occurred in the Olary province, Australia (Campana, 1958).

Magmatic Differentiation

Larsen et al., (1956) demonstrated the general tendency of uranium to increase with increasing differentiation index in several magma series. Similar results have been obtained in other studies on the behavior of uranium in magmatic differentiates (e.g., Smyslov, 1968; Tauson et al., 1968; Leonova and Balashov, 1968; Fillipov and Komlev, 1959; Lyons, 1964). Thus, for most magma series, uranium is highest in concentration in the most differentiated rock types. During magmatic differentiation, uranium is partitioned strongly into the residual melt relative to the common rock-forming minerals (Dostal and Capedri, 1975). Much of the uranium that is removed from the magma is contained in uranium-bearing accessory minerals such as zircon, sphene, apatite, and allanite because the highly-charged, large-radius uranium ion does not substitute easily in the lattice sites of quartz, feldspars, pyroxenes and other common rock-forming minerals. Some uranium may be removed from the magma by substitution of uranium in sites of dislocation in crystal lattices, while additional uranium may be trapped at intercrystalline boundaries. Limited removal of uranium from the melt may be caused by crystallization of accessory minerals which contain uranium as a trace element; such removal results in uranium enrichment in the residual melt.

High concentrations of volatile elements in the magma, particularly fluorine, also favor the accumulation of uranium into the residual magma during magmatic differentiation (Smirnov, 1962; Locardi and Mittempergher, 1969; Shatkov et al., 1970; Rosholt et al., 1971; Phair and Jenkins, 1975).

Decreasing contents of uranium with increasing differentiation index in cogenetic magmas is infrequently observed but has been attributed, in specific cases, to autometasomatic loss of uranium in the magma owing to the formation of uranium-halogen complex ions (Bhose et al., 1974; Ragland et al., 1967).

The Aqueous Vapor Phase

Strong circumstantial evidence suggests that an aqueous vapor or fluid phase rich in metal ions and volatiles participates in the formation of uranium deposits in or at the margins of igneous intrusives. Features of uraniferous occurrences in igneous rocks accountable to the effects of an aqueous vapor phase include:

1. albitization of the igneous host rocks and surrounding country rocks in the vicinity of uranium deposits;

2. metasomatic formation of uranium deposits in skarns and pyroxenites where minerals such as garnet, scapolite and diopside formed by reaction of a hydrothermal fluid with carbonate rocks;
3. metasomatic growth of uraniferous pegmatites attributed to the action of hydrothermal fluids;
4. formation of hydrothermal vein deposits.

The classical model for the origin of the aqueous vapor or fluid phases involved in ore generation suggests that these solutions and their ore metals emanated from a magma at or about the time of the pegmatite stage of crystallization.

During the latest stages of crystallization of granitic magmas, the residual melt becomes enriched in water, volatiles, certain ore metals and the low-melting silicate fraction of the original magma. An aqueous vapor or fluid phase separates from the melt, and pegmatites crystallize during these stages. Bateman (1951) terms the period of pegmatite crystallization the "igneo-aqueous" stage of crystallization since it represents a transition between the strictly igneous and hydrothermal stages of crystallization. High concentrations of uranium would be expected in the melt + vapors which crystallize to form pegmatites since uranium concentrates in late-stage, volatile-rich differentiates. There are numerous examples of uranium mineralization in pegmatites to support this notion; for example, Page (1960).

Conclusions

A number of speculative conclusions can be made about the environments and processes which were important in the formation of uranium ore deposits in pegmatites and alaskites in gneiss terranes. First, uranium deposits have not formed constantly throughout geologic time, probably because of secular variations in tectonic and magmatic styles during the evolution of the continental crust. The oldest uranium deposits, which represent the first ore deposits derived by crustal recycling of a mobile element, are the uraniferous conglomerates of Early Proterozoic-Late Archaean age. During the Proterozoic and Early Phanerozoic, the earth's crust was extensively reworked and remobilized. The majority of pegmatite-alaskite-gneiss deposits appear during this time span and occur primarily in ensialic, reworked mobile belts. Evidence from Canada, Australia, and Namibia indicates that granitization, anatexis, and high-grade metamorphism occasioned the formation of this type of deposit. Granites associated with the mineralized pegmatites and alaskites are gneissic to massive and formed by crustal anatexis or, alternatively, by "granitization". The tectonic and magmatic history of parts of the Wyoming and Churchill provinces in the United States are sufficiently similar to Canadian and Australian mobile belts that contain uranium deposits to suggest that there may be analogous uranium deposits here in the U.S. Wheeler Basin, Colorado, is already known to be the site of a deposit which shows some similarities to the Rössing, Namibia, deposit.

Enrichment of uranium into economic deposits in pegmatites and alaskites can be accomplished by the successive processses of anatexis, magmatic differentiation and pegmatite crystallization. In the deeper portions of mobile belts, it is possible that temperatures high enough to initiate anatexis are reached, and some investigators suggest that the initial steps in the evolution of these deposits were burial, metamorphism, and anatexis of uraniferous sediments to form uraniferous granite melts.

TH/U RATIOS

One of the most interesting parameters concerning the distribution of thorium and uranium is the Th/U ratio. The significance of this ratio for a wide variety of geologic processes is discussed by a number of writers, including: Rogers and Adams (1969b), with references to older literature; Tatsumoto and Knight (1969); and Gast (1968).

With respect to uranium ores, a clear separation of different types of deposits is possible by means of the Th/U ratio. The two classes of deposits are:

1. Deposits with Th/U << 1. This group includes deposits such as Rössing; Halliburton-Bancroft and other deposits of the Grenville area; the disseminated deposits of eastern Egypt; virtually all vein deposits of uranium (with the exception of the thorium-rich veins of Lemhi Pass, Idaho); and all sedimentary deposits.

2. Deposits with Th/U > 1. This group includes deposits such as Wheeler Basin and other areas in the Colorado Front Range; Bokan Mountain and neighboring areas; and the Conway Granite and associated rock types.

The Th/U ratio of the earth is apparently between 3.5 and 4. A similar value is interpreted for the entire solar system based on inferences concerning the parent bodies of meteorites. Consequently, those rocks and deposits that contain Th/U ratios near 3.5-4 are regarded as mantle-derived. Some fractionation occurs within the lithosphere by various processes, including: (1) the ability of the mantle to generate primary basalts containing Th/U ratios of approximately 1-2, particularly in oceanic areas, by partial melting; (2) leaching of uranium from rock phases during the latest stages of magmatic differentiation, thus yielding highly differentiated igneous rocks with Th/U ratios considerably greater than 4; and (3) metamorphic separation of thorium and uranium, with some indication of increase of Th/U ratio in high-grade rocks by selective mobilization of uranium.

Major separation, however, is accomplished on the earth's surface by soil-forming and sedimentary processes. Residual materials tend to have high Th/U ratios because of the relative immobility of thorium. Conversely, rocks formed by chemical sedimentary processes, such as limestones, have a very low Th/U ratio because of the ability of such materials to concentrate uranium from surface waters. For this reason, deposits with very low Th/U ratio may, in part, have undergone some episode of surficial processing.

Within this framework, those deposits containing great excess of uranium over thorium comprise an interesting group. This group contains not only the sedimentary and highly-fractionated vein deposits but also such apparently igneous deposits as Rössing. Rössing is located within a reactivated older cratonic area (see discussion in Appendix 3). As discussed particularly in Appendix 3, such cratonic reactivation, including incorporation of materials that have undergone sedimentary recycling, may cause extreme concentrations of uranium.

By contrast, the Bokan Mtn. deposit of Alaska contains a high Th/U ratio that correlates well with the location of the area within a recent eugeosynclinal terrane. Much of the material in such terranes appears to have been derived from the mantle with little surficial reworking, and the Th/U ratio at Bokan Mtn. indicates that the radioactive ores are also mantle-derived.

CHAPTER 4

EXPERIMENTAL STUDIES ON GRANITE CRYSTALLIZATION

Investigations into the behavior of granites crystallizing over a range of temperature, pressure and composition have direct bearing on the problem of the origin of pegmatites, alaskites and aplites associated with uranium deposits in gneiss terranes. The data appear to supply reasons for the empirical observation that pegmatite-alaskite gneiss deposits are primarily restricted to granites that crystallize in deeper, and therefore higher-pressure, regimes in the crust.

Experimental studies by Tuttle and Bowen (1958), Luth and Tuttle (1968), Jahns and Burnham (1969) and Whitney (1975) subdivide granite crystallization into three general stages:

1. Crystallization of liquidus crystals from the silicate melt (liquid + crystals);
2. crystallization of liquidus minerals and active generation of an aqueous fluid or vapor phase (hereafter called the fluid phase) from the coexisting melt (liquid + crystals + fluid);
3. subsolidus stage reactions, after completed crystallization of the silicate melt (crystals + fluid).

The main body of intrusive granite crystallizes during stage 1. Development of pegmatites and aplites can begin with either stage 1 or 2; however, Jahns and Burnham (1969) suggest that the processes involved in stage 2 are essential to the origin of pegmatites. Steps 2 and 3 can bring about important exchanges of materials between the fluid phase, the early-formed crystals and the wall rock. These effects can include metasomatism, autometasomatism, and hydrothermal alteration. The fluids separated from granite melts during crystallization are generally believed to be the ore solutions of hydrothermal vein deposits (see Holland, 1972, for a review of this theory). Figure 4-1, adapted from Jahns and Burnham (1969), illustrates the various stages of granite crystallization and correlates them to the resultant rock types; the various types of uranium deposits that would likely attend each stage have been added.

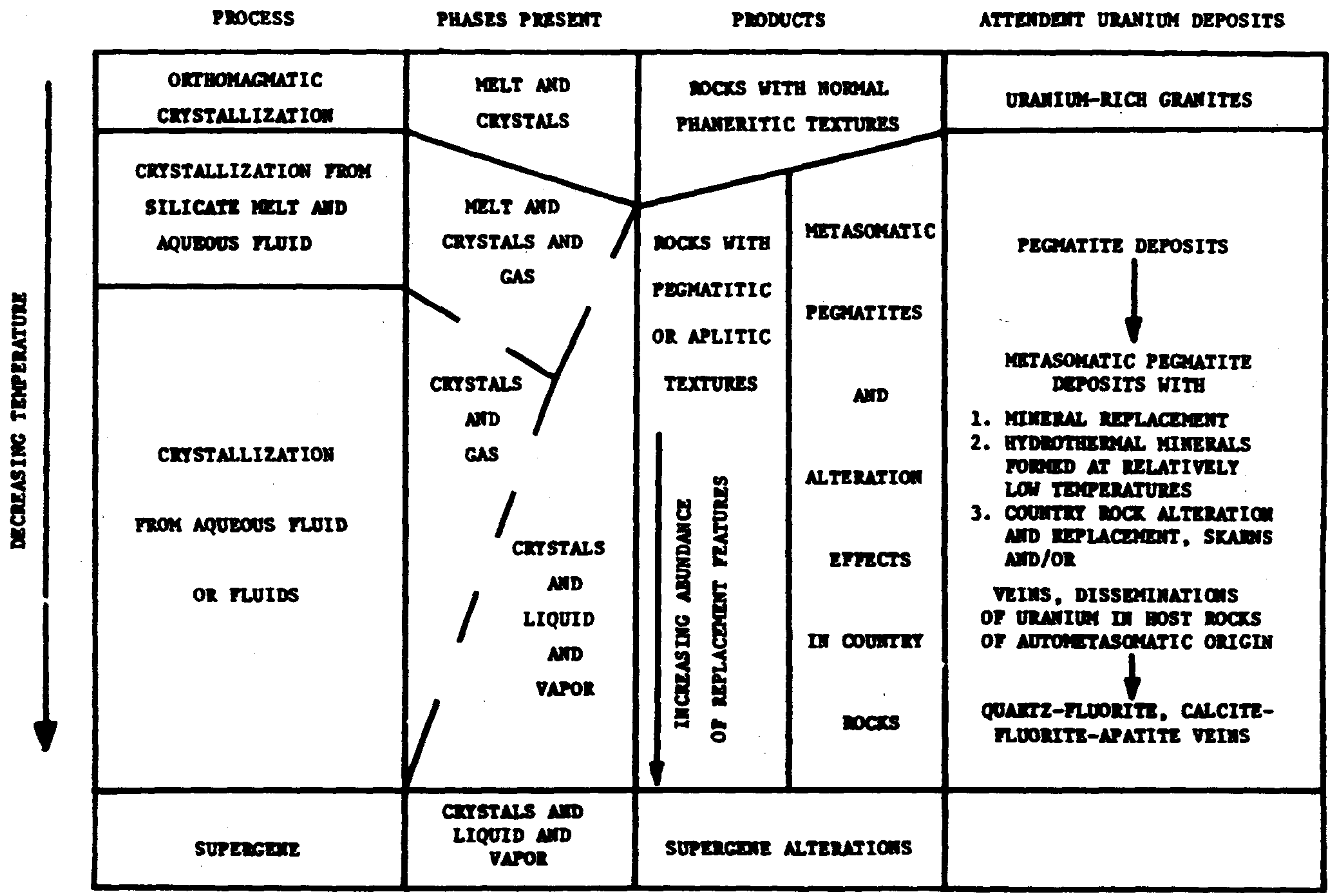
Variations in pressure, temperature, water content and volatile content of the magma cause differences in the duration and timing of these three stages of granite crystallization. At low pressures (less than 2 kb), granites with 3% to 4% initial water content will exsolve the fluid phase at relatively high temperatures above the solidus such that crystals, liquid, and fluid coexist over a large temperature range (Whitney, 1975). Second boiling, the early release of hydrothermal fluids from magmas, is believed to explain certain features of porphyry copper deposits. At higher pressures (5-10 kb), the behavior of water-undersaturated granites is quite different; the following are some of the differences between high- and low-pressure granite crystallization:

1. At high pressures, dissolved silicate solids are more soluble in the fluid phase (Tuttle and Bowen, 1958).

2. The composition of the dissolved solids in the fluid approaches the composition of the coexisting granite melt (Fig. 4-2); at low pressures, the composition of the dissolved solids approaches SiO_2 (Luth and Tuttle, 1968).

FIGURE 4-1
(Economic Geology, v. 64)

CRYSTALLIZATION OF GRANITE PEGMATITES (JAHNS AND BURNHAM, 1969)
AND ATTENDENT URANIUM ORE DEPOSITS IN GRANITES



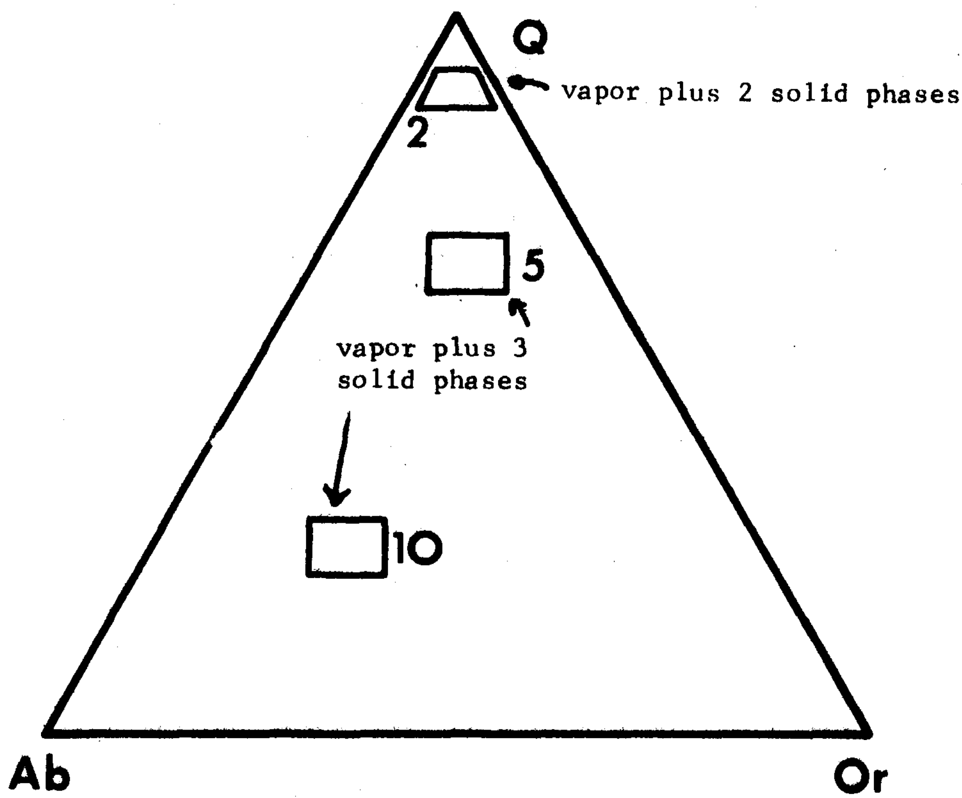


FIGURE 4-2

Anhydrous composition of the aqueous vapor phase coexisting with synthetic granite at 2,5 and 10 kilobars pressure

Q = quartz, Ab = albite, Or = orthoclase

After Luth and Tuttle (1968)

Geological Society of America Mem. 115

3. At pressures in excess of 2 kb and water-undersaturated conditions, the fluid phase is not exsolved until the melt and crystals are at a temperature that is approximately 20 degrees C above the solidus. Crystals, liquid and fluid thus coexist over a narrow temperature range above this pressure. However, crystals, liquid and fluid coexist over a large temperature range at pressures below 2 kb (Whitney, 1975).

If the uraniferous pegmatites at Bancroft and Rössing were formed as a consequence of stage 2 of granite crystallization (crystals + liquid + vapor), then the following features of these deposits may be explained by granite crystallization at high pressures:

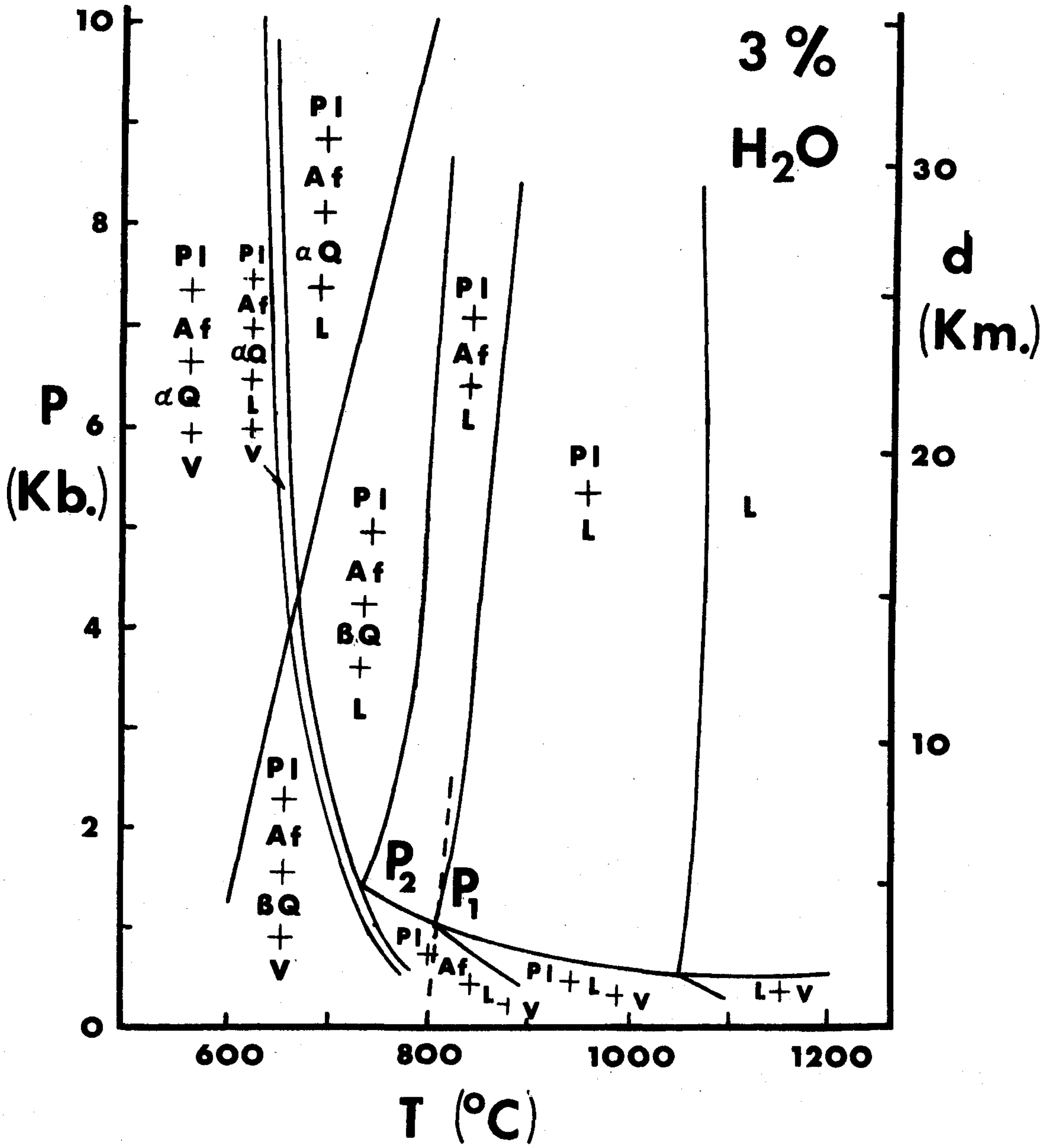
1. Because the solids in the fluid phase are similar to granite in composition, pegmatites and alaskites can crystallize from this phase. The uranium concentrated in the fluid phase can crystallize in a disseminated fashion in the pegmatites under the appropriate redox and temperature conditions.

2. The fluid phase at high pressures (greater than 5 kb) can contain only about 10% granitic solids (Luth and Tuttle, 1968). Once voided of these solids, the remaining fluid could constitute a more "normal" hydrothermal solution, giving rise to hydrothermal vein deposits; hydrothermal vein deposits grade into pegmatite deposits at Bancroft. While the granitic solids are still in solution, the fluid phase could act as a granitizing, metasomatizing agent. At Rössing, the alaskites allegedly grew as a consequence of metasomatism (Berning et al., 1976). Moreover, the wall rocks surrounding the alaskites apparently were altered by a granitizing, metasomatizing fluid, as it has been suggested that "granitizing fluids saturated and replaced already migmatized country rock" (Berning _et al._, 1976).

3. The narrow temperature range (less than 20°C) that separates the magmatic, pegmatitic and hydrothermal stages of crystallization of granites at pressures in excess of 2 kb (Figure 4-3) may account for the affiliation of pagmatitic, metasomatic and vein deposits in the vicinity of the batholiths at Bancroft.

It has been suggested previously that the catazone is a favorable environment in which to look for "porphyry" uranium deposits. The experimental data suggest that the composition of fluids coexisting with granite melts at high, rather than low, pressures could account for the apparent metasomatic growth of uraniferous pegmatites by "granitizing" fluids.

FIGURE 4-3



Liquidus diagram for a synthetic quartz monzonite

Symbols: L = liquid, Pl = plagioclase
Af = alkali feldspar,
αQ = alpha quartz,
βQ = beta quartz,
v = vapor

After Whitney (1975)
Economic Geology, v. 70

CHAPTER 5

PRELIMINARY NOTES ON EXPLORATION IN THE UNITED STATES

TARGET AREAS

The following comments are based on a limited review of data concerning uranium in igneous rocks in the U.S. Our study is primarily directed towards an evaluation of uranium deposits in granitic rocks throughout the world, and it is not within the scope of this report to review exhaustively the uranium favorability of igneous rocks in the U.S. Nonetheless, some of the reports consulted during the course of this investigation apply to domestic uranium potential and are considered here.

Alaska

1. Alkaline granitic rocks of the west-central Alaska-southeastern Seward Peninsula belt

Favorability: Unusually high concentrations (> 710 ppm) of uranium in many of the plutons (Miller, 1972; Miller and Bunker, 1976).

Prospecting guides: Attention should be paid to pegmatites, alaskites and felsic dikes. Very important as well are zones of hydrothermal and metasomatic alteration which may contain vein or disseminated uranium mineralization.

The Rockies

1. Wyoming province

Favorability

1. An area of known uranium potential
2. Contains uranium-enriched granites of Late Archaean age--the Owl Creek, Granite and Seminoe-Shirley Mts. (Malan and Sterling, 1970; Malan, 1972)

3. Basal Proterozoic beds overlie the Archaean; many uranium deposits in other parts of the world are spatially associated with this horizon.

4. An area of extensively reworked crust, some anatectic granites

Prospecting guides: Prospecting in this area should concentrate on migmatite-granite mixed zones, zones of metasomatic alteration and roof pendants.

2. Colorado Front Range

Favorability: A Th-U province (Phair and Gottfried, 1964) containing uranium-rich granite and bostonite dikes. The granitic rocks of the Front Range have unusually high Th/U ratios (commonly greater than 10).

Prospecting Guides:

1. Idaho Springs gneisses are migmatized and injected by uraniferous alaskites at Wheeler Basin, Colorado, very near a Silver Plume-type granite. Further prospecting should emphasize similar environments (as described in detail in Appendix 1, Wheeler Basin occurrence). This deposit is similar to Rössing.

2. Pegmatitic and/or metasomatic zones at the margins of the uranium-rich plutons are favorable areas to search for uranium mineralization. Since the ore deposits at Rössing are only 700 m in diameter, there could well be other deposits of the Rössing-Wheeler basin-type that have gone undiscovered in the Front Range.

3. Apart from granitic rock types, there are numerous Laramide bostonite dikes that average up to 80 ppm uranium (Phair and Jenkins, 1975).

Northwest

Favorability:

1. Quartz monzonite in the Midnite mine, Washington, area contains 12 ppm U.
2. Numerous, though minor, occurrences of uranium-rich pegmatites in Washington, Montana, and Idaho
3. Known uranium deposits in the Mt. Spokane area; Heinrich (1958) considers parts of the Northwest a segment of a large western-U.S. uranium province.

Prospecting guides:

1. Ferry County, Washington, contains numerous radioactive anomalies in pegmatite lenses (Weissenborn and Moen, 1974), and Armstrong (1974) suggests that this is a favorable locale to search for "porphyry" uranium deposits.

2. Lemhi Pass area, Idaho, is another district singled out by Armstrong as a potential "porphyry" uranium district

3. Silicified quartz monzonite at the Boulder batholith, Montana, hosts vein uranium deposits (Becraft, 1953). Further prospecting should emphasize hydrothermally altered zones within the quartz monzonites as well as the contact zones. Hydrothermal alteration zones with granitic host rocks, as at Bokan Mt., Alaska, can be sites of disseminated uranium mineralization.

4. Additional prospecting in parts of Idaho and Montana is warranted by the occurrence of numerous showings of uranium in pegmatites, for example, at Deer Creek, Montana, and the North Fork-Shoup district (Trites and Tooker, 1953).

5. Secondary uranium mineralization, as found in the contact of the Mt. Spokane and Midnite Mine area quartz monzonites (Nash and Lehrman, 1975), may occur in other, nearby plutons.

Great Lakes

Favorability: Glacial fill obscures much of the granitic rock in the Great Lakes region, but samples from Wapuca, Wisconsin, and Republic, Michigan, show high radioactivity (Malan and Sterling, 1972). Much additional sampling and geological reconnaissance work is required to delineate favorable areas for igneous uranium mineralization.

Northeast

Favorability:

1. High heat flow reflecting the high uranium content of certain New England granites; the heat flow data are interpreted to indicate high uranium contents extending to a depth of several km (Roy *et al.*, 1968)

2. Uraniferous granites (>10 ppm) at Conway, N.H., and Quincy, Massachusetts (Appendix 2)

3. Similarities between components of the White Mt. magma series and the alkali granites at the Bokan Mt. and Kaffo Valley uranium deposits (Ch. 2, Appendix 1).

4. Similarities between the geology of parts of the Adirondacks in New York and the Haliburton-Bancroft area of Ontario.

Prospecting guides:

1. The border zones of uraniferous granites are favorable sites for pegmatite and hydrothermal-metasomatic uranium mineralization. At Bokan Mt. and Kaffo Valley, uranium mineralization is associated with

albitization, so an emphasis on identifying albitized zones of the New England granites is warranted.

Southwest

Favorability:

1. Precambrian igneous (5.1 ppm e U_3O_8) and metamorphic rocks (9.2 ppm e U_3O_8) west of 114°W in the southwestern U.S. are anomalously high in uranium and thorium (Malan and Sterling, 1969), delineating a region of uranium-rich crust.

2. Abundance of secondary uranium minerals in veins and contact zones in the vicinity of granite intrusives in parts of Kern and San Bernadino counties.

Prospecting guides :

1. At Ord Mts., San Bernardino County, California, uraniferous veins and stringers of quartz and pegmatites occur in a granite-quartz monzonite-diorite series (Diblee, 1964). This and other secondarily mineralized plutons might be good areas to look for significant vein or autometasomatic uranium deposits.

Southern and Eastern U.S.

Relatively little radiometric work on igneous rocks has been completed in this section of the U.S. No uraniferous granites are known in the central and southern Appalachians, although scattered dikes bearing uranium, thorium and rare-earth minerals do occur in the Spruce Pine district. Other possible sources of disseminated igneous uranium in North Carolina are located near the Grandfather Mountain Window in the Blue Ridge.

SUPPLEMENTARY EXPLORATION METHODS

In addition to the usual field geological, petrological, geochemical, aeroradiometric and other routinely collected forms of data considered in exploration for uranium in igneous rocks, the following supplementary information may be useful in delineating potential areas of igneous uranium minerlaization:

1. Heat Flow: In regions that have not been tectonically active or subjected to recent hydrothermal activity, high heat flow may indicate crustal enrichment in uranium. Correlations of heat flow to the crustal concentrations of radioactive heat-producing elements (U, Th, K) are discussed by Sclater and Francheteau (1970) among others.

2. LANDSAT imagery: Computer enhancement of multispectral data from LANSDAT images has been considered as a possible method of discriminating areas of hematite and limonite alteration around sedimentary uranium deposits (Offield, in press). At Rössing, ore grade alaskites are often red-altered by hematite stains. It is possible that LANDSAT images could also be used to discriminate similar alteration zones around granites of known or predicted uranium potential. The resolving power of the method is approximately 60 meters.

3. Geochemical data: According to Semenov (1974), high concentrations of disseminated uranium in alkaline rocks appear to be correlative to high values (greater than 1.3) of the ratio of molecular $\frac{(Na_2O + K_2O)}{Al_2O_3}$. Geochemical data are not presently available to determine whether granites hosting uranium deposits have characteristic elemental associations or ratios. Data are needed on the concentrations of Zr, Fl, Mo, and many other trace elements, plus major elements in granites that contain uranium deposits.

4. Strontium isotopes: It has been suggested that crustal anatexis may be a critical process in the formation of Rössing-type deposits. Granites formed by anatexis should have relatively high $^{87}Sr/^{86}Sr$ initial ratios (>.710) in contrast to the low (.702-.706) ratios of magmas derived from the upper mantle. Alaskitic granites at Rössing ($^{87}Sr/^{86}Sr$ initial ratio > .730) and Type Y granites in the Athabasca region ($^{87}Sr/^{86}Sr$ initial ratio = .736) (Beck, 1969; 1970) have inordinately high strontium isotope ratios; however, this form of data is lacking for other pegmatite-alaskite-gneiss uranium deposits.

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APPENDIX 1

URANIUM DEPOSITS IN GRANITES, PEGMATITES AND MIGMATITES

Section 1 United States

Section 1.1 Alaska

Section 1.1.1 West-Central Alaska

This discussion of west-central Alaska is primarily concerned with the Alkaline Intrusive Belt, including the Selawik Basin area and the Southeastern Seward Peninsula.

Section 1.1.1.1 Location

The belt extends in a southeastwardly concave arc from near 154^{o}W and 66^{o}N in west-central Alaska to about 163^{o}W and 64^{o}N, which is on the Bering Sea.

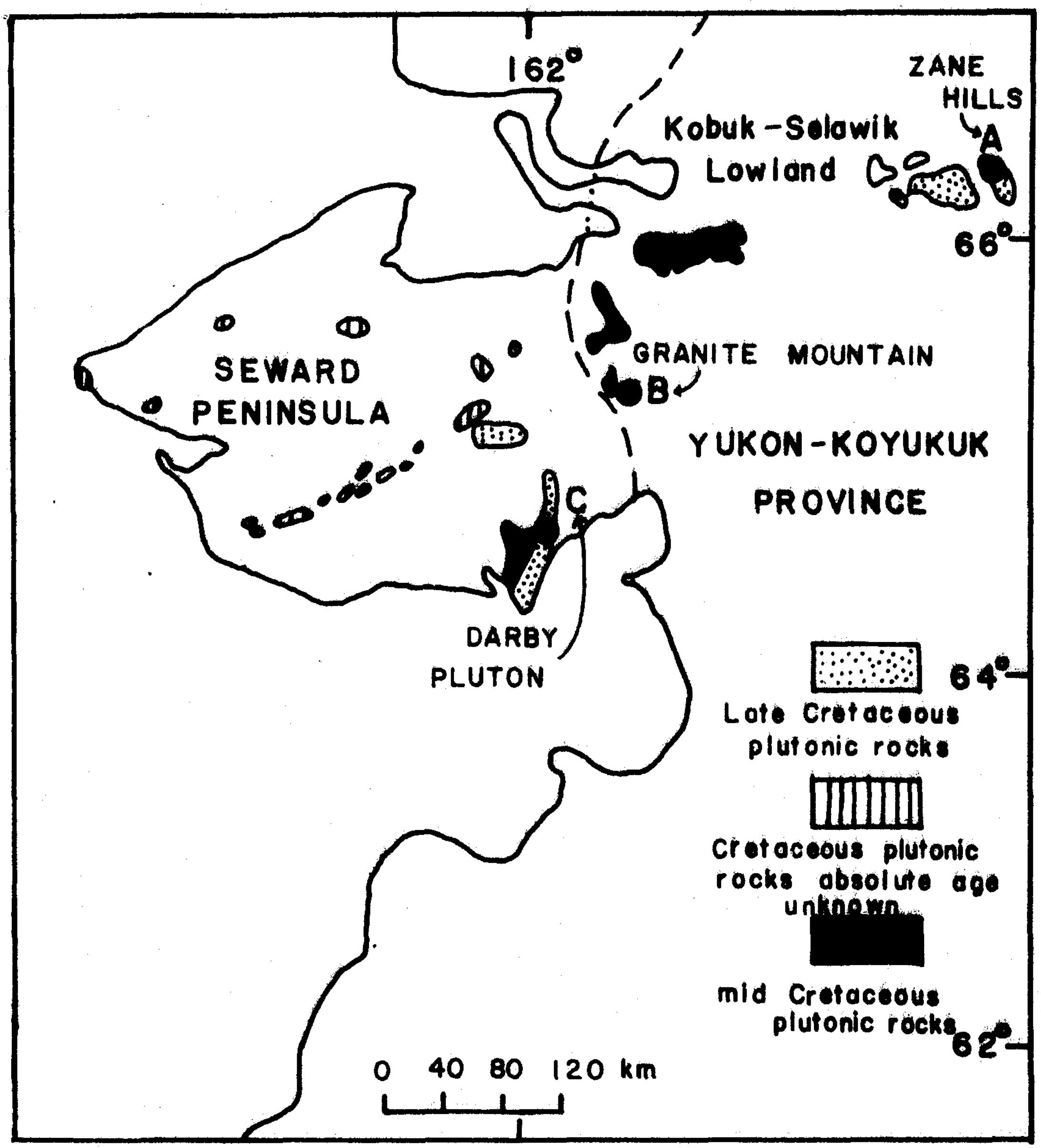
Section 1.1.1.2 Regional Geology

The belt of alkaline plutons cuts across two major geologic provinces in the east and the Seward Peninsula province in the west (Figure A-1). From the published descriptions (Miller, 1972; Eakins, 1975), the belt does not appear to be associated with any definable orogenic episode. The eastern Yukon-Koyukuk province is characterized by andesitic rocks of Late Mesozoic age that are overlain by eugeosynclinal sediments. The rocks are variably deformed but unmetamorphosed. The margin of the province is occupied by an ophiolite-type sequence of rocks of Late Paleozoic to Early Mesozoic age. This, along with the occurrence of thrust faults between the province and the Seward Peninsula province, implies the existence of a compressional orogeny previous to the time of alkaline intrusions. The Seward Peninsula is composed primarily of older metamorphics and sediments of Precambrian and Paleozoic age. It is likely that these lithologies

Location map for western Alaska

(Locations of intrusive rocks from Miller, 1972, Geological Society of America Bull., vol. 83)

Dashed line separates Yukon-Koyukuk Province from Seward Peninsula Province.



are part of a relatively stable continental region to the west that continues under the Bering Sea to Siberia.

The plutonic rocks represented in the alkaline belt are part of two major magmatic episodes occurring in the region during Early-Mid Cretaceous (∿100 m.y.) time in the west and later Cretaceous (80 m.y.) time to the east. The southeastern-most plutons on the Seward Peninsula appear somewhat younger than those to the north. Associated with the high-potassium alkaline rocks are other bodies of similar but more calc-alkaline character. These are considered as comagmatic members of the intrusive belt. In addition, there are innumerable dikes of alkaline character, both under-saturated and highly oversaturated with respect to silica.

As general characteristics, rocks of the belt occur in epizonal bodies; they are alkaline but not peralkaline (as aluminum values are not low). The earlier episode of intrusion produced the more alkalic magmas with lithologies including mafic syenites and monzonites, nepheline syenite, alkaline granite, quartz monzonite, and granodiorite. The younger plutons are more silicic and include granodiorite-quartz monzonite-alaskite series as well as minor monzonite and quartz syenite.

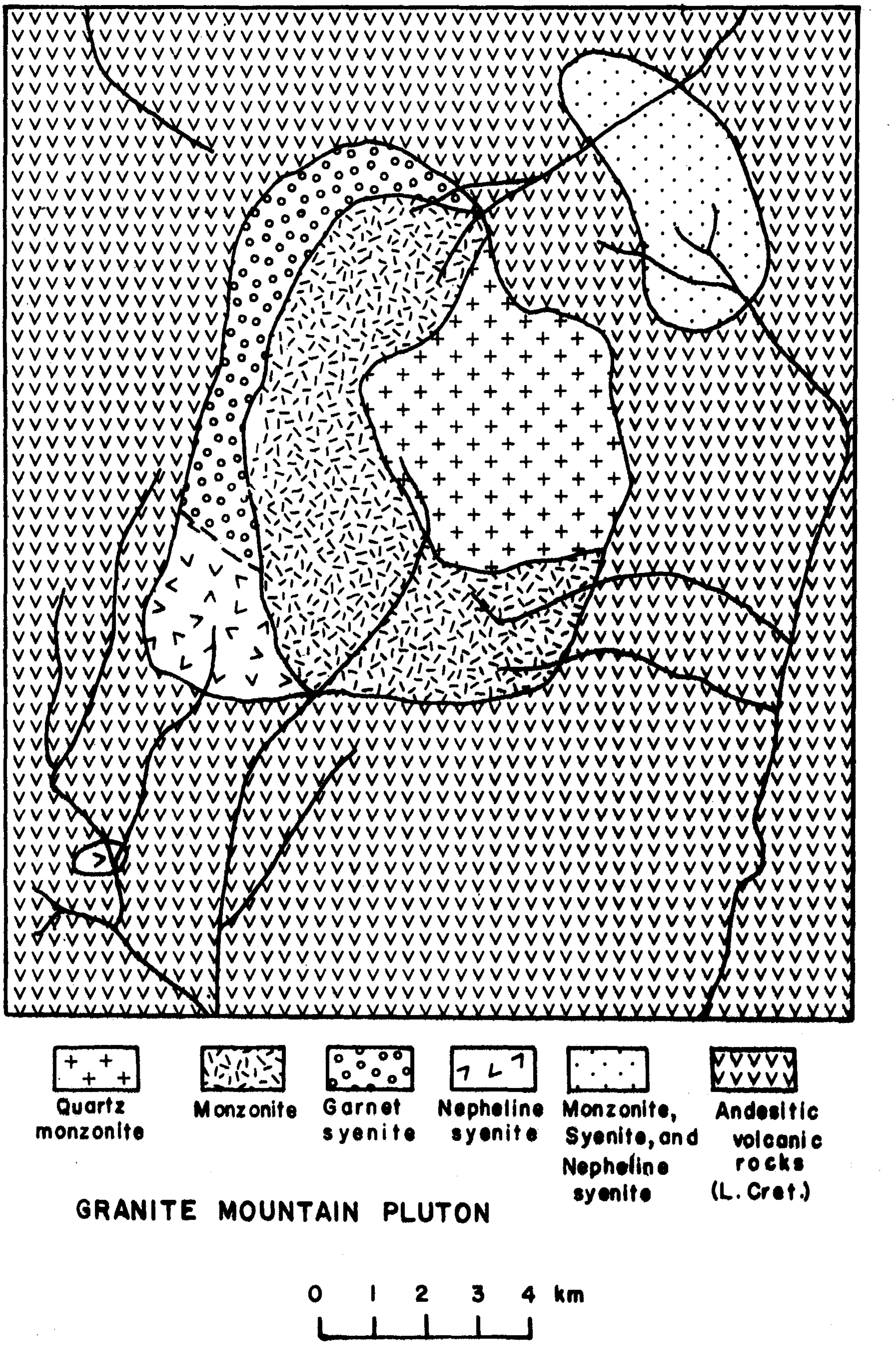
Although the intrusive belt in its entirety is of interesting uranium potential, a few of the most promising plutons deserve special attention.

Section 1.1.1.3 <u>The Granite Mountain Pluton</u>

Section 1.1.1.3.1 <u>Local Geology</u>

Discussions concerning the Granite Mountain pluton follow Miller (1972) and Eakins (1975). The Granite Mountain body (Figures A-1 and A-2) lies within the Yukon-Koyukuk volcanogenic province near its tectonic border with the Seward Peninsula Paleozoic sediments. The pluton is zoned,

Figure A-2



After Miller (1972); Geological Society of America Bulletin, v. 83.

circular and outcrops over nearly 70 km^2. There are four lithologic zones including a core of quartz monzonite that is roughly surrounded on three sides by texturally variable monzonite. The two outer zones are silica-undersaturated and are classified as nepheline-and garnet-syenites. Smaller satellitic bodies of nepheline syenite also occur southwest and northeast of the main pluton. The whole complex intruded lower Cretaceous andesites and in so doing produced a thermal aureole of albite-epidote- and hornblende-hornfels. Metasomatism is very minor. Andesite inclusions are observed throughout the body; however, no mineralization seems to have taken place as a result of contamination.

Unfortunately, no work has been done on determining the extent of possible uranium mineralization in this pluton or most of the others in the region.

The fundamental mineralogical constitution of the Granite Mountain pluton is presented in Table A-1. Note the presence of fluorite in the more silica-undersaturated zones.

K-Ar ages on the Granite Mountain rocks (Miller, 1972) are near 106 m.y. A lead- alpha of 100 $\pm$ 15 m.y. was also published. This body and the other alkaline intrusions in the western Yukon-Koyukuk province are of the oldest phase of Cretaceous magmatism.

Section 1.1.1.3.2 Uranium Mineralization and Potential

Due to the lack of radiometric investigations in the area, field reconnaissance studies and aeroradioactivity surveys have shown the only evidence of uranium potential. Uranium minerals were first discovered in the gravels around Granite Mountain during gold mining in the early 1900's. Aeroradiation and ground surveys indicate uranium anomalies of five times background occurring in nepheline syenite of the pluton and its satellites.

TABLE A-1

Table A-1

Petrography of Granite Mountain Pluton

After Miller (1972)

Quartz Monzonite.	Quartz, K-feldspar, plagioclase; 4% mafic minerals (mainly hornblende with minor biotite); accessory magnetite, zircon, allanite, sphene, and apatite; fine grained, equigranular, hypidiomorphic.
Monzonite.	K-feldspar and plagioclase with accessory quartz; up to 25% mafic minerals, mainly hornblende and pyroxene; accessory magnetite, sphene, and apatite; medium to coarse grained; outer part porphyritic and inner part equigranular.
Garnet Syenite.	K-feldspar and plagioclase with accessory nepheline; mafic minerals are garnet, hornblende, and pyroxene; accessory fluorite, magnetite, sphene, and apatite; medium grained, porphyritic to gneissic.
Nepheline Syenite. (Foyaite)	K-feldspar with minor plagioclase and nepheline; mafic minerals are garnet and hornblende; accessory fluorite, sphene, and apatite; slightly porphyritic; medium grained.

Uranium minerals found as placers (Eakins, 1975) were uranothorite and gummite. Fluorite, copper sulfides, iron oxides, molybdenite, thorite, native gold and silver, sphene and zircon were found with the uranium minerals.

Section 1.1.1.3.3 Areas of Similar Potential

Other plutons of similar chemistry and mineralogy are the Inland Lakes, Selawik Lake, Ekiek Creek, and Hunt alkaline intrusives. The larger (900 km^2) Selawik Hills pluton is of the same age and occurs in the same region but is characteristically more silica saturated, with syenites subordinate to monzonite and quartz monzonite. Many aeroradiation anomalies were discovered along the northern margin of this body.

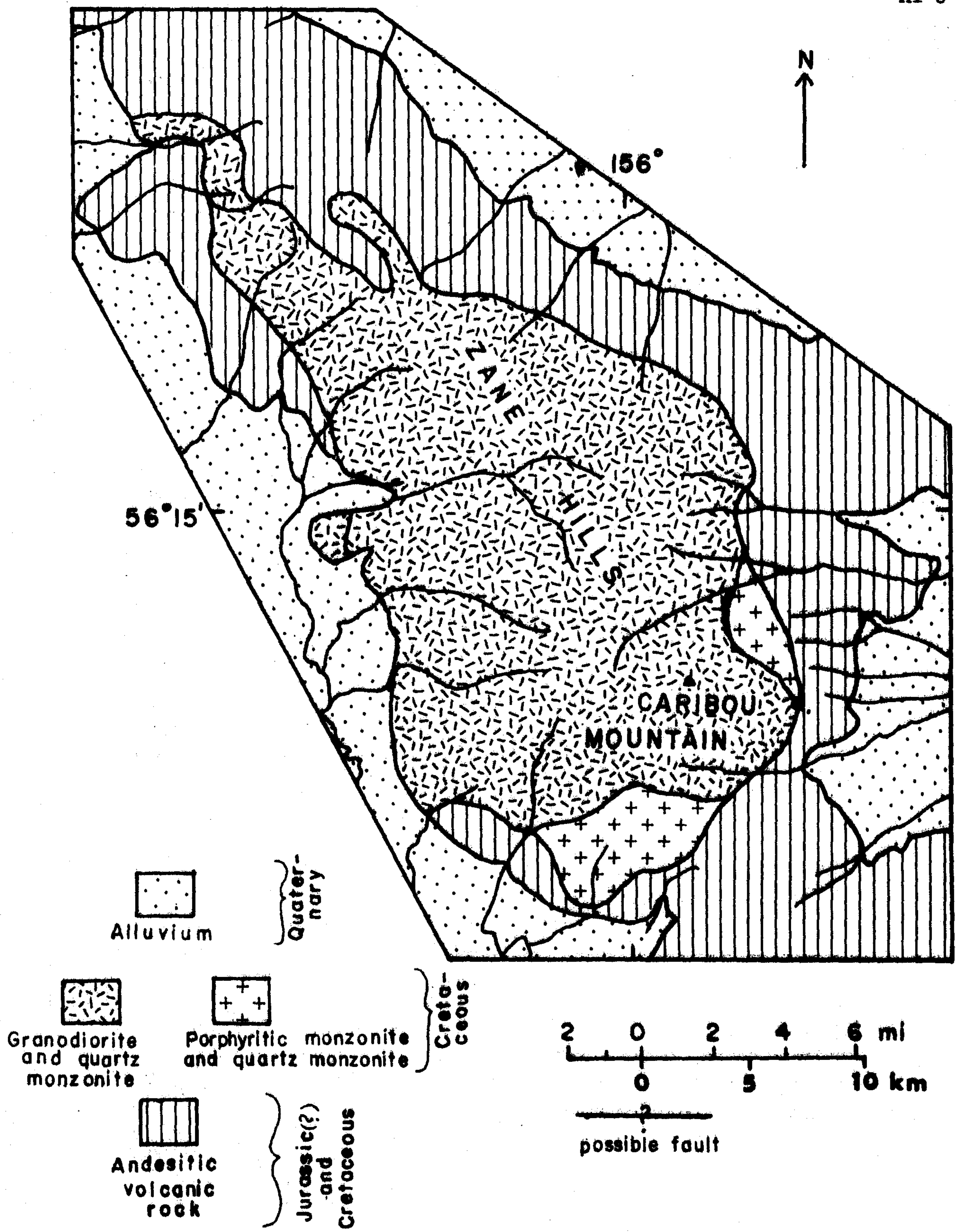
Section 1.1.1.4 The Zane Hills Pluton

Section 1.1.1.4.1 Local Geology

The Zane Hills pluton (Miller and Ferrians, 1968; Staatz and Miller, 1976) underlies an area of about 460 km^2 near 65°N and 156°W, which is in the easternmost group of alkaline plutons within the Yukon Koyukuk province (Figures A-1 and A-3). The country rock is the Early Cretaceous (Late Jurassic?) pyroxene andesite. The great majority of the body is composed of granodiorite, which locally grades into quartz monzonite. Monzonite and syenite comprise a small volume of the total pluton along the southern and southeastern margins. Alaskite and aplite dikes cut the pluton in several places. Additionally, there are a few quartz veins existing near contacts.

A K-Ar age of 80 m.y. for the Zane Hills (Staatz and Miller, 1976) places it in the episode of mid to late plutonism of the eastern Yukon-Koyukuk province. Similar intrusives in the area yield similar ages.

The predominant granodiorite of the pluton is medium-grained and equigranular. Mafic phases consist of primary biotite and hornblende.



GEOLOGIC MAP OF THE ZANE HILLS AREA

After Miller and Ferrians (1968)

The granodiorite grades into a quartz monzonite. Staatz and Miller (1976) describe the border phases of the pluton to be composed of hornblende-pyroxene monzonite and syenite, which are generally coarse-grained with gneissic or porphyritic textures. The aplites are characterized by the occurrence of tourmaline and are common in areas where dark-colored hybrid rocks have been produced from contamination of the intrusive magma by andesite. Conversely, potassium metasomatism has taken place in the andesite.

Section 1.1.1.4.2 Uranium Mineralization and Potential

Interest in the Zane Hills pluton as a potential uranium source stems from the identification of several anomalously radioactive areas within the border phases near Caribou Mountain (Figure A-3). Along the southeastern margin of the pluton samples were collected over 13 km^2 of the border phases. Table A-2 reflects the high uranium values of these rocks. The range of 11 to 129.5 ppm uranium are in eU units (equivalence of radon) as the assumed product of uranium decay. Actual uranium content, if measured, would be somewhat lower. However, this does not detract from the degree of enrichment obviously involved here. Samples from the southern radioactive border (Table A-2) were collected over an area of 25 km^2 and range from 14.5-32.9 ppm eU. Even the pluton's central granodiorite averages nearly 7 ppm uranium, which is indicative of the overall enrichment of the Zane Hills pluton as a uranium source.

Uranium-bearing minerals present include: allanite (nearly ubiquitous in samples), uranothorianite, thorite, betafite, zircons (highly concentrated within biotite and hornblende), and sphene. Other important accessory minerals include: pyrite, goethite, lepidocrocite, molybdenite, garnet, and chlorite.

TABLE A-2

URANIUM, THORIUM AND POTASSIUM CONTENT OF SELECTED GRAB SAMPLES FROM THE RADIOACTIVE PHASES OF THE ZANE HILLS PLUTON
After Miller and Ferrians (1968)

Sample No.	RaeU (ppm)	Th(ppm)	K(percent)	Description
		Southeastern phase		
A-1-74	23.12	117.3	6.11	Fine-grained gneissic monzonite
A-2-74	129.5	188.8	4.40	Aplitic dike
A-3-74	11.09	81.94	6.43	Medium-grained gneissic monzonite
A-4-74	40.25	83.23	5.41	Medium-grained gneissic monzonite
A-5-74	47.79	100.6	7.83	Coarse-grained gneissic monzonite
A-8-74	98.50	179.8	4.96	Medium-grained gneissic monzonite
67AMm150	26.07	46.10	5.67	Coarse-grained gneissic monzonite
67AMm150	45.06	268.85	5.94	Fine-grained gneissic monzonite
67AMm150	32.32	69.93	4.91	Coarse-grained gneissic monzonite
67AMm151	25.08	106.82	5.14	Coarse-grained gneissic monzonite
67AMm151	33.68	167.86	5.51	Fine-grained gneissic monzonite
		Southern phase		
67AMm246	22.47	117.61	4.86	Dioritic gneiss
67AMm256	14.48	75.17	4.01	Medium-grained, porphyritic gneissic monzonite
67AMm259	32.94	135.0	4.65	

Also located within the same general province with the Zane Hills body are other plutons of the later magmatic episode. These include the Wheeler Creek, Mount George, Indian Mountain, and McLanes Creek bodies. Because of the similarities among all these bodies, it follows that their uranium potential may be as great as that of the Zane Hills pluton.

Section 1.1.1.5 The Darby Pluton

Section 1.1.1.5.1 Local Geology

The Darby pluton (Miller and Bunker, 1976) is a long, thin body that covers an area of about 400 km^2 in the eastern Darby Mountains of southeastern Seward Peninsula (Figures A-1 and A-4). The pluton constitutes a homogeneous mass of quartz monzonite not unlike other granitic stocks in the region. Tourmaline-bearing aplites occur throughout the pluton. Lamprophyre dikes are massed near the southern contact of the quartz monzonite with metasediments. Stratigraphy of the country rock is presented in Table A-3. This stratigraphy is generally applicable to most of the southeastern peninsular region. The oldest rocks found near the Darby pluton are Precambrian schists and gneisses with minor marbles and calc-silicates. These rocks are mostly in the greenschist facies, but higher-grade metamorphics do exist. Extensive faulting along the eastern margin of the Seward Peninsula province has juxtaposed Paleozoic carbonates against the older rocks. Faults appear to bound the Darby pluton on its eastern border. No important contact effects with the country rock have been mentioned for the igneous rocks.

Quartz monzonite is the only major rock type represented in the Darby intrusive. Texturally, the rocks are typically coarse-grained and porphyritic. Phenocrysts are large, pink perthitic feldspars. Mafic

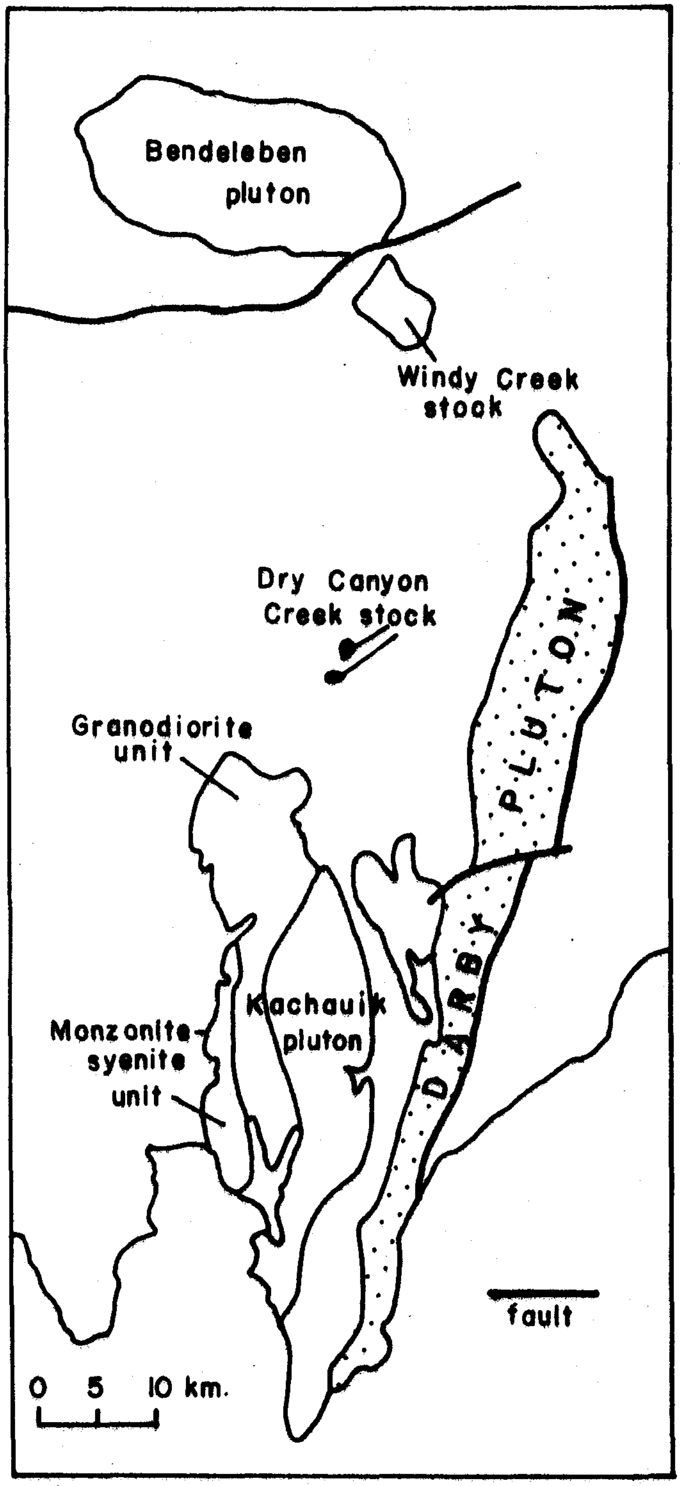


Figure A-4

Geology of the Darby Pluton Area
After Miller and Bunker (1976)

TABLE A-3

STRATIGRAPHIC COLUMN OF ROCKS EXPOSED IN THE CENTRAL YORK MOUNTAINS, WESTERN SEWARD PENINSULA
After Miller and Bunker (1976)

Age	Unit	Thickness (feet)	Description
Quaternary	Cal	Variable	Includes alluvium, terrace gravels, glacial moraines, outwash gravel, talus cones and beach deposits, all of which occur on all geomorphic units older than Recent in age
Quaternary	Qpc	10-110	Conglomerate on the York terrace lower part of marine origin, upper part of continental origin
			UNCONFORMITY
Late Cretaceous to early Tertiary	TKd	Dikes and plugs	Dikes, including lamprophyre, diabase, rhyolite, quartz-porphyry and andesite
Late Cretaceous to early Tertiary	TKg	Stocks	Medium- to coarse-grained biotite granite
Early to Middle Ordovician	Odl	At least 1250	Principally medium-gray to dark-gray, medium-bedded fossiliferous limestone
			FAULT
Early to Middle Ordovician	Oshl	At least 2400	At base, black shale and siltstone; grades upward to black, augary-textured limestone, and thence to medium-gray to dark-gray limestone, largely dolomitized
Early to Middle Ordovician	Ol	Probably 6500	Massive to thick-bedded micritic limestone containing chert nodules locally, and subordinate interbeds of thin-bedded, argillaceous limestone
Early to Middle Ordovician	Cal	Possibly 4500	Thin-bedded argillaceous and silty limestone, dolomitic limestone and carbonaceous limestone, with subordinate interbeds of massive limestone
			FAULT
pre-Ordovician	pOg	Plugs, sills, dikes	Medium- to coarse-grained gabbro
pre-Ordovician	pOal	Several hundred	Thin-bedded argillaceous and dolomitic limestone, silty limestone, and shaly limestone that contains numerous veins and veinlets of quartz and carbonate
pre-Ordovician	pOa	Undetermined	Includes slate, phyllite, slaty limestone, siltstone, graywacke, and minor argillaceous limestone, all moderately to intensely deformed

phases make up 5-10% of the rock with biotite dominant over hornblende. These minerals are unaligned and the resulting rock is nonfoliated. Miller and Bunker (1975) mention the occurrence of mafic inclusions in the pluton. However, these may be restricted to certain positions in the body.

Any alteration processes affecting the rocks have left only minor results, such as slight sericitization and oxidation. A high oxidation factor is indicated by large Fe_2O_3/FeO ratios (Table A-4). High SiO_2 and K_2O values are also very characteristic. Chemically, the Darby rocks are very nearly granitic, in opposition to the quartz monzonite classification based on mineralogy.

Biotite mineral ages using K-Ar techniques (Miller and Bunker, 1976) have yielded ages of 92.1 $\pm$ 2.8 and 94.0 $\pm$ 3 m.y. Additional ages of 92.8 $\pm$ 2.6 and 88.3 $\pm$ 1.5 m.y. were obtained from a coexisting hornblende and biotite, respectively. These ages roughly correspond with those of the Zane Hills and related granitic rocks.

Section 1.1.1.5.2 Uranium Mineralization and Potential

Of the three major plutonic bodies in the Southeastern Seward region, the Darby is the only one with an average uranium content above 10 ppm (11.2 ppm, Table A-5; from Miller and Bunker, 1975). The anomalous radioactivity measured in the pluton is not restricted to any one part but appears to be characteristic of the entire mass. The highest values for uranium were reported for the northern area west of Vulcan Creek. The mineral phases responsible for the anomalies do not seem to be highly segregated; on the contrary, they are most likely present as disseminated phases.

Uranium-bearing minerals present include: an unidentified uranium-bearing niobate, allanite, sphene, and zircon. Important accessory minerals include: magnetite, rutile, and fluorite.

TABLE A-4

AVERAGE MAJOR ELEMENT COMPOSITION
OF THE DARBY PLUTON
After Miller and Bunker (1976)

	Avg.	Range
SiO_3	71.5	68.8 - 74.1
Al_2O_3	14.6	13.5 - 15.7
Fe_2O_3	1.05	.66- 1.5
FeO	.97	.60- 1.7
MgO	.53	.28 - .90
CaO	1.5	1.1 - 2.2
Na_2O	3.55	3.1 - 3.9
K_2O	4.97	4.7 - 5.4
H_2O+	.50	.31- .75
H_2O-	.15	.08- .23
TiO_3	.24	.12- .37
P_2O_5	.10	.04- .18
MnO	.05	.00- .10
CO_2	.02	.01- .08
Fe_2O_3/FeO	1.08	-----------

TABLE A-5

URANIUM AND THORIUM DATA FROM THE DARBY PLUTON

After Miller and Bunker (1976)

Sample	Field No.	U (ppm)	Th (ppm)	K (percent)	Heat (μcal/g·yr)	Th/U	U/K×10-	Th/K×10-
D1	68AMm276	7.92	55.15	4.31	17.98	6.96	1.84	12.80
D2	71AMm409	10.29	51.92	3.86	18.94	5.05	2.67	13.45
D3	70AMm212	19.89	83.75	4.08	32.37	4.21	4.88	20.53
D4	71AMm421	17.73	68.80	3.73	27.71	3.88	4.75	18.45
D5	70AMm186A	10.36	64.65	3.72	21.50	6.24	2.78	17.38
D6	70AMm160B	13.50	50.76	4.19	21.24	3.76	3.22	12.11
D7	70AMm160A	8.81	48.77	4.54	17.41	5.54	1.94	10.74
D8	70AMm161	6.18	54.89	4.39	16.67	8.88	1.41	12.50
D9	70AMm159B	7.02	55.16	4.23	17.30	7.86	1.66	13.04
D10	70AMm146	11.71	66.58	4.11	22.97	5.69	2.85	16.20
D11	70AMm145	8.33	68.58	4.02	20.88	8.23	2.07	17.06
D12	70AMm210	9.32	40.84	3.99	16.05	4.38	2.34	10.24
D13	70AMm225	14.61	52.92	3.92	22.31	3.62	3.73	13.50
Average		11.2	58.7	4.08	21.0	5.2	2.78	14.46
Range		6.18-19.89	40.84-83.75	3.72-4.54	16.05-32.37	3.62-8.88	1.41-4.88	10.24-20.53

In the southern end of the plutonic belt on the Seward Peninsula, there are several other alkaline and granitic bodies that are possible uranium source rocks. The felsic dike rocks in the region should not be overlooked for their potential. The small Windy Creek pluton, northwest of the Darby, contains fluorite and various metal anomalies (Au, Mo, Pb, and An); the Serpentine Hot Springs granite, further to the northwest of the Darby pluton, possesses aeroradiation anomalies and average 80 ppm eU. Uranium minerals have been identified from placer concentrates in the following bodies as well: the Kachanik, Brooks Mountain, Ear Mountain, and Kigluaik Mountains pluton.

Section 1.1.2 Bokan Mountain and Vicinity

Section 1.1.2.1 Location

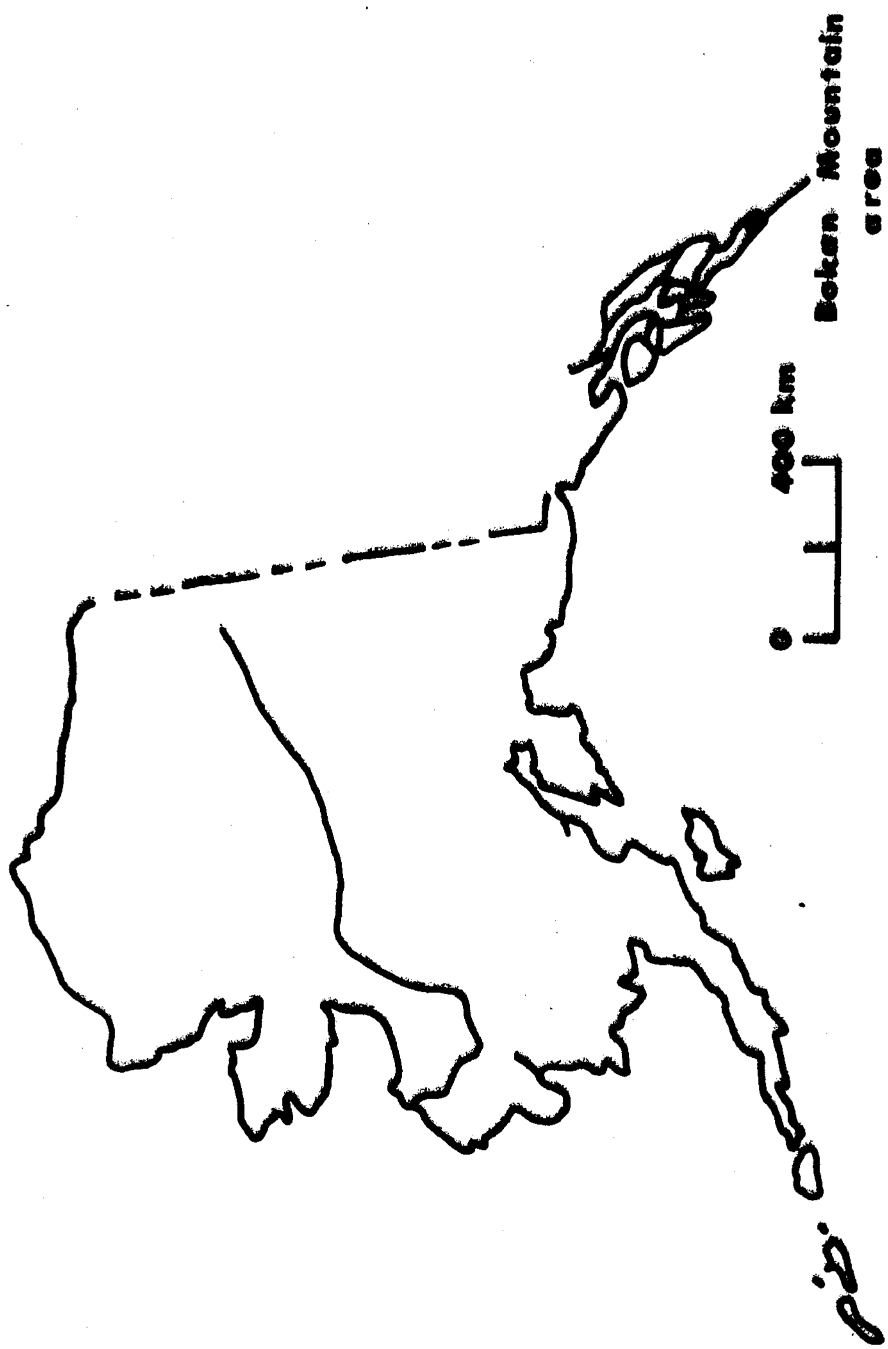
The Bokan Mountain uranium district (about 220 km^2) is located on the southern end of Prince of Wales Island at 54°55'N and 132°10'W. This is the southernmost tip of the Alaskan panhandle where Alaska borders British Columbia and the Pacific Ocean (Figure A-5).

Section 1.1.2.2 Regional Geology

The igneous rocks associated with uranium mineralization at Bokan Mountain (MacKevett, 1963) appear to be uniquely situated in this region of the western North American cordillera. The northwest-trending belt of rocks, which includes Prince of Wales Island, contains many intrusive rocks ranging in composition from ultramafics to highly differentiated felsic plutons. Dioritic and granodioritic intrusives are dominant. The peralkaline granite and syenite observed at Bokan Mountain have not been reported elsewhere in the belt or in rocks to the east. Ages of the intrusives range from Early Paleozoic (?) to at least Early Mesozoic

Figure A-5

Locality of Bokan Mountain Area



Plutons were intruded into deformed volcanics and sediments that were metamorphosed to upper greenschist-lower amphibolite grade. Stratigraphic relations indicate that the volcanics, ranging from mafic andesites to quartz keratophyres, were deposited first as flows and tuffs. A basal clastic unit includes volcanic breccias and conglomerates with limestone cobbles. Typical eugeosynclinal sediments including graywacke, shales, and conglomerates followed volcanism. The last rocks deposited before plutonism ensued were carbonates; this may have indicated a return to more stable tectonic conditions. Through metamorphism, the volcanics were converted primarily to greenstones. The early sediments were converted to slates, impure quartzites, mafic schists and gneisses, and amphibolites; the carbonates became marbles and calc-silicate rocks. Intrusion further modified the rocks by forming hornfels in contact with carbonates and slates. Metamorphic foliation is variably developed, with the best pronounced foliation seen in the schist units. Intrusive contacts are usually conformable with the foliation, which implies either intrusion contemporaneous with deformation or that the plutons were emplaced along tectonic weaknesses.

The metavolcanics and metasediments have been correlated with unmetamorphosed rocks to the north (Buddington and Chapin, 1929). The Devonian age of the sediments and their lack of metamorphic effects make the comparison unlikely. In fact, this whole section of the Cordillera is very complex structurally. The metamorphics and sediments are interrupted and repeated by large-scale folding. Faulting exists on two scales, locally in the Bokan Mountain area and regionally in large thrusts and shears.

To the east of the belt that includes Bokan Mountain there is another linear tectonic unit containing thick accumulations of Mesozoic volcanics and sediments. It is possible that these two zones are separated by a regional fault of some type. Beyond the Mesozoic deposits to the east lies the mainland Coast Range batholith. It was initially believed that the western belt of intrusives was satellitic to the batholith; however, the ages do not correlate.

Undoubtedly, the Cordilleran continental margin in this area has undergone multiple orogenies, resulting in the formation of belts representing distinct episodes of magmatism and deposition. The relationship between uranium mineralization and orogenesis is not clear in this case, but it appears as though Bokan Mountain was an isolated source of uranium with few or no contemporaries. Minor uranium showings and anomalies have been discovered elsewhere near the western islands and associated with plutons, but nothing of the character of Bokan is known anywhere in the region.

Section 1.1.2.3 The Bokan Mountain Area

Section 1.1.2.3.1 Local Geology

The plutonic rocks that are exposed in the Bokan Mountain area (Figure A-6) are separated into two periods of intrusion (Lanphere et al., 1964). The first group includes (in decreasing age), augite pyroxenite, augite gabbro, diorite, quartz diorite, granodiorite-quartz monzonite, and gneissic quartz monzonite. Syenite and a later peralkaline granite were intruded through the older series of intrusives. Aplites and pegmatites are abundant in and around the 9 km^2 area of the peralkaline granite stock. The dikes are late-stage differentiates comagmatic with the granite. The first episode of magmatism also produced felsic dikes, but these are sparsely distributed throughout the area. Other dikes of unknown origin include andesite porphyries, dacite, rhyolite, and diabase. Diabase is evidently the youngest magma represented as it occurs in dikes intrusive into all other lithologies.

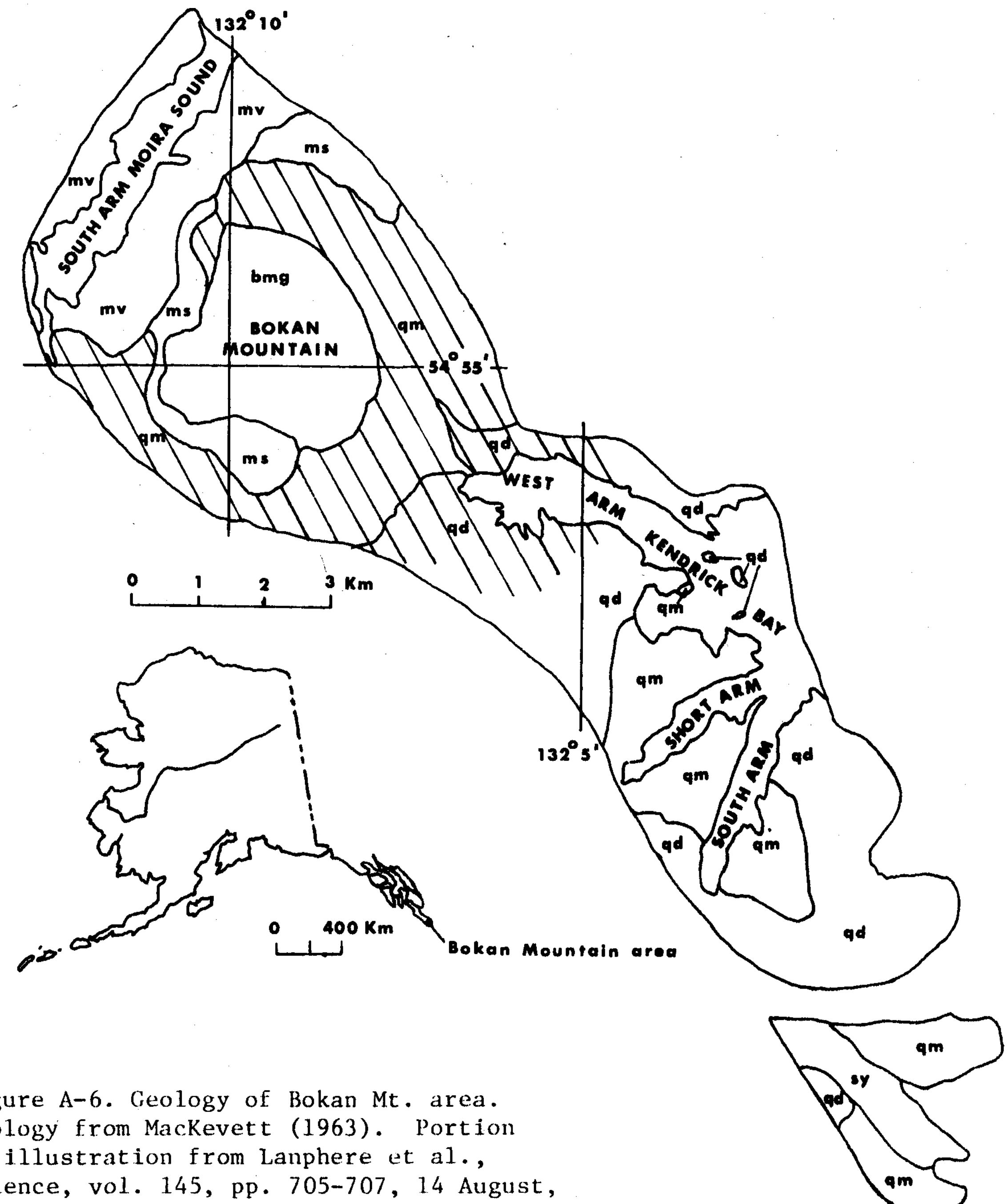


Figure A-6. Geology of Bokan Mt. area. Geology from MacKevett (1963). Portion of illustration from Lanphere et al., Science, vol. 145, pp. 705-707, 14 August, 1964, Figure 1. Copyright 1964 by American Association for the Advancement of Science.

Generalized outcrop patterns of rock units are depicted in Figure A-6. The granite, known as the Bokan Mountain granite, forms a circular stock-like body surrounded by quartz monzonite and metasediments. Quartz monzonite and quartz diorite near the contact with the granite have been albitized. Small-scale faulting and fracturing in addition to the chemical alteration are very common within the albitization aureole. Uranium mineralization is directly associated with the peralkaline granite, the related aplites and pegmatites, and the albitization process.

Section 1.1.2.3.2 Petrography

The earlier magma series (if it is one series) may have started with the formation of the pyroxenite. MacKevett (1963) believed the pyroxenite was an older intrusion separate from the rest. However, the basic mineralogy of augite + hornblende $\pm$ biotite with lesser amounts of plagioclase and magnetite is different from the later gabbros and diorites only in mineral percentages. With increased differentiation, amphibole, biotite and quartz become more abundant. With extreme differentiation, potassium feldspar, andesine, quartz and minor biotite coexist together in the quartz monzonites. In albitized zones the overall silica content is increased. The category of gneissic quartz monzonite is so named because of the cataclastic foliation observed in these rocks in and near the albitized zones. Characteristic features are the foliation, the scarcity of mafics, and the abundance of cross-cutting quartz veins.

The aplites of the younger series include rocks that could be called alaskites. The usual fine-grained texture of the dikes can change over short distances into pegmatites. Mineralogy includes: abundant quartz, potassium feldspar, $\pm$ biotite, $\pm$ fluorite, $\pm$ albite, $\pm$ riebeckite. Primary uranium mineral disseminations are present in the aplites as well as the correlative pegmatites. Like the aplites, the pegmatites may be as much as 1.5 km in length but only a few meters in maximum width. Quartz + perthite is the dominant assemblage in the pegmatites, but many accessory minerals may also be present.

The Bokan Mountain granite itself must be considered the major source of magmatic uranium in the immediate district. Textures are variable from coarse- to fine-grained, and include porphyritic, cataclastic, hypidiomorphic granular, and xenomorphic granular. This is a light colored rock with 10% or less mafic minerals, of which riebeckite is more common than acmite, but both may occur together. The granite is very silica-rich, as is reflected in a high quartz content. Feldspars average about 60% of the rock, and the potassium-bearing feldspars are highly dominant over albite. The primary potassium feldspar is an intermediate microcline that has been overgrown rapakivi-style by second stage microperthite that contains a high percentage of sodium. Accessory minerals include: zircon, xenotime, fluorite, uranothorite, and cordierite. Micas are absent in the fresh rock but may occur where alteration has taken place. In the vicinity of uranium mineralization and within the granite, quartz content drops. The syenite of the district is believed to be temporally related to the granite (MacKevett, 1963) and perhaps of the same parental magma. Syenite occurs only in the southern extreme of the area and is isolated from the granite. In places, the rock grades into a monzonite. All rocks are cut by the syenite with the exception of a few aplites. The syenite is usually a pinkish rock owing to the high abundance of potassium feldspar, which may constitute over 90% of the mineral grains in a given hand specimen. Biotite, plagioclase, minor quartz, and rarely garnet constitute most of the remainder. Uranium minerals or other interesting accessories are very rarely present in trace amounts.

Section 1.1.2.3.3 Age

According to Lanphere and MacKevett (1964), the existence of two separate magma suites is supported by K-Ar age dating. Ages of 181 ± 8 and 186 ± 8 m.y. were obtained from two riebeckites from the Bokan Mountain granite. Hornblendes were analyzed from the quartz monzonite and quartz diorite; respective ages of 431 ± 21 and 446 ± 2 m.y. were obtained. An additional biotite age of 373 ±18 m.y. for the quartz monzonite is reasonable considering a probable argon loss in the biotite. These results strongly suggest that the granite and related rocks were intruded during Early Jurassic into a sequence of Early Paleozoic plutonics. Consequently, the preexisting volcanics and metasediments are at least Early Ordovician deposits. These ages are some of the oldest known for intrusives within the western North American Cordillera.

Section 1.1.2.3.4 Igneous Petrogenesis

There is at present no way to determine if the two magma series are more than spatially related. Ages tend to negate the possibility. It is also difficult to place the plutons in any tectonic framework. The Early Paleozoic bodies have no real contemporaries in the region. This may be due to lack of data, however. The Jurassic plutons could conceivably be related to the major Coast Range batholith. More information is very important in an understanding of the region, especially in any systematic search for mineral deposits.

As discussed by MacKevett (1963), the first magma series appears to be a differentiation sequence with progressively more felsic rocks being produced. Cross-cutting field relations verify the relative ages. Due to mineralogy and other similarities, the pyroxenite is considered as the oldest member of the series. Overall major element chemistry (Table A-6) classifies this as a typical calc-alkaline series without any unusual aspects. The peralkaline granite and syenite are of a very different nature.

Because of the lack of chemical variation, aside from differences between granites and syenites, there can be no real classification of the later intrusives into a particular magmatic rock series. The processes by which these two rock types were derived could be quite different. The peralkaline granite is high in sodium and silica, whereas the syenite is only silica-saturated and possesses high potassium contents. It is likely that one or both of these lithologies were produced in a multistage magmatic scheme more complex than the earlier differentiation series. In the granitic magma late, relatively low-temperature, fluids formed the aplites and pegmatites and may also have been responsible for albitization and the concentration of uranium minerals.

Section 1.1.2.3.5 Ore-Host Rock Relations

Four types of uranium deposits have been recognized by MacKevett (1963) for the Bokan Mountain district.

1) Primary disseminations and segregations of uranium minerals in the peralkaline granite. It appears that the minerals became more concentrated in the later phases of crystallization, possibly as a result of magmatic hydrothermal activity.
2) Primary mineralization (syngenetic) in the aplites and pegmatites associated with the granite.
3) Secondary hydrothermal deposition (epigenetic) in veins and fractures with some replacement.

TABLE A-6

MAJOR ELEMENT ANALYSES OF THE BOKAN MOUNTAIN ROCKS
from MacKevett (1963)

Chemical analyses and norms of the plutonic rocks

[Analysts, P. L. D. Elmore, S. D. Botts, H. H. Thomas, and M. D. Mack, U.S. Geol. Survey, 1958]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Analyses (weight percent)																	
SiO_2	52.6	46.0	46.4	55.1	66.8	68.6	66.6	61.6	76.9	74.6	63.1	62.1	73.4	74.1	73.6	74.6	73.8
Al_2O_3	18.4	19.2	16.9	17.8	16.6	15.2	16.5	16.7	12.9	13.6	17.9	18.9	11.0	12.3	11.6	11.9	11.5
Fe_2O_3	3.2	3.8	4.1	2.7	1.0	1.5	1.4	1.9	.3	.1	1.3	1.0	3.6	1.5	2.1	1.2	2.6
FeO	4.9	8.8	7.2	5.2	1.7	1.8	1.9	3.0	.9	1.5	1.3	1.2	1.8	2.0	2.5	2.5	2.5
MgO	4.8	3.9	7.4	3.3	.82	1.4	1.2	2.6	.30	.76	.65	.42	<.05	<.05	<.05	.09	.08
CaO	9.5	10.2	11.5	6.1	3.6	3.5	4.6	5.0	.62	1.0	1.2	1.4	<.05	<.05	<.05	.27	.14
Na_2O	3.6	2.8	1.6	4.0	4.6	3.4	4.2	4.0	4.6	4.5	5.7	6.3	4.5	4.8	4.9	4.9	5.0
K_2O	.74	.42	1.1	1.9	1.5	3.2	2.1	2.3	2.8	2.6	6.7	5.3	4.6	4.7	4.5	4.1	4.2
H_2O	.94	2.1	2.0	1.9	.82	.92	.83	1.0	.52	.90	.58	.54	.35	.38	.37	.46	.31
TiO_2	.96	1.2	1.0	.98	.36	.32	.36	.54	.14	.20	.44	.16	.20	.15	.14	.12	.12
P_2O_5	.24	.23	.05	.35	.14	.10	.11	.17	.05	.02	.06	.06	.00	.00	.00	.01	.00
MnO	.17	.22	.22	.20	.12	.08	.07	.10	.02	.06	.08	.08	.05	.08	.10	.10	.10
CO_2	<.05	<.05	<.05	.36	<.05	<.05	<.05	<.05	<.05	.11	.90	1.4	.26	.29	.26	<.05	<.05
Sum	98.6	98.9	98.5	99.9	100.1	100.1	99.9	99.9	100.1	99.7	99.9	98.9	99.9	100.4	100.2	100.3	100.4
Specific gravity	2.86	2.92	2.98	2.82	2.70	2.70	2.72	2.76	2.63	2.62	2.64	2.58	....	2.66	2.66	2.68	2.72
Norms (weight percent)																	
Q	2.22	....	....	5.40	26.82	26.46	22.56	13.56	37.14	34.20	1.38	1.32	30.06	27.60	27.36	28.38	28.14
or	4.45	2.22	6.67	11.12	8.90	18.90	12.23	13.34	16.68	15.01	39.46	31.14	27.24	27.80	26.69	24.46	25.02
ab	30.39	23.88	13.62	34.06	38.77	28.82	35.63	34.06	38.77	38.25	48.21	53.45	30.92	37.20	34.58	38.25	35.63
an	31.69	38.64	35.88	26.02	16.96	16.66	20.02	30.85	3.06	5.00	3.34	6.12	....	....	....	....	....
C	....	....	....	....	1.22	....	....	....	1.12	1.43	....	.51	....	....	....	....	....
di	11.06	8.96	17.24	2.26	....	....	1.57	5.96	....	....	1.33	....	....	....		1.24	.75
hy	12.02	4.56	10.88	13.14	4.28	5.22	3.96	6.84	1.90	4.14	1.63	2.42	1.55	3.27	4.59	4.27	4.01
ac	....	....	....	....	....	....	....	....	....	....	....	....	6.47	2.77	6.01	2.77	6.01
ol	....	8.47	7.41	....	....	....	....	....	....	....	....	....	....	....	....	....	....
il	1.37	2.28	1.98	1.88	.61	.61	.76	1.06	.30	.46	.76	.30	.46	.30	.30	.15	.15
mt	3.25	8.35	6.96	3.94	1.39	2.09	2.09	2.78	.46	.23	1.86	1.39	2.09	.70	....	.46	.70
ap	.34	.34	....	1.01	.34	.34	.34	.34	....	....	.34	.34	....	....	....	....	....

1. Hornblende quartz diorite, 8,800 ft S. 22° E. of loading dock on West Arm of Kendrick Bay.
2. Hornblende diorite, 4,300 ft N. 27° W. of head of South Arm of Kendrick Bay.
3. Hornblende diorite, from an island in Kendrick Bay 14,000 ft S. 67° E. of loading dock on the West Arm of Kendrick Bay.
4. Hornblende quartz diorite, from an island 5,800 ft S. 77° E. of the head of Gardner Bay.
5. Biotite granodiorite, 13,000 ft S. 23° E. of the east end of Hessa Lake.
6. Quartz monzonite, west shore 5,000 ft N. 12° E. of the head of the South Arm of Kendrick Bay.
7. Hornblende granodiorite, from an island in Kendrick Bay 12,000 ft S. 54½° E. of loading dock on the West Arm of Kendrick Bay.
8. Biotite-hornblende granodiorite, from an island in Kendrick Bay 14,500 ft S. 60½° E. of loading dock on the West Arm of Kendrick Bay.
9. Gneissic quartz monzonite, east shore 11,600 ft N. 23° E. of the head of the South Arm of Kendrick Bay.
10. Gneissic quartz monzonite, on headland between the east shore of the South Arm of Kendrick Bay and Kendrick Bay.
11. Syenite, south shore of Stone Rock Bay.
12. Syenite, on headland between Stone Rock Bay and Mallard Bay.
13. Bokan Mountain granite, 850 ft S. 78° W. of Ross-Adams mine.
14. Bokan Mountain granite, 1,300 ft S. 88° W. of Bokan Mountain.
15. Bokan Mountain granite, 4,000 ft N. 18° W. of Bokan Mountain.
16. Bokan Mountain granite, 3,650 ft N. 40° W. of Bokan Mountain.
17. Bokan Mountain granite, 2,600 ft S. 87° E. of Bokan Mountain.

4) Secondary hydrothermal deposition in pore space of clastic sedimentary rocks.

With a very few exceptions, the uranium deposits are in or near the granite stock. The exceptions include prospects in older series pegmatites associated with quartz monzonite-granodiorite and one in a fractured mafic dike. There can be little doubt, however, that the sole source of the ore uranium is the peralkaline granite. The ore-forming process may have taken place in two stages, or it might have acted in a continuous progression. In the first case, a peralkaline granite of anomalous uranium content would initially crystallize forming the type 1 and 2 concentrations. Sometime later, hydrothermal activity moved uranium-rich solutions into the surrounding country rocks and thus produced type 3 and 4 deposits, which constitute most of the Bokan Mountain ores. The two-stage process was suggested by MacKevett (1963). The contrasting continuous process requires the hydrothermal enrichment system from granite to country rock to be original magmatic. This is to say that the same magmatic fluids that caused the primary uranium ore mineralization within the granite (Ross-Adams deposit) also produced mineralized aplites and pegmatites and enriched the country rock in uranium during albitization.

Section 1.1.2.3.6 The Ore Deposits

Section 1.1.2.3.6.1 The Ross Adams Mine

The Ross-Adams Mine is located on the southeast flank of Bokan Mountain (Figure A-5) and is situated within the peralkaline granite. The mine was operated by Climax Molybdenum Company for a small part of 1957. During this time 15,000 tons of ore 0.6% U and above were removed. The main ore body averaged about 12 m in width and attained a length of over 55 m. Vertical thicknesses ranged from 3 to about 15 m. There are, however, no sharp contacts between ore and host granite. A few major faults and many smaller ones cut the ore, with some actually displacing it. Jointing and fracturing are very common in the mineralized zone. These features are mostly post-mineralization.

Ore grade decreases outward from a high of 2.5 % U (0.4% U average). Much of the high-grade ore contains nearly 1% U. Thorium contents are mostly greater than uranium, which is reflected in the ore mineralogy. The granite in the ore body is of various textures and is characteristically stained reddish-brown because of the association of iron oxides with the radioactive minerals. Other characteristics of granite in the ore zone are: lack of potassium; slight enrichment in zirconium, titanium, magnesium, calcium, manganese, and arsenic; and slight depletion in silica. Acmite is apparently the dominant mafic mineral.

The vast majority of ore minerals are primary but are often metamict with groups of fractures (radiation damage?) radiating from them into other minerals. These fractures are often filled with hematite and minor secondary ore material. The ore mineral grains are concentrated in the host granite and in some cases are truly disseminated; in others they coalesce in veinlets. The dominant ore minerals include: uranothorite and uranoan thorianite, with uraninite and coffinite less important. Directly associated with the ore minerals are: hematite, fluorite, pyrite, galena, quartz, calcite, and clay minerals. Secondary uranium minerals found in minor amounts include: gummite, sklodowskite, beta-uranophane, bassetite, and novacekite.

The best indicators of uranium mineralization at the Ross-Adams deposit are the hematite staining of the ore body, the proximity of faulting, and the occurrence of unusual amounts of fluorite, pyrite, and calcite in particular.

Section 1.1.2.3.6.2 The Atom Marietta Prospects

The Atom Marietta mineralized prospects occur at the intersection of two fault sets in the albitized aureole of the main granite about 490 m N73°E of the Ross Adams mine. This, like all but the Ross-Adams deposit, is not an important economic working. The local quartz monzonite and dikes (dacite ? and aplite) are highly altered and fractured. The ore minerals are found in the dacite dike near zones of intense shearing and alteration.

Ore minerals occur in veinlets, irregular lenses, and disseminations in the dacite. The ore typically has higher U/Th ratios than the Ross-Adams. This is substantiated by the greater amount of uraninite relative to more thorium-rich minerals occurring in the region. Dominant ore minerals include uranothorite and uraninite. Uranophane is the only identified secondary ore phase. Gangue minerals include: hematite, fluorite, calcite, quartz, and chlorite.

Prospecting guides are the dacite dikes, faults and fractures, and alteration.

Section 1.1.2.3.6.2 Carol Ann Prospects

About 2 km southeast of the Ross-Adams mine are the Carol Ann prospects. These deposits are also located in mineralized dacite dikes within the albitized zone. Country rock is either quartz monzonite or quartz diorite. The dikes are not as highly sheared and fractured as the Atom Marietta prospects. Alteration is ubiquitous where radioactivity anomalies occur.

Quartz veinlets in altered calcite are the prime carriers of uranium minerals. The veinlets typically display pegmatitic qualities, inasmuch as albite and several other minerals occur with the ore. Because of this the veinlets were probably a result of granite-fluid dispersal associated with albitization of the country rock.

The dominant primary ore mineral is uraniferous allanite. Sphene may also contribute to the total uranium content of the ore. No secondary uranium minerals were identified. Gangue and accessory minerals in the ore zone include: clinozoisite, clay minerals, sericite, fluorite, and magnetite.

Ore guides are the same as for the Atom-Marietta prospects.

Section 1.1.2.3.6.4 Cheri Prospects

The Cheri prospects are situated in the albitized quartz diorite, where a roof pendant of quartzite and a mafic dike are exposed. There is strong alteration, fracturing, and quartz vein intrusion in all the local rocks.

The quartz veins and quartzite, in particular, have been mineralized by allanite grains, which is the only known uranium-bearing phase. Associated minerals in the ore zone are albite, quartz, calcite, epidote, and chlorite. All these minerals fill the pore space in the quartzite.

Section 1.1.2.3.6.5 I. and L. Prospects

Five claims are included in the I. and L. properties. All of these are within the peralkaline granite near its margin, both on the northwestern and southeastern flanks of Bokan Mountain. The ore is located primarily in pegmatites but also occurs along the hanging wall of a major fault.

Some of these deposits are syngenetic ore concentrations in the pegmatites. The pegmatites and faults, however, have been acted upon by later hydrothermal alteration, which is responsible for the great majority of economic concentrations.

The ore solutions hydrated the feldspars such that sericitization and clay formation took place. The same fluids enriched the area in iron, causing red-to-brownish staining of the ore zone.

The syngenetic process in the pegmatites concentrated uraninite and the thorium/uranium phases in quartz-rich segregations. Where preserved, the syngenetic ores occur with albite and potassium feldspars. Zircon, xenotime, sphene, magnetite, and ilmenite (?) also occur where alteration is severe and higher concentrations of ore minerals exist. Potassium has been removed and sodium has been added; silica is higher in the ores of the I. and L. deposits than elsewhere.

The later epigenetic ore processes may have taken place in hydrothermal fluids that remobilized the earlier uranium minerals and redeposited these in fractures and along grain boundaries. The ore vein minerals include: uraninite, uranothorite, uranoan thorianite, brannerite, ellsworthite, xenotime, bastnaesite, parisite (rare-earth mineral), and an unidentified niobate. Beta-uranophane was the only secondary uranium mineral found. Gangue accessories included: iron and manganese oxides, calcite, fluorite, pyrite, galena, chlorite, and clay minerals.

The iron oxide staining and the formation of clay mineral alteration of feldspars are the two major ore guides to these deposits.

There are several other claims and prospects in the Bokan Mountain district, but they are relatively minor and are not significantly different than those presented to warrant individual description.

Section 1.2 Conterminous United States

Section 1.2.1 Wheeler Basin

Section 1.2.1.1 Location

The disseminated uranium deposit in the Wheeler Basin, Grand County, Colorado (Figure A-7), is located near 40°02'30"N and 105°40'W, just west of the Continental Divide and about 8 km southeast of Monarch Lake in Rocky Mountain National Park.

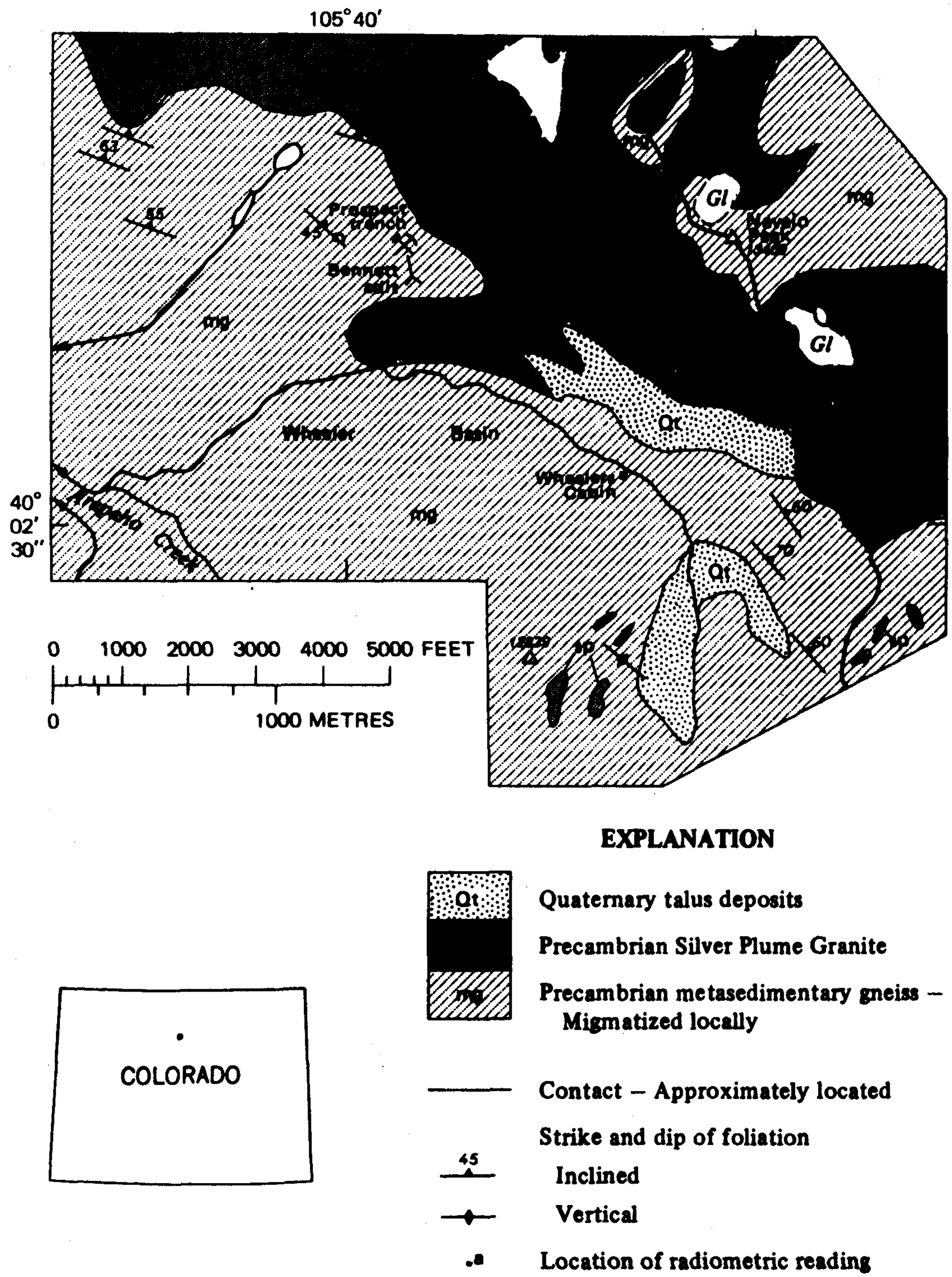
Section 1.2.1.2 Regional Geology

The Wheeler Basin is a U-shaped glacial valley cut in a migmatite-gneiss terrain. The regional geology is dominated by the Precambrian gneiss terrain and a portion of the Silver Plume granite (Figure A-7). Both these units were exposed during the Laramide uplift. The gneiss unit is roughly equivalent to the 1.7-b.y.-old Idaho Springs Formation, which outcrops out in the Colorado Rockies. Near the granitic mass, the gneiss is highly migmatized and injected with pegmatites. The 1.4-b.y.-old Silver Plume granite is actually a complex plutonic series ranging from granodiorite to granite with quartz monzonite as the most common rock type. This report on the Wheeler Basin has drawn extensively from the work of Young and Hauff (1975).

Section 1.2.1.3 Local Geology

In the area of the deposit, granite-pegmatite intrusion forms a "mixed" zone with the country rock gneiss. The gneiss attained the upper amphibolite grade of regional metamorphism. This fact, together with the abundance of migmatites, indicates that the uranium is concentrated at a deep level of granitic magma intrusion.

Scattered throughout the injection zone are large quantities of biotite masses. These concentrations of biotite range in size from very small pods to large bodies several square meters in exposed area. It is these biotite masses that are the prime hosts for uranium minerals.



Geologic sketch map of Wheeler Basin. From Young and Hauff (1975, fig. 1).

The gneiss-migmatite is composed primarily of plagioclase and quartz with subordinate amounts of biotite and sillimanite. The rocks are characteristically fine-grained. Pegmatites as individual bodies and mixed with the gneiss consist of perthite, quartz and smaller amounts of biotite and muscovite.

Biotite masses found in the Wheeler Basin "mixed" zone were found during field studies to be anomalously radioactive. In nearly all cases, the recorded radioactivity was greater than fifty times the background. Chemically analyzed samples of the biotite concentrations contained up to 560 ppm uranium with common values over 1000 ppm (Young and Hauff, 1975, page 308).

Typical mineralogy of the biotite masses consists of:

	Volume percent		Volume percent
Biotite	40-80	Hematite	Tr-2
Sillimanite	15-40	Uraninite	Tr-1
Quartz	5-10	Zircon	Tr
Pyrite	1-4	Molybdenite	Tr
Muscovite	Tr-3	Chalcopyrite	Tr
Monazite	Tr-2	Fluorite	Tr-rare

Secondary uranium minerals included: uranophane, curite, and fourmarierite.

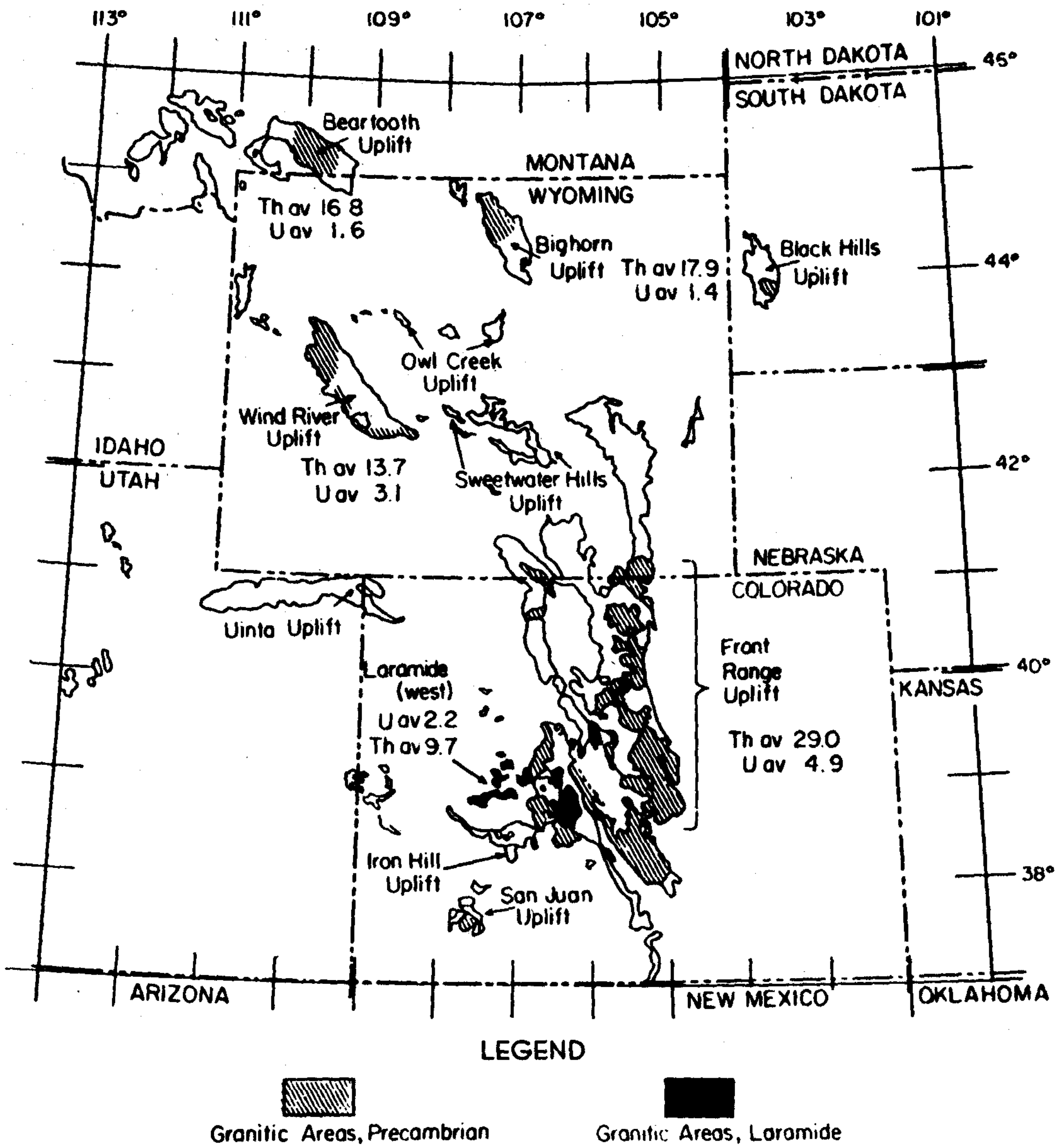
Monazite and uraninite U-Pb dates (Ludwig and Young, 1975) from the Wheeler Basin deposit yielded a concordia age of 1446 $\pm$ 20 m.y., which is roughly contemporary to the age of Silver Plume granite intrusion. Both minerals were significantly affected by an event 880 $\pm$ 130 m.y. ago; this secondary disturbance may have been due to the intrusion of dikes related to the Pikes Peak batholith, dated at 1,041 $\pm$ 13 m.y. ago. The uraninite and monazite data do not indicate Mesozoic and Tertiary disturbances, a pattern found in all zircons from both Silver Plume age plutons and older (1,650-1,820 m.y.) rocks from the Southwestern United States.

Section 1.2.2 Front Range Province

Section 1.2.2.1 Location

The Colorado Front Range (Figure A-8) is a physiographic province formed by the Laramide uplift exposure of Precambrian igneous and metamorphic rocks. The portion of the Front Range interesting in relation to economic

Figure A-8


113°
111°
109°
107°
105°
103°
101°
45°
44°
42°
40°
38°
NORTH DAKOTA
SOUTH DAKOTA
MONTANA
WYOMING
IDAHO
UTAH
NEBRASKA
COLORADO
KANSAS
ARIZONA
NEW MEXICO
OKLAHOMA
Beartooth Uplift
Th av 16.8
U av 1.6
Bighorn Uplift
Th av 17.9
U av 1.4
Black Hills Uplift
Owl Creek Uplift
Wind River Uplift
Th av 13.7
U av 3.1
Sweetwater Hills Uplift
Uinta Uplift
Front Range Uplift
Th av 29.0
U av 4.9
Laramide (west)
U av 2.2
Th av 9.7
Iron Hill Uplift
San Juan Uplift
LEGEND
Granitic Areas, Precambrian
Granitic Areas, Laramide

uranium potential is located east of the Continental Divide in parts of Park, Clear Creek, Gilpin, and Boulder Counties, Colorado. The area is approximately bound by 39°30'N to 40°0'N and 105°20'W to 105°45'W.

Section 1.2.2.2 Regional Geology

The regional setting for the Front Range province is essentially the same as that for the Wheeler Basin deposit to the west. Uranium is associated with Tertiary (Laramide) alkaline magmatism represented by groups of small stocks and dikes intrusive into Precambrian metasediments of the Idaho Springs Formation and into later Precambrian calc-alkaline plutons of the Mt. Evans, Boulder Creek, and Silver Plume granites (Phair and Gottfried, 1964). The Laramide intrusions comprise part of a 320-km-long belt trending northeast across central Colorado. Those bodies in the Front Range are the northeastern trendings of the belt where it intersects the north-south trend of the Precambrian plutons. This region has been historically known for its mineral resources, including the gold of the Central City district. It is particularly interesting to note that the areas of highest uranium potential are found where mining for other ores was very intense.

It is not known exactly what role the Precambrian rocks in this region played in the introduction of anomalous amounts of uranium. However, some of the Precambrian plutons of the Front Range display uranium and thorium abundances above average for granitic rocks (Phair and Gottfried, 1964).

Section 1.2.2.3 Local Geology

Discussions of the Front Range Tertiary intrusives and their association with uranium concentrations are presented in Wells (1960), Phair and Gottfried (1964), Phair (1952), and Phair and Jenkins (1975). Wells (1960) describes thirteen separate types of intrusive rocks that he combines into four genetic groups: hornblende granodiorite, leucogranodiorite, quartz monzonite, and bostonite. While rocks from all four groups show varying degrees of uranium enrichment, only the bostonite group is characterized by uranium concentrations high enough to be considered as primary economic sources.

The local geology in areas where high uranium concentrations have been found may vary considerably. Nevertheless, in the Front Range district one common denominator, bostonite dikes, is associated with well over 90% of the uranium ore veins and mineralized fracture zones. Individual dikes may be over 8 km in length. Outcrop widths are seldom greater than a few meters, however.

Section 1.2.2.4 Petrography

The bostonite group includes porphyritic bostonite, trachytic granite porphyry, biotite-quartz monzonite porphyry, and biotite-quartz latite porphyry (Wells, 1960). Bostonite per se can be subdivided into bostonite, garnet bostonite, and quartz bostonite. The quartz bostonite is supposedly the most differentiated of the alkaline suite. It also is the most highly enriched in uranium. The most notable characteristic of the bostonites is the low concentration of CaO and MgO. This can be seen in the mineralogy, where plagioclases are high in albite content and ferromagnesians are uncommon. Mineralogic variation in bostonites is: 1-25% quartz, 50-70% potassium feldspar (including perthitic types), 20-45% plagioclase, and 1-10% mafics (usually aegirine-augite or biotite).

A summary of the bostonite-group mineralogy (Table A-7) indicates a petrologic break between the quartz bostonite and other members of the group. The uraniferous quartz bostonites typically have low percentages of macroscopic

TABLE A-7

BOSTONITE GROUP
(BOSTONITIC GROUNDMASS, SPARSE FERROMAGNESIAN MINERALS, GENERAL REDDISH BROWN TO LILAC)

Rock Name	Potassic feldspar	Plagioclase	Quartz	Ferromagnesian mineral	groundmass minerals	Remarks
Bostonite porphyry	X*	Albite-oligoclase	......	Bladed mineral	Same as phenocrysts plus minor quartz.	Less than 10% quartz
Garnet bostonite porphyry	X	Albite-oligoclase	......	Aegirine-augite	Same as phenocrysts plus minor quartz.	Contains andraditic garnet. Less than 10% quartz.
Trachytic granite porphyry	X	Albite-	......	Bladed	Same as phenocrysts plus anhedral grains between feldspar laths.	
Quartz bostonite porphyry	X	....	......	....	Same as phenocrysts plus anhedral quartz quartz grains between feldspar laths.	

*X indicates mineral is present but variety not determined

After Wells (1960)

phenocrysts. In addition, anorthoclase is present rather than two feldspars. Fresh quartz bostonites are reddish in color, indicative of fine groundmass hematite. Other accessory minerals include apatite, zircon, and rare fluorite and carbonate.

Textures in the bostonite group are dominantly trachytic-porphyritic. Feldspar lath phenocrysts display good flow alignment in most samples more often than aphanitic quartz bostonite.

Section 1.2.2.5 Age

The Front Range Laramide intrusives range in age from 65 to 50 m.y. These ages were obtained from K-Ar techniques on alkalic rocks and from U-Pb dating of pitchblende ores associated with the dikes. Through cross-cutting relationships it can be reasoned that the quartz bostonites and latites were the last intrusions in the sequence. The formation of ore veins supposedly took place after quartz bostonite intrusion and before intrusion of the latite.

Section 1.2.2.6 Uranium Mineralization

The bostonite dike rocks of the Front Range province are themselves enriched in uranium up to several hundred ppm. The highest content for a single dike averages 83 ppm uranium over the entire dike. The highest concentrations of uranium in the region occur in mineralized veins associated with the dikes. These veins were formed as a result of the fracturing associated with dike emplacement. The dominant uranium minerals in the veins are pitchblende (mainly uraninite) and a secondary phase, such as uranophane. Many of the veins contain mesothermal base metal and massive sulphide ores rich in lead, copper, silver, gold, and zinc. Quartz is ubiquitous and pyrite is very common. Some veins closely associated with Silver Plume-type pegmatites possess assemblages that contain fluorite and coffinite as well as pitchblende.

Within the source dikes of quartz bostonite, uranium-bearing phases include zircon, allanite, and thorite. These occur as disseminated grains. Brownish matter, amorphous or perhaps cryptocrystalline, which is observed along cracks and grain boundaries, also contributes to the whole-rock radioactivity.

Alteration is common among the uranium-enriched dikes. It is distinctly possible that the late-stage hydrothermal activity which created the vein deposits in the region also altered the bostonites. Ferromagnesian minerals are generally changed to clays and chlorite. Feldspars show sericitization and saussuritization.

The area with the greatest number of mineralized dikes is the Central City district; dikes in the district average about 40 ppm U with an average Th/U of 3.6. The most highly uraniferous dikes occur in and around Quartz Hill. Other districts of particular importance include: Chicago Creek, Gold Hill, Jamestown, Lawson, North Gilpin, Alice, Idaho Springs, Dumont, and Fall River.

The uraniferous quartz bostonites were essentially the last magmas produced in the Laramide alkaline episode. There is strong evidence (Phair, 1953; Phair and Jenkins, 1975) that a volatile-rich fluid phase was associated with the bostonites. These fluids were strongly oxidizing (high Fe_2O_3/FeO), which is a major requirement in the solubility of uranium. Obviously, substantial amounts of uranium were left in the source bostonites, but after crystallization of the magma the fluid phase may well have leached additional uranium from pre-existing minerals and redeposited the uranium with other incompatible elements in veins. Fluorite is most abundant in samples with the highest content of uranium. Up to a few percent zirconium is contained in highly uraniferous quartz bostonites. Albitization is observed along the margins of dikes as well as around mineralized veins. Uranium apparently is not enriched in the albitized zones, however.

The principal ore guides for uranium deposits in the region are the quartz bostonites themselves. Quartz segregations, faults and fractures, and anomalous base-metal concentrations are also viable ore guides.

Section 1.2.3 The Conway Granite

Section 1.2.3.1 Location

The Conway granite, as an intrusive phase of the White Mountain magma series, is exposed in several N-S trending plutons covering an area of over 1100 km^2 in east-central New Hampshire (Fig. A-9).

Section 1.2.3.2 Regional Geology

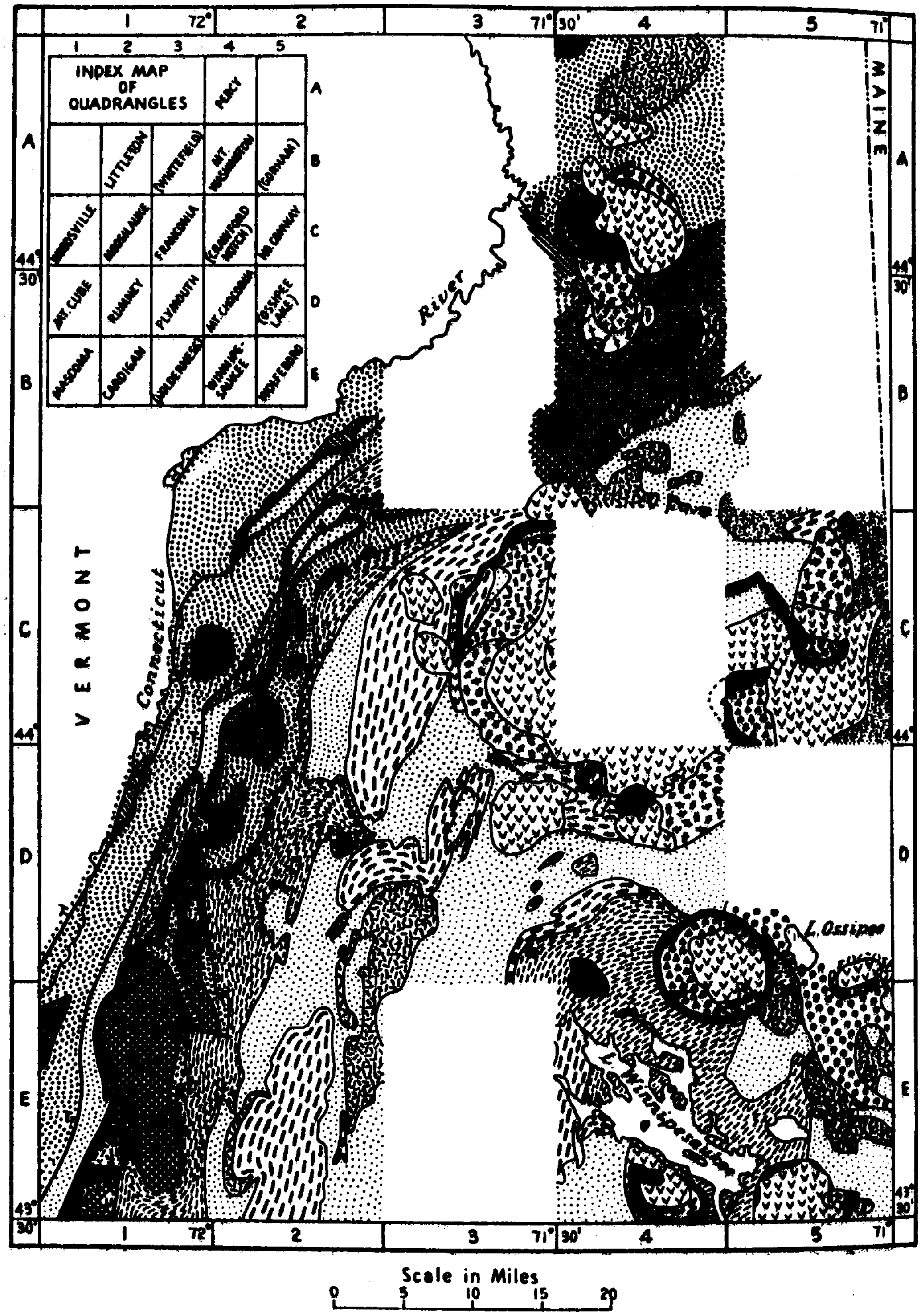
The White Mountain magma series of New Hampshire is the youngest of four major plutonic groups that were intruded into metasediments, metavolcanics, and earlier igneous rocks. The other three plutonic groups, in order of decreasing age, are the Highlandcroft, Oliverian, and New Hampshire.

Tectonically, the first two groups were pre-Acadian, and the New Hampshire group was intruded during the Acadian orogeny (Billings and Keevil, 1946). All but the White Mountain plutons follow the trend of deformation in the Appalachian Mountain system. The White Mountain bodies were intruded across the prevailing structural grain and metamorphic isograds. White Mountain magmatism was probably related in some way to tensional tectonics during the Mesozoic rifting of eastern North America.

Section 1.2.3.3 Local Geology

Unlike the calc-alkaline-type magmatic trends of the earlier plutonic groups, the White Mountain series is typified by more alkalic affinities,

Figure A-9



Geological map of central New Hampshire
from Billings and Keevil (1946)

From Billings and Keevil (1946); Geological Society of America Bulletin, v. 57.

Figure A-9

LEGEND

MISSISSIPPIAN ? — White Mountain Magma Series

- Glacial drift, where extensive
- Biotite granite (Conway)
- Amphibole granite
- Quartz syenite (Albany)
- Granite porphyry
  Felsite (intrusive)
- Quartz syenite
- Syenite
- Nepheline-sodalite syenite
- Granodiorite and quartz monzonite
- Monzonite and monzodiorite
- Gabbro and diorite
- Moat volcanics

LATE DEVONIAN ? — New Hampshire Magma Series

- Bickford granite and Concord granite
- Chatham group
- Kinsman quartz monzonite and Meredith granite
- Bethlehem gneiss and Winnipesaukee quartz diorite
- French Pond and Lebanon granites

- Oliverian magma series (Middle Devonian ?)
- Devonian strata
- Silurian strata
- Highlandcroft magma series (Late Ordovician ?)
- Ordovician (?) strata
- Thrust fault
- Gravity fault

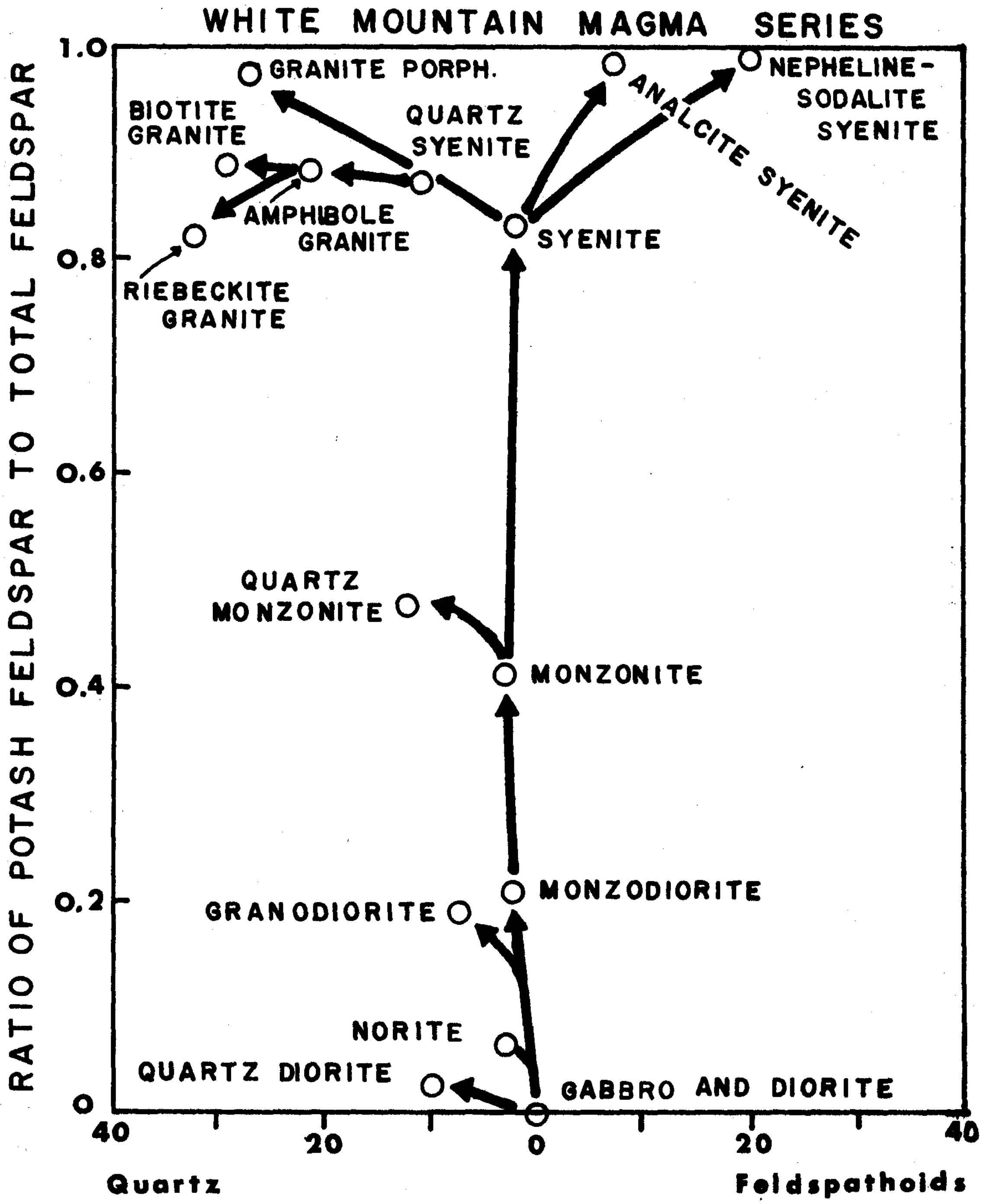
especially the late differentiates. Rock types, in their proposed order of differentiation, include gabbro, norite, diorite, quartz diorite, granodiorite, monzonite, quartz monzonite, syenite, and the last differentiates that consist either of silica-oversaturated or silica-undersaturated types (Fig. A-10). Quartz syenite, biotite granite, and riebeckite granite comprise oversaturated types, and felspathoidal syenites make up the undersaturated types.

The Conway granite is alkaline and biotite-or riebeckite-bearing. It is of economic interest as a disseminated uranium source. Associated with the Conway and White Mountain plutons are hundreds of dikes, ranging from mafic diabases and lamprophyres to bostonites and trachytes. At the present erosional level, there are no comagmatic pegmatites.

The Conway granite is a name given to all phases of the White Mountain series that possess the same mineralogy as the "type" granite at Conway, New Hampshire. The predominant mineralogy of the Conway type is characterized by biotite, while the riebeckite- and hastingsite-bearing granites are less common. The range in mineralogy for the Conway granite is not extreme: quartz, 20-35%; plagioclase (An_{20} or less), 5-12%; potassium feldspar (perthitic orthoclase, microcline, and perthite), 50-60%; biotite, 1-10%; amphibole (riebeckite and/or hastingsite), 0-6%. Accessory minerals include apatite, zircon, allanite, sphene, magnetite, ilmenite, and fluorite. Texturally, these rocks may be porphyritic and coarse-grained or more massive and finer-grained.

There have been various problems in the dating of the White Mountain plutons. Dates, using various techniques, tend to range between 170 and 190 m.y. Assuming this range is valid, the series is roughly Jurassic.

Figure A-10



From Billings and Keevil (1946); Geological Society of America Bull., v. 57.

Section 1.2.3.4 Uranium Mineralization

Various papers have been concerned with the Conway granite's uranium and thorium distribution (Billings and Keevil, 1946; Adams et al., 1962; Richardson, 1964; and Rogers et al., 1965). As in many other uraniferous granites, the Conway represents a highly differentiated member of an alkali-granite magma series. Rogers (1964) found an average of 9.5 ppm uranium as an average for 19 surface samples of Conway granite. He also analyzed other members of the magma series and obtained high average uranium values for all later differentiates (Table A-8). Other analyses of uranium in the Conway granite have yielded values in the range of 7-18 ppm. Rogers et al. (1965), however, show that some leaching of uranium has occurred in the upper parts of drill cores (extending to about 300 meters total depth), and the total uranium concentration for the body is probably higher than surface measurements indicate. Th/U values are commonly near five and tend to increase with progressive differentiation in the White Mt. magma series (Rogers and Ragland, 1961).

The minerals responsible for the uranium content of the granites are all primary accessory phases. Allanite, huttonite, thorite, and zircon occur as disseminated grains and are nowhere concentrated in vein, pegmatite, or contact segregations of economic importance. No secondary uranium minerals have been reported.

Table A-8

After Rogers (1964)

THORIUM AND URANIUM CONTENTS OF ROCKS
OF THE WHITE MOUNTAIN MAGMA SERIES

Rock Type	U (ppm)	Th (ppm)
Conway Granite	9.5	48
Mt. Osceola Granite	10	37
Hastingsite Granite	7.4	26
Syenite and Quartz Syenite	2.9	16
Monzonite	3.1	16

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Section 2. Canada

Section 2.1 Introduction

Little (1970) reports that productive uranium deposits in Canada are of four types:

1. conglomeratic
2. hydrothermal veins and disseminations with simple mineralogy
3. hydrothermal veins and disseminations with complex mineralogy
4. pegmatitic

A classification scheme of Canadian igneous-related uranium deposits after Little (1970) is presented on Table A-9. Minor occurrences of uranium in carbonatites and large plutonic bodies of granite are classified separately from pegmatite deposits; the Charlebois Lake deposit is termed a metasomatic deposit. However, uranium mineralization is largely confined to pegmatites. By far the greatest number of mines, showings, deposits, and tonnages of ore are found in the Aphebian and Helikian provinces of the Canadian Shield. No major uranium deposits occur in rocks of Archaean age.

Among Canadian uranium deposits in pegmatites, granites and migmatites, only the Bancroft pegmatite deposits have been mined. Nonetheless, hundreds of uranium deposits in pegmatites and granites have been reported. The bulk of these occurrences is in Northern Saskatchewan, Ontario, and Quebec, although scattered showings occur in British Columbia, in the Shuswap complex, and the Northwest territories. Figure A-11 is a map of the distribution of some of the many uraniferous pegmatite deposits in eastern Canada and is taken from Little (1970). Recent compilations of the locations, assessments, and descriptions of uranium deposits in Ontario have been published under the auspices of the Ontario Department of Mines by Hewitt (1967A) and Robertson (1968). Hewitt (1967B) also reviewed the specific occurrences of uranium in

TABLE A-9

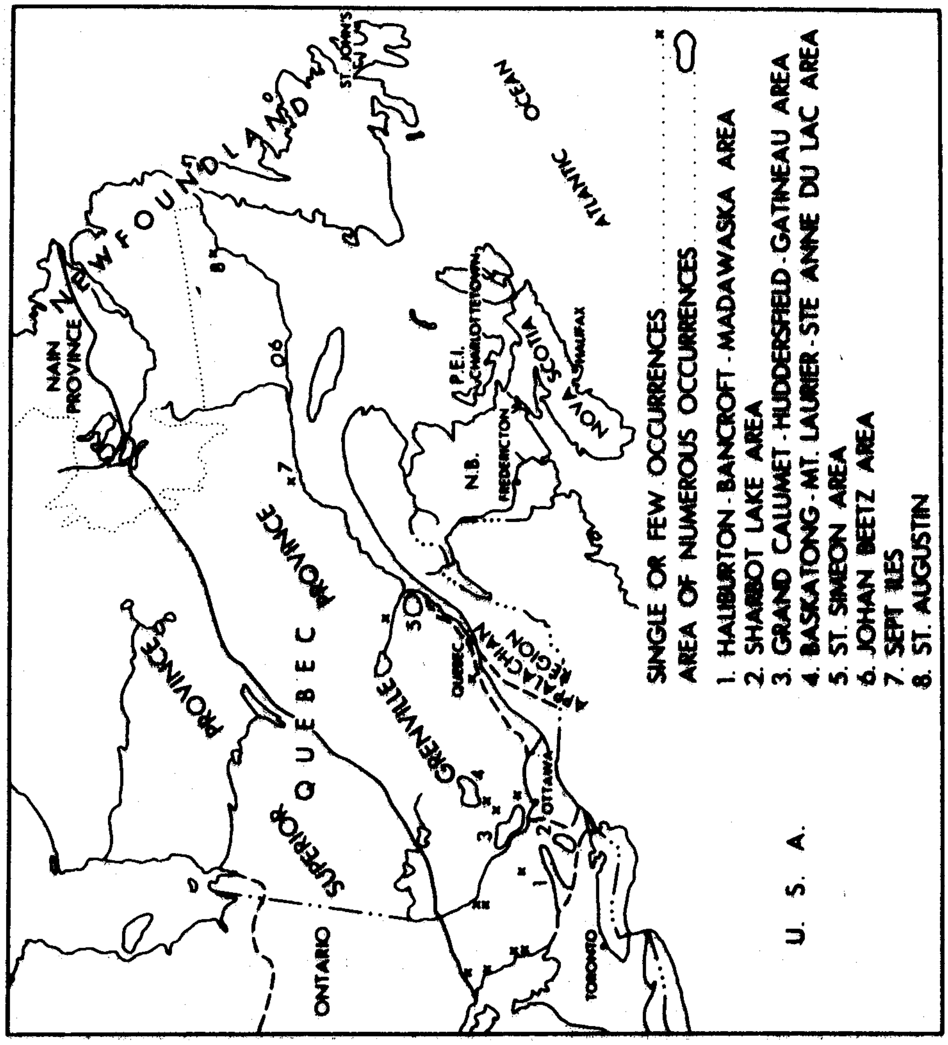
CLASSIFICATION OF IGNEOUS AND RELATED URANIUM DEPOSITS IN CANADA

Types			Characteristic elements	Characteristic uraniferous minerals	Other characteristic minerals	Example(s)
GRANITIC (large plutonic bodies)			Th U Zr Si	Allanite, zircon, thorite, uraninite	Magnetite, sphene, apatite	St. Pierre Uranium property, Johan Beetz area, Quebec
PEGMATITE	UNZONED	RED PEGMATITES	Th U Zr (Si F S P Ce)	Uranothorite, uraninite, thorite, allanite, cyrtolite	Uralite, hematite, pyrite, pyrrhotite, magnetite, sphene	Faraday and Bicroft mines, Bancroft area, Ontario
		WHITE PEGMATITES	Mo U Th Si (Nb RE*)	Uraninite, uranothorite, betafite, euxenite, allanite	Biotite, magnetite, molybdenite, hornblende	Grandroy prospect, Johan Beetz area, Quebec
	ZONED		Li Be Nb Mo Si (Nb Sn RE*)	Pyrochlore, betafite, allanite, columbite-tantalite	Molybdenite, cassiterite, calcite	Richardson mine, Wilberforce, Ontario
ANHYDRITE			Th U Zr (Si S P)	Uranothorite, uraninite, cyrtolite	Uralite, calcite, pyrite, pyrrhotite, magnetite	Lower levels of Faraday mine Bancroft, Ontario
CARBONATITE (with associated fenite)			Nb U Th	Pyrochlore, betafite, perovskite, niocalite	Calcite, soda pyroxene and amphibole, apatite, biotite, magnetite	Newman property, Lake Nipissing, Ontario
METASOMATIC			U Th P Si (F Mo Fe S)	Uraninite, thorite, thorianite, monazite	Calcite, pyroxene, quartz, feldspar, hematite	Charlebois Lake, Saskatchewan
HYDROTHERMAL	Type I (complex mineralogy)		Cu Ag Co Ni As S Se (Au, Pt)	Colliform pitchblende, thucolite	Hematite, calcite, chlorite, quartz	Eldorado mine, Great Bear Lake, District of Mackenzie
	Type IIa (simple mineralogy)		U C Fe Se	Massive pitchblende, thucolite	Hematite, pyrite, calcite	Fay-Ace-Verna mines, Beaverlodge area, Saskatchewan
	Type IIb (simple mineralogy)		U C	Sooty pitchblende, thucolite (?)	Kaolin, ankerite, pyrite (hematite)	Rabbit Lake prospect, Wollaston Lake area, Saskatchewan

After Little (1970); from Uranium Exploration Geology, published by International Atomic Energy Agency.

Figure A-11

Pegmatite deposits of Uranium
in eastern Canada, After Little (1970)



From Uranium Exploration Geology,
published by International Atomic
Energy Agency.

pegmatites in Ontario. Hewitt (1959) reviewed the details of radioactive occurrences in the Bancroft area. Radioactive mineral occurrences in Quebec have been studied by Shaw (1958); several deposits occur in granites, syenites, and pegmatites. A compendium of Northern Saskatchewan uranium deposits can be found in Beck (1969). The major uranium deposits in Canada are compared to eastern European deposits in Ruzicka (1970).

Section 2.2 Churchill Province

Section 2.2.1 Charlebois Lake

Section 2.2.1.1 Location

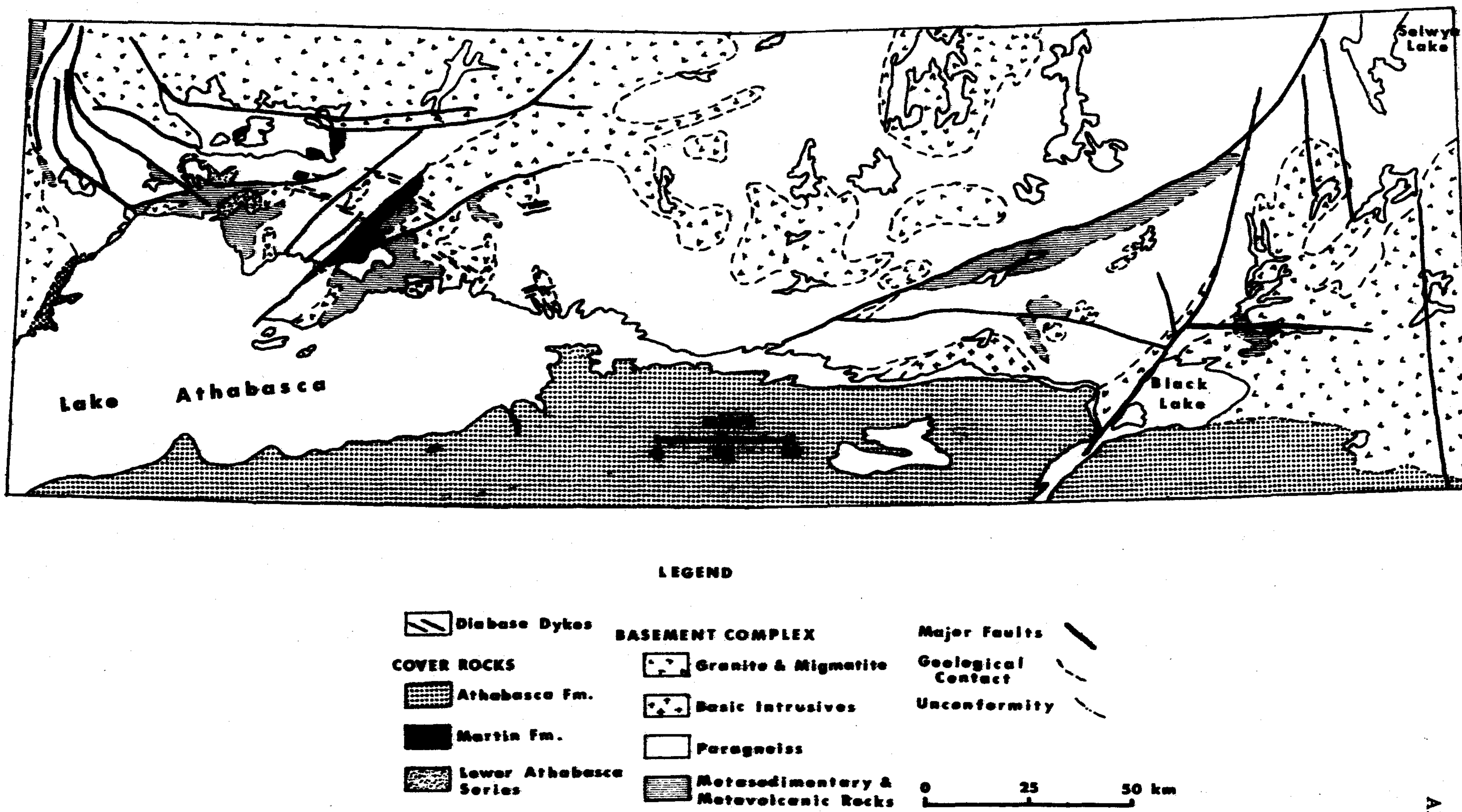
The Charlobois Lake area is located approximately 59°24'N, 104°52'W, in north-northwestern Saskatchewan, 16 km NE of the northeastern end of Black Lake.

Section 2.2.1.2 Regional Geology

The Charlebois Lake uranium prospects are located on the extreme eastern edge of the Athabasca region (Fig. A-12) as defined by Beck (1969, 1970). The Athabasca region forms part of the large Churchill Province of the Canadian Shield. This region is underlain by a basement complex of Archaean or Aphebian assemblages of regionally metamorphosed and granitized rock strongly affected by the Hudsonian thermal event and orogeny (1750-1950 m.y.). Large-scale erosion after the Hudsonian orogeny resulted in basins of deposition, and in places the eroded orogen is covered by younger sediments such as the Martin and Athabasca Formations. The relationship of syngenetic uranium crystallization to the tectonic and magmatic events in the Athabasca region are discussed in Chapter 3; however, it is notable that this region is also the locale of widespread vein-type uranium mineralization. The Athabasca sediments contain numerous economic deposits of vein-type uranium in the Beaverlodge district.

Figure A-12

Geology of the Athabasca province
(Charlebois Lake is on the east side of Black Lake)



After Beck, 1969, Sask. Dept. Min. Res.; 1970, Can. Inst. Min. Met.)

The Hudsonian granites are the host rocks for syngenetic uranium mineralization and are largely of metasomatic or replacement origin. It is speculated that the various uraninite-bearing occurrences (isolated dike-like pegmatites, lit-par-lit zones of pegmatite, irregular bodies of pegmatite in migmatite zones) represent stages of recrystallization in the transformation (granitization) of country rock and that pitchblende deposits resulted from the release of pitchblende-bearing solutions at a late stage in the granitization process. Table A-10 summarizes the variety of uranium deposits found in the Athabasca region; subdivision of pegmatite deposits is on the basis of geological environment. None of the pegmatite deposits have been mined.

Section 2.2.1.3 Local Geology

Figure A-13 is a geologic sketch map of the Charlebois Lake area with an accompanying table of formations. All bedrock in the area is of Archaean age; approximately 15 miles south of Charlebois Lake, flat-lying sandstones and conglomerates of the Athabasca Series crop out (Mawdsley, 1952, 1955, 1958).

The Tazin Group sediments comprise a diverse assemblage of high-grade (amphibolite facies) metasediments. They are presumably of Archaean age and are mainly metamorphosed impure quartzites and schists. Diopside-rich gneisses and schists, marble, and other calcareous metasediments are present in subordinate amounts. Meta-gabbros presumably younger than the metasediments and cut by granite occur on the west side of Charlebois Lake.

Approximately two thirds of the map area is underlain by granite and granite gneiss, of which there are four main varieties as delineated by their modal feldspar compositions.

a. potash feldspar-rich

b. 30-70% potash feldspar, the balance is sodic to intermediate

Table A-10

TYPES OF DEPOSITS, ATHABASCA REGION

After Beck (1969, 1970)

- PRIMARY DEPOSITS
  - Pegmatite Deposits
    - Lit-par-lit type(21) e.g. Charlebois Uranium-Row claims
    - Dyke-like pegmatites(11) e.g. Gwillim Lake Gold Mines-Bert claims
    - Pegmatites in migmatite zones(4)e.g. Camsell Portage pegmatite
  - Uraninite in country rock(6)e.g. Goldfields Uranium showing no. 49-TT-1
  - Pitchblende Deposits
    - Complex Mineralogy(16)
      - Mines and properties with underground development (7)e.g. Consolidated Nicholson Mines
      - Minor occurrences(9)e.g. Camdeck Mines-zone no.4
    - Simple Mineralogy(268)
      - Mines and properties with underground development (33)e.g. Rix Athabasca-Smitty Mine
      - Deposits with high-grade potential or warranting further work(49)e.g. Baska-Dot claims-zone no.D19
      - Minor occurrences(186) e.g.Amax Athabasca-showing no.49-CC1-6
- SECONDARY DEPOSITS
  - Autunite Deposits(1) e.g.Dee Exploration-Middle Lake showings

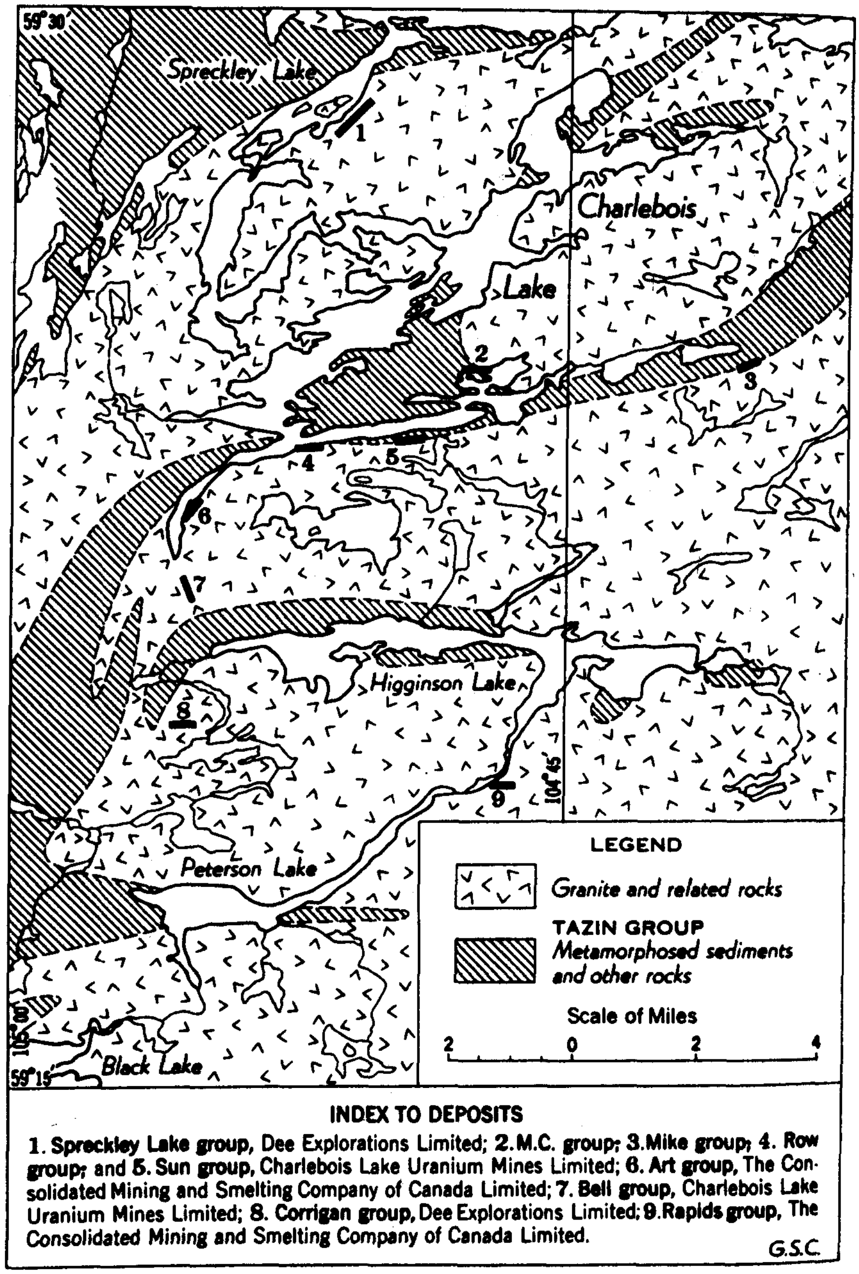


Figure A-13

General geology of the Charlebois Lake region,

After Lang et. al. (1962); Geol. Surv. Can.

oligoclase (the dominant variety)

c. Plagioclase-rich (intermediate oligoclase)

d. Subequal amounts of potash feldspar and calcic oligoclase

Mafic minerals generally make up less than 10% of the mode. The gneissic granites, which grade into the more massive varieties, generally are of types c and d. Pegmatite granite, pegmatite, and injection gneiss are found at the border of large granite bodies. The gneissic and schistose structures in the metasediments next to the granite contacts usually conform to the trend of these contacts and the gneissic structure in the granite. No pronounced fault displacements are apparent in the map area.

Section 2.2.1.4 The Ore Deposits

Section 2.2.1.4.1 Host Rocks

The uraninite deposits are in the migmatite zones bordering granite masses. The host migmatites are composed of calcium-rich metasediments and intruded (injection) gneiss and are replaced by a fine-grained white pegmatite phase. The mineralized fine-grained pegmatites are texturally and mineralogically similar to their neighboring consanguineous granites except that the plagioclase is more calcic in the pegmatites. The metasediments which are intruded by the uraninite-bearing pegmatites are conspicuous, however, in that they are lime-rich. Radioactive deposits are lacking in adjacent areas that do not contain lime-rich metasediments. Calcium metasomatism from the metasediments into the pegmatites is implied.

The fine-grained pegmatite facies is usually light gray to white and consists predominantly of feldspar and quartz; however, some varieties grade from dark gray to gray black due to high modal biotite content and smoky quartz.

The age of the pegmatites is very tentatively Hudsonian based only on generalizations by Beck (1970) as to the age of uraninite mineralization in the Athabasca region.

Section 2.2.1.4.2 Mineralogy

Modes and uranium content for selected examples of pegmatite are listed on Table A-11. Both uranium content and modes vary greatly; however, this tabulation indicates a rough correlation between uranium content and modal quartz. The eight samples highest in uranium contain little or no feldspar, and the remainder of the samples all assayed at less than 0.17% eU. Molybdenite is commonly present in samples high in radioactivity, and there is also a slight tendency for samples rich in biotite to have high uranium content.

Quartz can be of the dark, smoky variety, probably due to high radioelement content. Oligoclase, of intermediate or calcic content, is the most common feldspar. Both orthoclase and microcline are generally perthitic. Biotite, with pleochroic halos and inclusions of quartz, apatite, sphene and zircon, is commonly closely associated with uraninite grains. Accessory minerals include apatite, zircon, sphene, tourmaline, pyrite, pyrrhotite, and molybdenite.

Uraninite and minerals of the gummite group that replace uraninite crystals are the identifiable uranium minerals. Uraninite is commonly well developed into euhedral, cubic crystals and is fairly uniform in size, averaging 0.20 mm in diameter.

Section 2.2.1.4.3 Origin of the Ores

These deposits are considered to be related to the differentiation of granitic magma, but because of evidence for calcium metasomatism, the uraninite-bearing pegmatites have been classified as metasomatic rather than pegmatitic deposits (Mawdsley, 1952, 1958). The addition of calcium to the late magmatic fluid allegedly is thought to raise the solidus temperature of the

TABLE A-11

MODES OF CHARLEBOIS LAKE PEGMATITES

After Mawdsley (1952); Can. Inst. Min. Met. Bull.

SPECIMEN NO.	138	54-9	54-8	194	195	133	54-5	132	130	39-4	134	137	46-11	140	43-9	143	47-23	131
Location*......	D(3)	A	A	D(4)	D(4)	D(3)	A	D(3)	D(X)	A	D(3)	D(3)	A	D(3)	A	D(X)	A	(DX
U_3O_8 equiv.....	1.76	0.948	0.676	0.59	0.44	0.46	0.272	0.197	0.170	0.160	0.125	0.106	0.074	0.071	0.050	0.023	0.004	
Quartz.........	78	40	73	85.7	45	73	65	65	20	58	34	10	9	2	20	9.5	5	27
Microcline.....		9	2	5.0			4		12	30	6	44	X		56	1.0	88	38
Orthoclase.....											30	18						20
Plagioclase....		8	15	3		X	20		53	4	4	23.0	85	75	24	68.0	7	2.0
Biotite........	20	40	8	5	46	25	10	33	11	8	21	3.5	5	19		20.0	X	8.5
Muscovite......			X	0.6	7	X			X		X	X		1		0.3		1.0
Zircon.........	X	X	X	0.2	0.15	X		X	X		X	X		X	X	X		X
Apatite........		1	0.5	X	X		X	1	0.15									2.5
Sphene.........	X																	
Uraninite......	0.5	1	0.5	0.3	1.6	0.7	0.5	1	0.1		1		X		X	0.1		
Molybdenite....	0.5	1	X	0.2	0.25		0.5	X			X		X					
Pyrrhotite.....		X	1						0.75	X			1		X			
Chlorite.......	1		X	X		0.3	X		X	X	X	X		X	X	X		X

pegmatite-forming fluid so that rapid crystallization occurred. After the fine-grained white pegmatite was nearly solid, the "end product relatively richer in silica, sulfides, and Mo, Fe and U locally replaced earlier formed minerals". These localized replacement bodies, relatively rich in uranium, would be at points where stresses shattered the previously consolidated pegmatite. Barren pegmatites are explained by the loss of the uranium oxide (in a fluid or aqueous vapor phase?) during slow crystallization of the pegmatite magma; this uranium oxide would possibly appear as low-temperature pitchblende deposits. Mawdsley definitely implies the evolution of a uranium-rich aqueous vapor phase during late stage magmatic crystallization.

Favorable structural conditions for uraninite mineralization in pegmatites include any unusual change of attitude along a contact or in pegmatites.

Section 2.2.2 Lac La Ronge

The Nunn Lake deposits (Figure A-14), near Lac La Ronge, Saskatchewan, occur in a zoned pegmatite of dimensions 210 m long and 90 m wide. Uraninite occurs in the potassium-rich wall zone, the aplitic phase, and as a fracture-filling in the zoned body.

In the wall zone, uraninite crystals form: (1) a sheet-like mass immediately inside a biotite selvage; (2) isolated crystals largely within the outer 1 m of the wall zone. Uraninite in the aplitic phases and fracture fillings probably represents crystallization from the latest-stage liquids of the pegmatites.

The pegmatite is zoned in the following manner:

Border zone (country rock and biotite selvage)

- quartz
- albite
- hornblende
- sparse magnetite, apatite, sillimanite

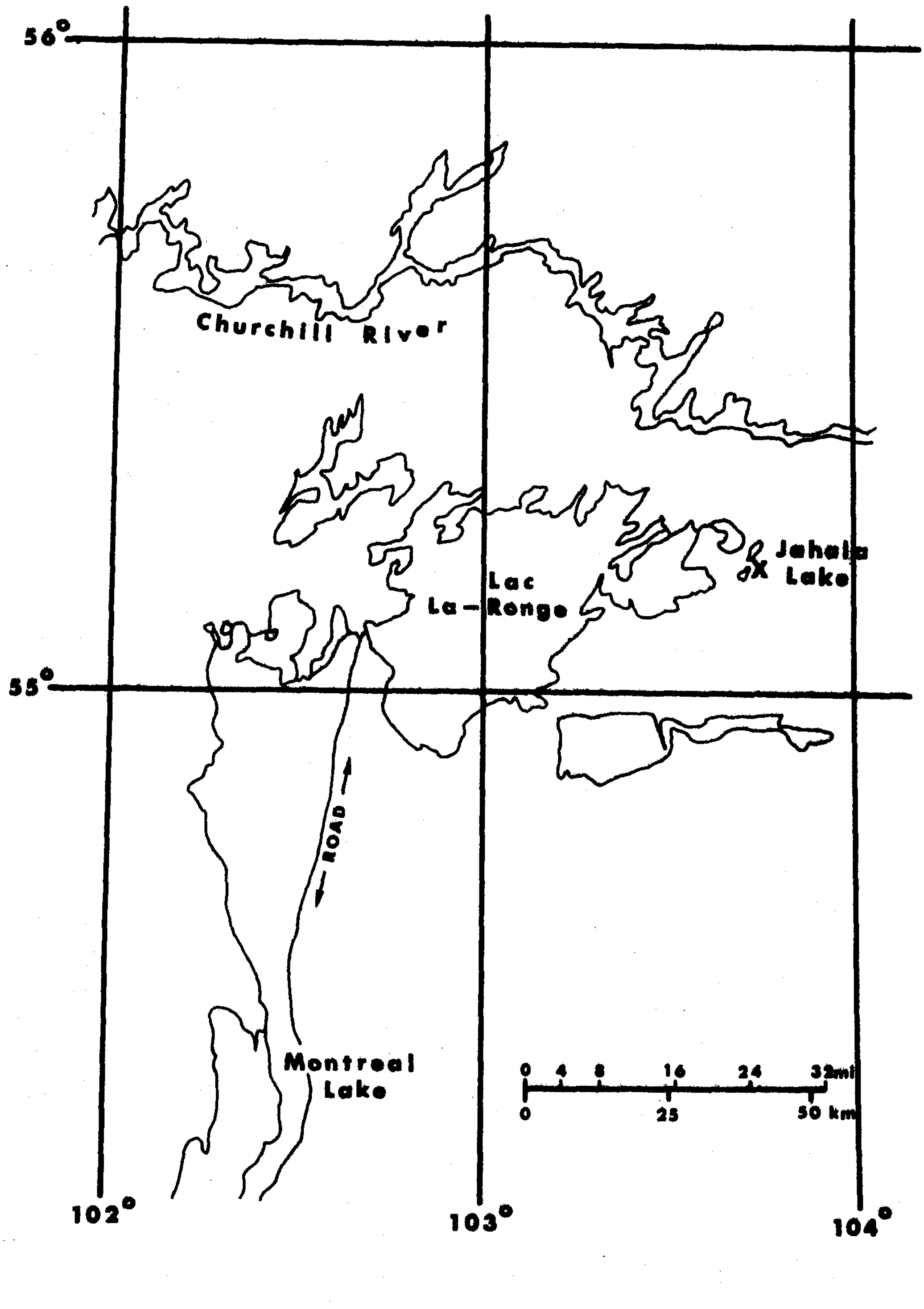


Figure A-14

Lac La Ronge region, Canada

a border selvage of biotite with albite, zircon, apatite, magnetite, monazite, uraninite, allanite and sericite

Wall zone

quartz (smoky)

perthite

plagioclase

biotite

uraninite

red stain (hematite?)

zircon

sericite

Intermediate zone

plagioclase

quartz

perthite

muscovite

Central zone

plagioclase (An7)

quartz

muscovite

Fracture fillings in hornblende gneiss country rock include the following minerals:

orthoclase

biotite

magnetite

uraninite

monazite

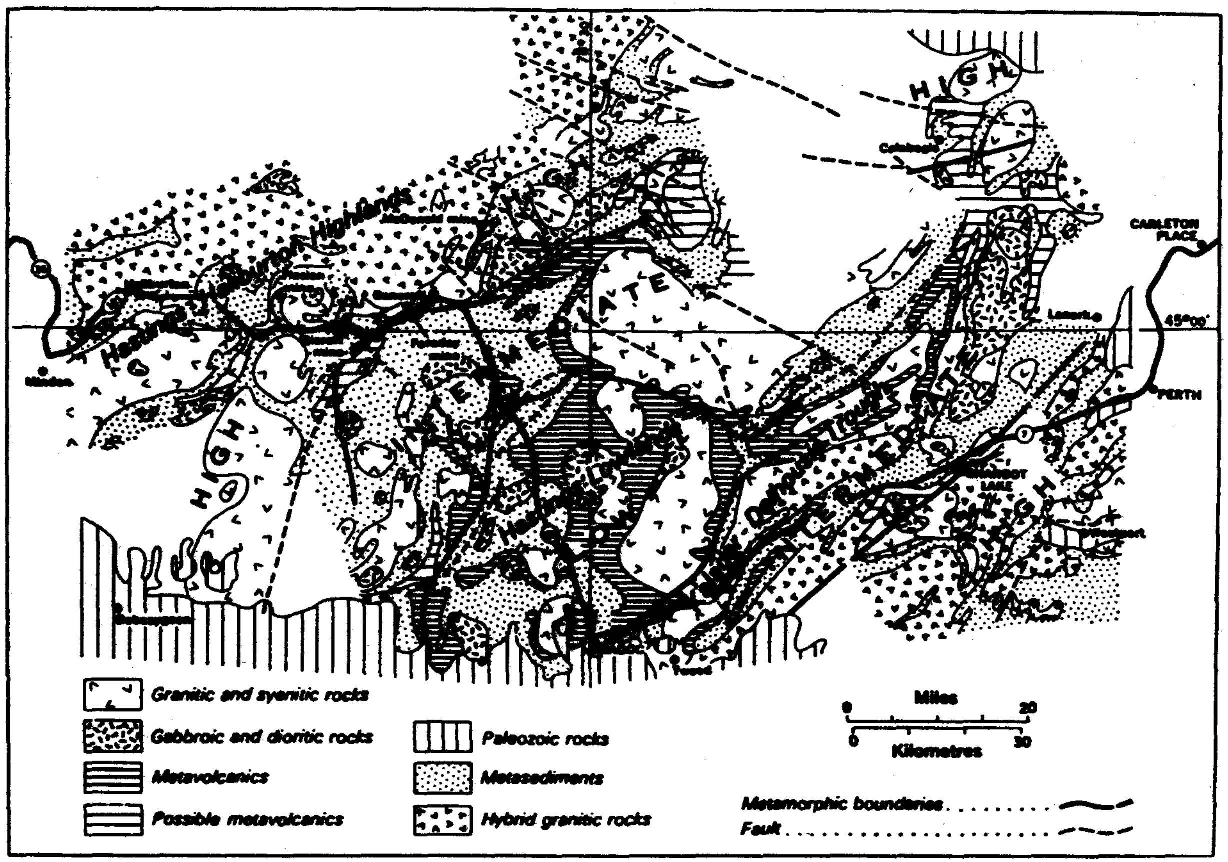
allanite

fluor-apatite

limonite stains

Figure A-15

Geology of the Haliburton-Bancroft region
After Little et al. (1972)



After Little et al. (1972); International Geological Congress Guidebook published by Geological Survey of Canada.

Section 2.3 The Bancroft District

Section 2.3.1 Location

The majority of radioactive occurrences are located in Faraday, Cardiff, and Monmouth townships in the Bancroft district, Ontario, 45°N, 78°W.

Section 2.3.2 Regional Geology

The Bancroft uranium deposits occur in a segment of the Grenville province of the Canadian Shield (Figure A-15; Little *et al.*, 1972) termed the Hastings-Haliburton highlands. The region is dominated by high-grade (amphibolite to granulite facies) metamorphic rocks and a series of mantled gneiss domes with catazonal characteristics. The belt of high-grade metamorphic rocks includes marbles, silicic marbles, mafic volcanic rocks largely altered to amphibolite schists and gneisses, metagabbro, metapyroxenite, metadiorite gneiss, para-amphibolites, and paragneiss. The gneiss complex consists mainly of hybrid granite gneiss with migmatite, pink leucogranite gneiss, and granite pegmatites. Extensive bodies of nepheline syenite occur. Most of the granitic bodies show concordant relationships to country rock. Table A-12 (Hewitt, 1959) compares the stratigraphic sections of the Hastings-Haliburton highlands and the nearby Hastings lowlands. In contrast, granite and gabbro bodies from the Hastings lowlands are discordant, truncating the regional structure of metasediments; contact metamorphic aureoles are developed about some plutons.

Section 2.3.3 Local Geology

The productive uranium mines and the majority of the uranium prospects in the Bancroft region are in or very near three granitic complexes (Figure A-16): the Cheddar granite, the Cardiff plutonic complex, and the Faraday granite.

Table A-12

FORMATIONS IN CARDIFF AND FARADAY TOWNSHIPS (after Hewitt, 1959, p. 8).

		Hastings-Haliburton Highlands	Hastings Basin
Pleist.		Boulder clay, sand, gravel.	Boulder clay, sand, gravel.
		Great unconformity	Great unconformity
Precambrian	Plutonic rocks	Hybrid granitic and syenitic gneisses, migmatites, pegmatites. Faraday granite, Centre Lake granite, Monok Lake granite, Cheddar granite.	Silent Lake granite.
		Intrusive contact	Intrusive contact
		Dear Lake syenite and associated syenite gneisses, pegmatites.	(Not represented)
		Intrusive contact	
		Nepheline syenite gneiss.	(Not represented)
		Intrusive contact	
		Gabbro: Faraday metagabbro and associated basic intrusives.	Gabbro: Umfraville gabbro and associated basic intrusives.
		Intrusive contact	Intrusive contact
	Grenville metasediments	LITHOLOGIC SUBDIVISION	Hermon fm.: Pelitic schists and paragneiss, amphibolite, arkose, quartzite.
		Marble: silicated marble; lime silicate rocks, skarn, metamorphic pyroxenite.	Dungannon fm.: Marble. Detlor feather amphibolite. Marble.
		Paragneiss: amphibolite, pyroxene granulite, quartzite, schist.	

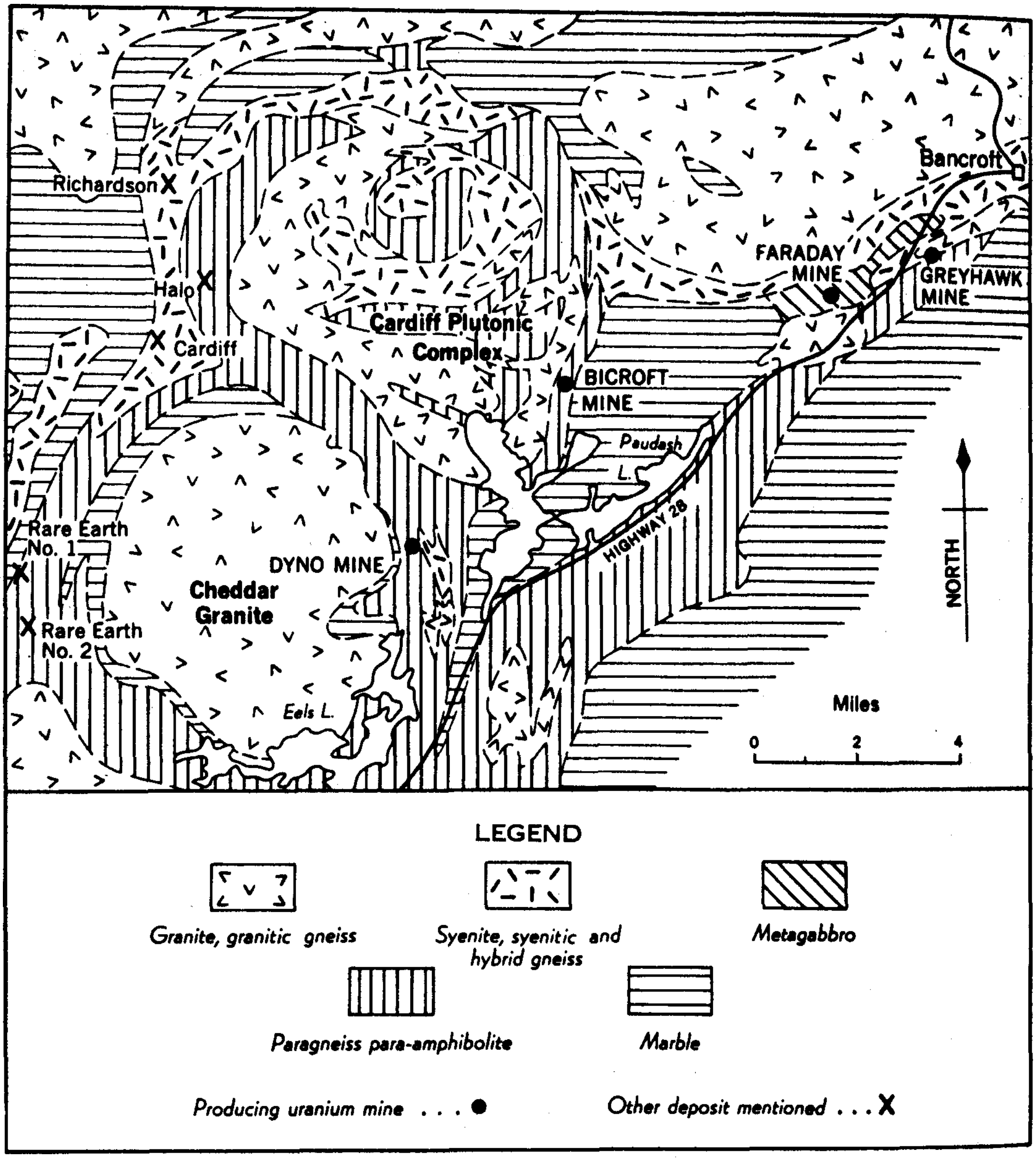


Figure A-16

Geology of plutonic rocks, Bancroft district

After Lang et. al. (1962); Geol. Surv. Canada

All three bodies are subcircular in outline and are approximately 10 km in diameter.

The Cheddar granite is predominantly a granite gneiss body; however, massive pink and reddish granites are common in gneissic areas, and included patches of the invaded schist occur within the mass. Much of the border zone of this pluton is characterized by the development of pegmatitic facies. Hybrid gneiss and migmatite occur within the body but are not common.

The central body on Figure A-16 is the Cardiff plutonic complex, which consists of three main intrusive sheets: the Centre Lake granite, the Monck Lake granite, and the Deer Lake syenite. The body is flanked by metasediments that are intruded and invaded by syenitic and granitic rocks. Much sedimentary material occurs as interlayered wide bands in the complex. The Centre Lake leucogranite sheet is a "U"-shaped southward-pitching anticlinal sheet. Pink, leucocratic, alaskitic gneiss comprises the bulk of the sheet; however, the margins of the sheet are hybrid granitic gneiss with some pegmatitic facies. The Monck Lake leucogranite forms a central, steeply dipping fold. This leucogranite body is similar to the Centre Lake granite and is a pink, equigranular gneiss. The Deer Lake syenite is a medium-to coarse-grained syenite gneiss which is intruded and replaced by the Monck Lake granite and also intrudes and replaces Grenville metasediments.

The northernmost plutonic body, the Faraday granite, is a medium- to fine-grained leucogranite gneiss which forms a south-dipping sheet extending in an E-NE direction. This sheet is overlain by a narrow zone of migmatite and hybrid gneiss and a wide zone of metamorphic gneisses, including para-gneiss, amphibolite, marble, nepheline syenite, and syenite gneiss. It is underlain by a complex of hybrid granitic gneiss.

Modal and major element analyses of these granites are included on Table A-13.

TABLE A-13

ANALYSES OF GRANITES AND SYENITE IN THE BANCROFT DISTRICT, After Satterly (1957)

	1	2	3	4
SiO_2	74.96	75.99	57.37	76.06
Al_2O_3	13.06	12.15	14.73	12.01
Fe_2O_3	0.34	1.40	4.61	1.43
FeO	1.00	1.13	4.52	1.19
MgO	0.12	.25	0.44	0.23
CaO	0.91	.81	5.15	0.83
Na_2O	3.85	4.40	6.70	4.15
K_2O	4.55	3.80	3.51	3.70
H_2O^+	0.23	.38	0.28	0.34
H_2O^-	0.01	.03	0.08	0.17
CO_2	0.32	.17	0.72	0.10
TiO_2	0.24	.19	0.79	0.22
P_2O_5	0.00	0.00	0.14	0.12
Cr_2O_3	0.01	.01	0.01	0.01
MnO	0.03	.03	0.13	0.02
V_2O_3	0.01	.01	0.01	0.01
Total	99.64	100.75	99.29	100.47

1, 2 Center Lake granite
3 Deer Lake Syenite
4 Monck Lake Syenite

Section 2.3.4 The Ore Deposits

Section 2.3.4.1 General

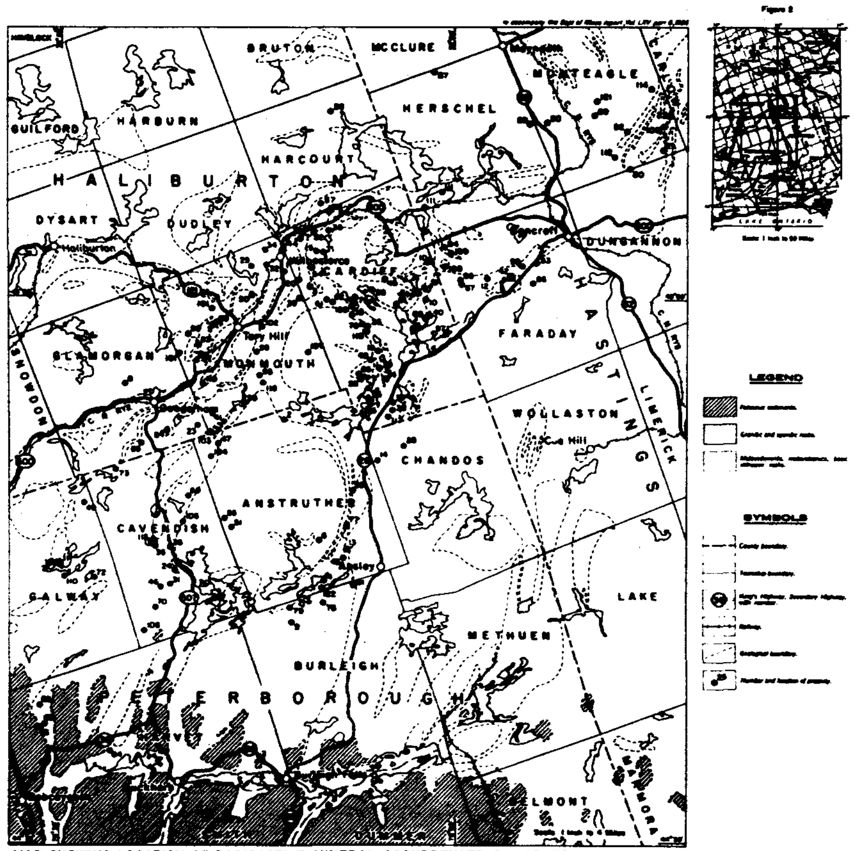
Satterly (1957) lists 122 separate uranium properties in the Bancroft district (Figure A-17). There are several types of uranium deposits at Bancroft, including pegmatite, metasomatic, and hydrothermal vein deposits; all gradations occur among these three types. Carbonatite or fenite uranium deposits have also been reported. Table A-14 (Satterly, 1957) is one of several classification schemes of Bancroft uranium deposits. Only the pegmatite deposits have been mined for uranium; the principal producers are the Bicroft and Faraday mines. Lesser amounts of uranium were mined from the Greyhawk and Canadian Dyno Mines.

The mixed gneiss and paragneiss that surround much of the granitic gneiss plutons are the chief host rocks for the radioactive deposits. The deposits occur either within the mixed gneiss bodies near the contacts of granitic gneisses or within the granitic gneiss bodies near their margin. Lead isotope studies yield ages of 950-1070 m.y. for uraninites, whereas K-Ar biotite ages for the ores range from 899-1245 m.y. (Robinson, 1961).

Section 2.3.4.2 The Bicroft Uranium Mine

Section 2.3.4.2.1 Host Rocks

The Bicroft mine lies on the southeastern margin of the Cardiff plutonic complex (Figure A-16), very near the Centre Lake granite and within a northerly-trending belt of paragneiss and amphibolite. The ore-bearing pegmatites lie in country rocks composed of biotite paragneiss, amphibolite, scapolite-biotite paragneiss, a narrow band of silicated marble, and metasomatized gneisses. A variety of pegmatites intrude and replace the country rock. Among the varieties of pegmatites are: (1) pyroxene syenite



MAP SHOWING LOCATION OF RADIOACTIVE MINERAL OCCURRENCES, BANCROFT AREA, ONTARIO

Figure A-17

After Satterly (1957)

Table A-14

URANIUM DEPOSITS OF THE BANCROFT DISTRICT
(examples indicated in parentheses)

After Satterly (1957)

- I. Deposits in granitic and syenitic pegmatites
  - A. Zoned pegmatites (MacDonald)
  - B. Unzoned pegmatites
    - 1. Red pegmatites (Faraday)
    - 2. White pegmatites (Zenmac)
- II. Metasomatic deposits in limy rocks
  - A. Metasomatic deposits in marble (Canadian All Metals)
  - B. Metasomatic deposits in metamorphic pyroxenite (Bicroft, in part)
- III. Hydrothermal deposits
  - A. Calcite-fluorite-apatite veins (Fission)
  - B. Calcite-fluorite-apatite-biotite-pyroxene veins (Cardiff)
  - C. Anhydrite-calcite-uralite veins (Faraday, in part)
- IV. Carbonatite
  - A. Calcite-biotite-hornblende-apatite vein (Basin)

pegmatite, (2) porphyroblastic granite pegmatite, (3) pyroxene granite pegmatite, (4) cataclastic quartz-rich pegmatite, and (5) microcline-quartz granite pegmatite. Types 3 and 4 contain economic concentrations of uranium.

Section 2.3.4.2.2 Mineralogy

Ore minerals of the quartz-rich pegmatites include (Cunningham and Dunlop, 1967):

1. uraninite
2. uranorthorianite
3. allanite
4. pyrochlore-microlite
5. betafite
6. "rare earth phosphate-silicate"

Gangue minerals of the dikes' quartz-rich facies are:

1. quartz (smoky)
2. zircon
3. pyrite, pyrrhotite
4. molybdenite
5. fluorite (purple)
6. calcite
7. amphibole
8. anatase

Minerals of the ore-bearing pyroxene granite pegmatite are:

1. microcline microperthite
2. albite
3. quartz (white, smoky or red stained)
4. augite
5. biotite

6. hornblende
7. apatite
8. pyrrhotite
9. fluorite
10. uranothorite

Section 2.3.4.2.3 Ore Guides

The main ore guides for prospecting are:

1. Richest ore is found at footwalls or hanging walls of contacts.
2. Ore bodies most frequently cut or are within garnetiferous paragneiss.
3. Most high grade sections are red altered.
4. Ore is most highly concentrated in fine shatter-zones.

Section 2.3.4.2.4 Well rock alteration

Some epidotization, tourmalinization, and scapolitization of the wall rocks occur in the vicinity of the dikes. Where dikes intrude pelitic sillimanite-garnet gneisses, there is frequently the development of a lit-par-lit gneiss zone of 0.3-7.5 m wide. A limited amount of syenitization of wall rocks possibly takes place in the vicinity of the dikes.

Section 2.3.4.3 Faraday Mine (Metal Mines Ltd.)

The pegmatites are the host rocks for the uranium ore. In the vicinity of the mine, no uranium has been found in the pyritic rocks or mafic intrusives except as scattered and isolated crystals.

The mine workings are in the western portion of the large, complex, mafic intrusive known as the Faraday metagabbro. Uranium ore bodies occur in a swarm of leucogranite, leucogranite pegmatite, pyroxene granite and pyroxene granite dikes that cut gabbro and amphibolite. Both the Grenville metasediments and the metagabbro are intruded by nepheline syenite, syenite, and granite. This assemblage forms a zone of mixed hybrid gneisses lying on the south margin of the Hastings highland gneiss complex.

Anhydrite-pegmatite deposits grade into dike rocks that have been variously classified as pegmatite or hydrothermal deposits. Anhydrite commonly occurs as a minor interstitial mineral in pegmatite; but over the distances of a few centimeters or meters, it may become the dominant mineral.

Section 2.3.4.3.1 Mineralogy

Ore minerals in the pegmatites include:

1. uraninite
2. uranothorite
3. thorite
4. allanite
5. uranophane
6. beta-uranophane (rare)
7. davidite
8. euxenite
9. cyrtolite

Mineralogy of the granite dikes is:

1. microcline; microcline perthite
2. albite, var. peristerite or oligoclase
3. augite (hornblende-chlorite replaces)
4. quartz; clear to smoky, rusty to jasper red
5. magnetite
6. pyrite, marcasite (not common)
7. hematite
8. zircon
9. calcite (in vugs)
10. sphene
11. fluorite

Mineralogy of the anhydrite dikes is:

1. anhydrite
2. green diopsidic pyroxene (uralitized)
3. peristerite
4. red microcline
5. quartz (smoky or amythest)
6. calcite (locally)
7. apatite
8. uraninite
9. uranothorianite
10. cyrtolite
11. secondary uranophane
12. hematite

The paragenetic sequence in anhydrite dikes is as follows: pyroxene-peristerite-anhydrite-microcline-quartz.

Section 2.3.4.3.2 Ore Guides

The main ore guides are (Satterly, 1957; Bullis, 1965):

1. abundant magnetite
2. abundant pyroxene
3. reddening of feldspar by hematization
4. red flecking or staining of quartz
5. fracturing on platy sheeting parallel to walls
6. granitic rather than pegmatitic texture
7. The important controlling factor for the pegmatites is a larger tight fold with subsidiary fractures across it; however, there are a number of ore-bearing pegmatites that have no apparent relationship to the fold.

Section 2.3.4.3.3 Wall Rock Alteration

Tourmaline-scapolite alteration is noticeable along margins and contacts or along shear planes and fractures of the metagabbros and pyroxenites. The alteration is probably due to metasomatic alteration caused by the injection of the granitic-syenitic pegmatites. Alteration zones contain scapolite, tourmaline, magnetite, sphene, pyrite, pyrrhotite, rutile, and minor apatite.

Magmatic stoping or engulfing of the country rock has taken place on a large scale; there are many blocks of paragneiss and pyroxenite in the pegmatite.

Section 2.3.4.4 Greyhawk Mine

The Greyhawk mine is on the eastward extension of the metagabbro body that serves as the country rock for the Faraday ore deposits. A wide belt of mixed syenitic gneiss lies to the north, and a complex metagabbro and gabbroic amphibolite lies to the south. The metagabbro is cut by ore-bearing, uraniferous, pegmatitic granite dikes.

The country rock throughout the mine workings is ortho-amphibolite derived from the metagabbro. The metagabbro is strongly fractured and jointed; some pegmatite dikes follow the joint directions.

Two facies of mineralized pegmatites occur: a magnetite-rich variety and a quartz-rich variety. The typical dike rock is a red, porphyroblastic, pegmatite-leucogranite containing brick-red albite, microcline-perthite porphyroblasts, smoky to white quartz, and minor pyroxene.

Section 2.3.4.4.1 Mineralogy

Ore minerals of the granite pegmatites from the ore body are:

1. uranothorite
2. uraninite

3. pyrochlore
4. allanite
5. uranophane

Gangue minerals of the ore-bearing granite pegmatites include:

1. quartz
2. sphene
3. magnetite
4. zircon
5. pyrite
6. hornblende
7. hematite
8. calcite
9. epidote
10. titanite

Mineralogy of pegmatites in the mine area is:

1. peristerite
2. microcline perthite
3. quartz (clear to smoky)
4. pyroxene
5. magnetite
6. pyrite
7. tourmaline
8. biotite
9. calcite

Section 2.3.4.4.2 Ore Guides

The main ore guides are:

1. Ore-grade pegmatites are generally red while barren dikes are typically pink.
2. Ore shoots are characterized by cataclastic structure, abundance of magnetite, deep red staining, and uralitization of pyroxenes.
3. Ore shoots occur as hanging wall or footwall zones of enrichment.

Section 2.3.4.4.3 Wall Rock Alteration

Amphibolite shows deep red coloration when adjacent to mineralized pegmatite dikes. Dikes are cut by chlorite-coated fractures.

Section 2.3.4.5 Canadian Dyno Mine

The deposits are in a belt of paragneiss, para-amphibolite, and other rocks at the east flank of the Cheddar granite. The host rocks are commonly biotite-hornblende-feldspar gneiss cut by a swarm of pink, pegmatitic leucogranite dikes. The radioactive dike rocks are pink to red leucogranite with albite, microcline, smoky quartz, magnetite, and accessory minerals.

Section 2.3.4.5.1 Mineralogy

Ore minerals in the pegmatite dikes are:

1. uraninite
2. uranothorite
3. allanite
4. uranophane

Gangue minerals of the pegmatite dikes include:

1. microcline
2. peristerite
3. smoky quartz
4. magnetite
5. titanite
6. zircon
7. hematite
8. pyrite

Section 2.3.4.5.2 Ore Guides

Ore sections may be at the hanging wall or footwall or across the whole width of the dike. Feldspars in the ore shoots are a deeper red due to more intense hematization. High-grade sections are commonly adjacent to inclusions of amphibolite.

Section 2.3.4.6 Richardson Deposit, Wilberforce, Ontario

The Richardson deposits are a series of lenses in a belt of rocks mapped as metasedimentary gneiss invaded by granite in a terrane containing granite, granite gneiss, pegmatite and hybrid gneiss (Rowe, 1952). Four types of wall rock are associated with the deposits; oligoclase-biotite-magnetite gneiss, scapolite-biotite gneiss, oligoclase amphibolite, and perthite quartz pegmatite. The principal host rock, oligoclase-biotite-magnetite gneiss, is generally foliated due to alignment of biotites, but appears massive in other areas.

The deposits occur in zoned veins containing a uranium-rich calcite-, fluorite-, apatite-rich core. The internal structural and textural features of these veins are quite similar to those of granitic pegmatites.

Section 2.3.4.6.1 <u>Mineralogy</u>

Zonation of the Richardson pegmatites is as follows:

1. Outer oligoclase-microcline zone
   a. oligoclase
   b. microcline
   c. minor biotite, hornblende, carbonate, fluorite, apatite, zircon, opaques
2. Antiperthite zone
   a. antiperthite
   b. oligoclase
   c. hornblende
   d. calcite
   e. fluorite
   f. tourmaline
   g. zircon
3. Hornblende zone
4. Calcite-fluorite-apatite core
   a. calcite
   b. fluorite
   c. apatite
   d. labradorite
   e. magnetite
   f. hematite
   g. uraninite

The following paragenetic sequence has been observed:

1. oligoclase of the oligoclase-microcline zone
2. microcline of the oligoclase-microcline zone
3. antiperthite
4. hornblende
5. calcite-fluorite-apatite core
6. uraninite

Minor mineral constituents are pyrite, pyrrhotite, chalcopyrite, molybdenite, allanite.

Section 2.3.4.7 Metasomatic Deposits

Seventeen deposits in the Bancroft district are metasomatic deposits in marble; all deposits are quite similar (Satterly, 1957). The host rock is a silicated marble usually containing diopside,phlogopite, and occasionally tremolite. Accessory minerals include: apatite, titanite, scapolite, dravite, pyrite, pyrrhotite, and molybdenite. Pink calcite is a conspicuous mineral at 12 of the deposits. The most common radioactive mineral is uraninite, followed by uranothorite; pyrochlore and thorite are rare.

Metamorphic pyroxenite bodies are found as lenticular metasomatic deposits in amphibolites and marbles that have been intruded by syenitic or granitic rocks. The pyroxenite is composed mainly of dark green pyroxene with accessory black mica, apatite, scapolite, titanite, purple fluorite and uraninite. Uraninite appears to be controlled or associated with:

1. the abundance of mica
2. scapolite-rich bands
3. pyroxenite contacts with syenite or syenite pegmatite

Section 2.3.5 Origin of the Ores

Suggested sources of the uranium are:

1. "sweated out of host metasedimentary rocks during pegmatite emplacement" (Robinson, 1960; Evans, 1962);
2. fusion of uraniferous conglomerates or black shales producing magmas enriched in uranium (Cunningham-Dunlop, 1967).

Dominant processes in the crystallization of the ores reported are:

1. Kelly (1958) concluded that metasomatic replacement played a large part in the formation of the Bicroft pegmatites.
2. Bateman (1955) believed the Bancroft deposits are the result of late magmatic or deuteric stage of evolution of pegmatite.
3. Robinson (1968) stated "the granitic, pegmatite , and metasomatic deposits are largely characterized by field evidence pointing to dominance of replacement processes with fracture filling playing a minor role."
4. Satterly (1957): "Deposits are of the pegmatitic granite type and these are usually accompanied by metasomatic replacement and assimilation of wall rocks."
5. Evans (1964) on the Bicroft pegmatites: "It is concluded that the dikes are largely of metasomatic origin."
6. Cunningham-Dunlop (1967): "The marked association of the pegmatites is interpreted as evidence that these sources were differentiating magmas which gave rise to metasomatizing fluids, intrusive bodies, and water-bearing solutions enriched first in Na, then K and Si, and ultimately in accessory elements and volatiles."

If, in fact, pegmatites crystallize from the aqueous vapor phase (metasomatizing fluid) evolved by granitic magmas in the late stages of solidification of granite (Jahns, et al., 1964), then much of the confusion about whether these deposits are pegmatite or metasomatic would be reduced to a problem of semantics.

Section 2.4 Quebec

Section 2.4.1 Location

The main location is in eastern Quebec, along the North Shore of the Gulf of St. Lawrence. The main occurrences are near Sept Iles, Baie Johan Beetz, Romain, and St. Augustin. Shaw (1958) reported many other deposits occurring between Sept Iles and the Ontario-Quebec border along the North Shore of the St. Lawrence River.

Section 2.4.2 Regional Geology (Baldwin, 1970)

All of the known radioactive deposits along the North Shore of the Gulf of St. Lawrence occur in the consolidated rocks of the Grenville province of the Canadian Shield (Figure A-11; Baldwin, 1970). A series of metamorphosed sedimentary rocks comprise the oldest formations in the region; the rock types included are: metamorphosed calcareous and argillaceous sandstones, quartzone sandstones. The most common rock type is quartzofeldspathic gneiss; however, minor amounts of amphibolite and calc-silicate rocks occur.

The metasediments have been intruded by granitic and gabbroic rock, resulting in the development of migmatite. Granites vary in composition from syenitic to quartz-rich and in texture from massive to foliated. Some granite stocks have intrusive, igneous characteristics,while other granites appear to have formed by granitization.

Sills, dikes and lenses of granite pegmatite occur throughout the North Shore; these pegmatites apparently are spatially and genetically related to local granite bodies.

Mafic rocks locally intrude the metasediments in sill-like bodies and are probably genetically related to the granites.

The Precambrian rocks of the region have been complexly folded and faulted; several generations of folds have been identified.

Section 2.4.3 Johan Beetz

Section 2.4.3.1 Local Geology

A stratigraphic section (Table A-15; Cooper, 1957, p. 9) summarizes the major units in the Johan Beetz area. The oldest consolidated rocks of the area include metasedimentary rocks grading from quartzite to biotite schist, some of which have been transformed into migmatite. Altered gabbro sills intrude the metasediments. Granite gneisses cut the metasediments; the granites are in turn cut by a younger, medium-grained, generally massive granite (Lac Turgeon granite). Two generations of pegmatite are recognized, correlating with the granite gneiss and massive granites. The radioactive deposits occur in the pegmatites of the younger, Lac Turgeon granite (Figure A-18).

Section 2.4.3.2 The Ore Deposits

Section 2.4.3.2.1 Host Rocks

Pegmatite masses in or at the margins of the Lac Turgeon granite or in a small stock just south are the host rocks for uranium mineralization. The pegmatites vary from white to pink to red in color and from medium to coarsely crystalline in texture. There is more radioactivity in the pegmatites at the north and east margins of the Lac Turgeon granite. Mineralized granites and gneissic granites are either phases of late-stage pegmatite injection or are a consequence of mineralization due to alteration and mineralization by nearby pegmatites.

TABLE A-15

TABLE OF FORMATIONS, JOHAN BEETZ AREA
After Cooper (1957)

Cenozoic	Sand, clay, gravel, erratic boulders	
	Great Unconformity	
Precambrian	Intrusive Rocks	Pegmatite
		Intrusive Contact
		Medium-grained biotite granite Coarse-grained biotite granite
		Intrusive Contact
		Gneissic Granite and Pegmatite
		Intrusive Contact
		Uralite Gabbro and Derivatives (a) Uralite Gabbro (b) Amphibolite (c) Amphibole gneiss (d) Hybrid rocks
	Intrusive Contact	
		Migmatite (Injection gneiss)
	Metasedimentary Rocks	Micaceous quartzite, quartz-biotite schist, quartz-biotite gneiss
		Grey quartzite, calcareous quartzite, crystalline limestone, thin conglomerate lens

After Cooper (1957; Quebec Dept. Mines Geol. Rept..

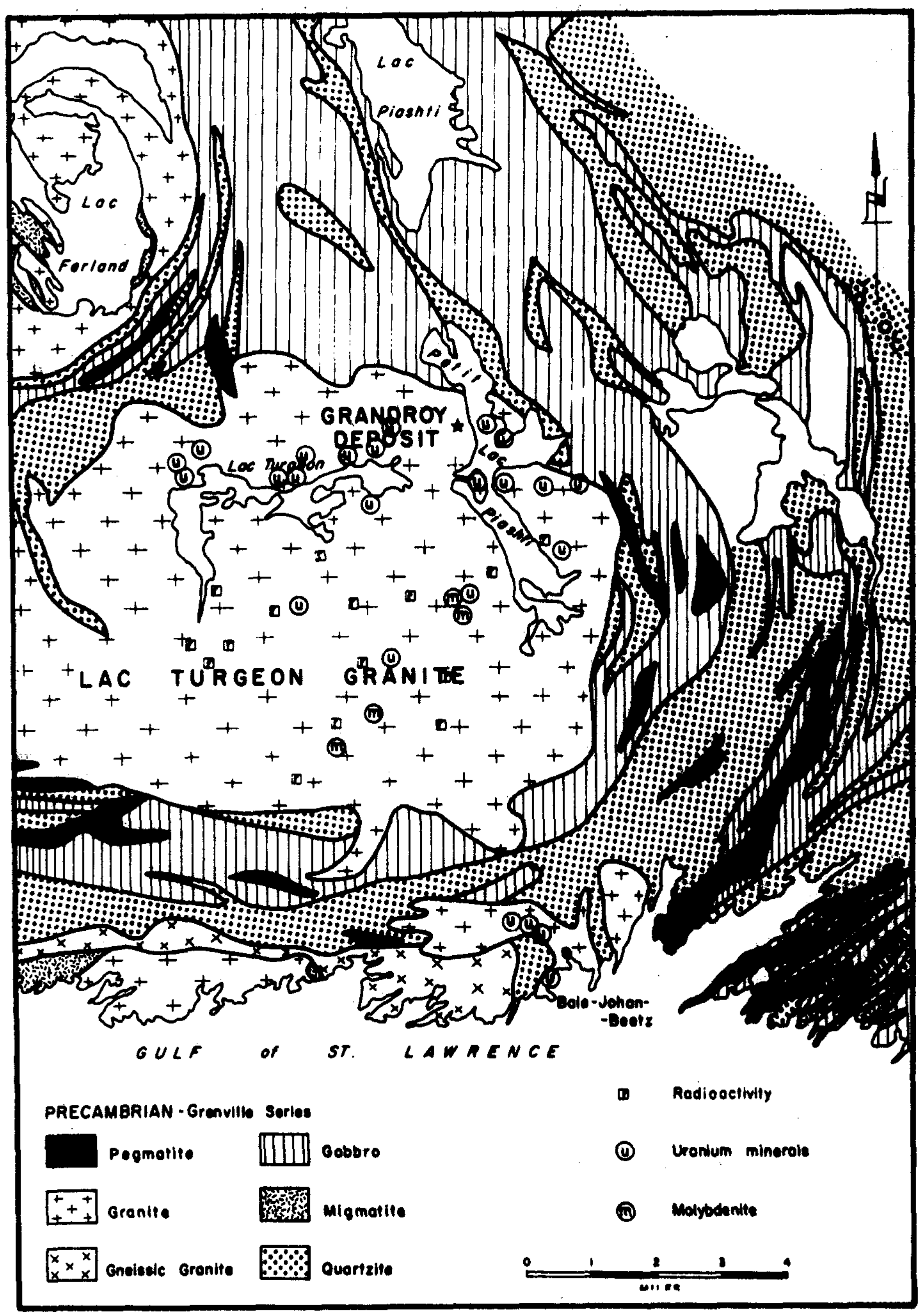


Figure A-18

Geology of the Johan Beetz area, Quebec

After Baldwin (1970); Can. Min. Met. Bull.

Close-spaced drilling has revealed a large body of red granite that contains several zones of small irregular patches of pegmatite that has a mean uranium content of 70 ppm of acid-soluble uranium. The largest of the zones is 300 x 760 m and has been tested to 45 and 90 m depth.

Section 2.4.3.2.2 Mineralogy

Ore minerals at the Grandroy Prospect in pegmatites are (Cooper, 1957; Little, 1970; Baldwin, 1970):

1. uranothorianite
2. uranothorite
3. betafite
4. euxenite
5. cyrtolite

Mineralogy of the pegmatites is:

1. plagioclase
2. smoky quartz
3. biotite
4. hornblende
5. microcline
6. magnetite
7. molybdenite
8. monazite
9. zircon
10. hematite (locally)

Characteristic U minerals and other characteristic minerals in the St. Pierre uranium property (uraniferous red granite) include:

1. uraninite
2. zircon
3. thorite
4. allanite
5. magnetite
6. sphene
7. apatite

Section 2.4 3.2.3 Ore Guides

1. White pegmatites containing muscovite are barren.
2. The highest concentrations of uranium are in white and gray pegmatites rich in plagioclase and biotite.
3. Many joint planes have higher-than-average radioactivity; however, it is not thought that jointing, faulting, or shearing were important in the genesis of radioactive mineralization.

Section 2.4.4 St. Augustin

Section 2.4.4.1 Geology

The St. Augustin river area comprises a diverse assemblage of Precambrian gneisses, granites, amphibolites, quartzites and calc-silicate rocks (Figure A-19; Davies, 1963, 1965; Baldwin, 1970). Diabase and gabbro dikes of uncertain age intrude this terrane. Veins of quartz pegmatite and aplite occur throughout the area. The occurrences of uranium and thorium are quite varied and possibly reflect the complexity of the geological history of the area.

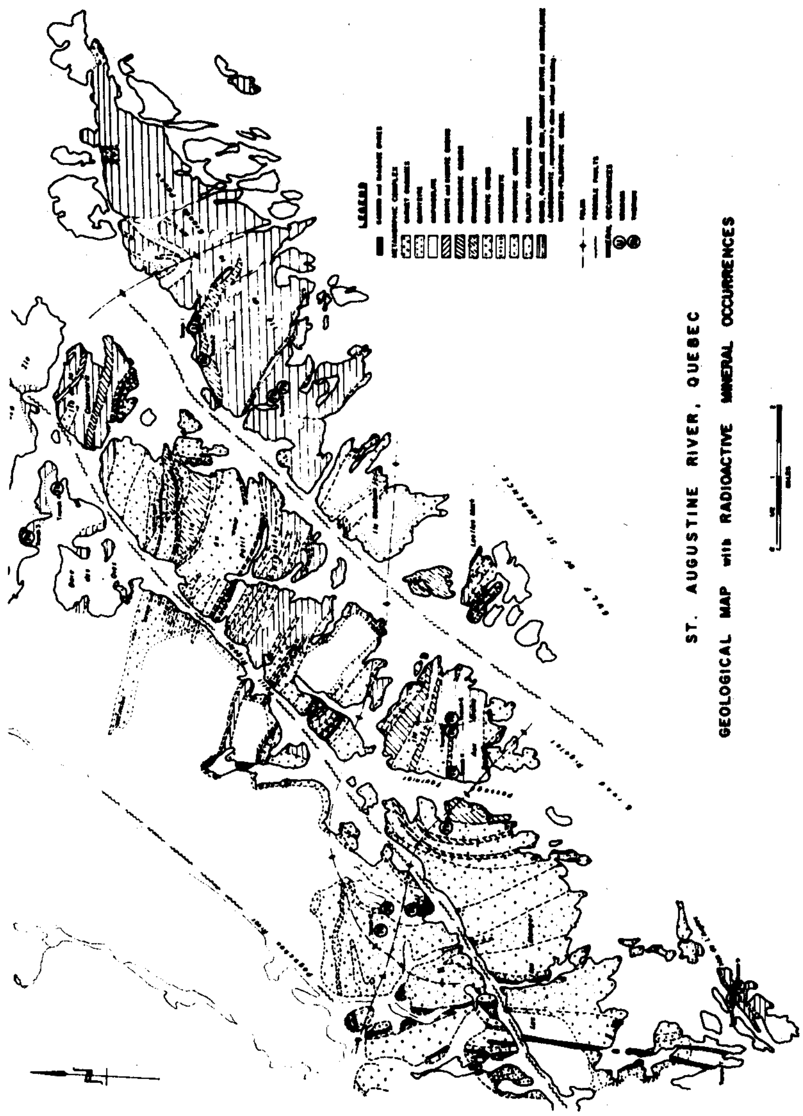
Section 2.4.4.2 Mineralogy

Uraninite is observed along joint planes in grey to pink quartzofeldspathic gneisses (Baldwin, 1970). Alteration of the host rocks is observed near the uraninite. Folding and faulting apparently are important controls for mineralization.

Monazite deposits occur as well and are:

1. in migmatite with veins of granite pegmatite and red porphyry invading paragneiss;
2. in narrow irregular veins of pegmatite;
3. associated with magnetite in paragneiss;

Figure A-19



After Baldwin (1970): Can. Min. Met. Bull.

4. disseminated in a stratigraphic horizon within the quartzo-feldspathic gneiss;
5. disseminated in coarsely crystalline granite porphyry;
6. with clots of biotite in coarsely crystalline, massive, granite porphyry.

Section 2.4.5 St. Simeon

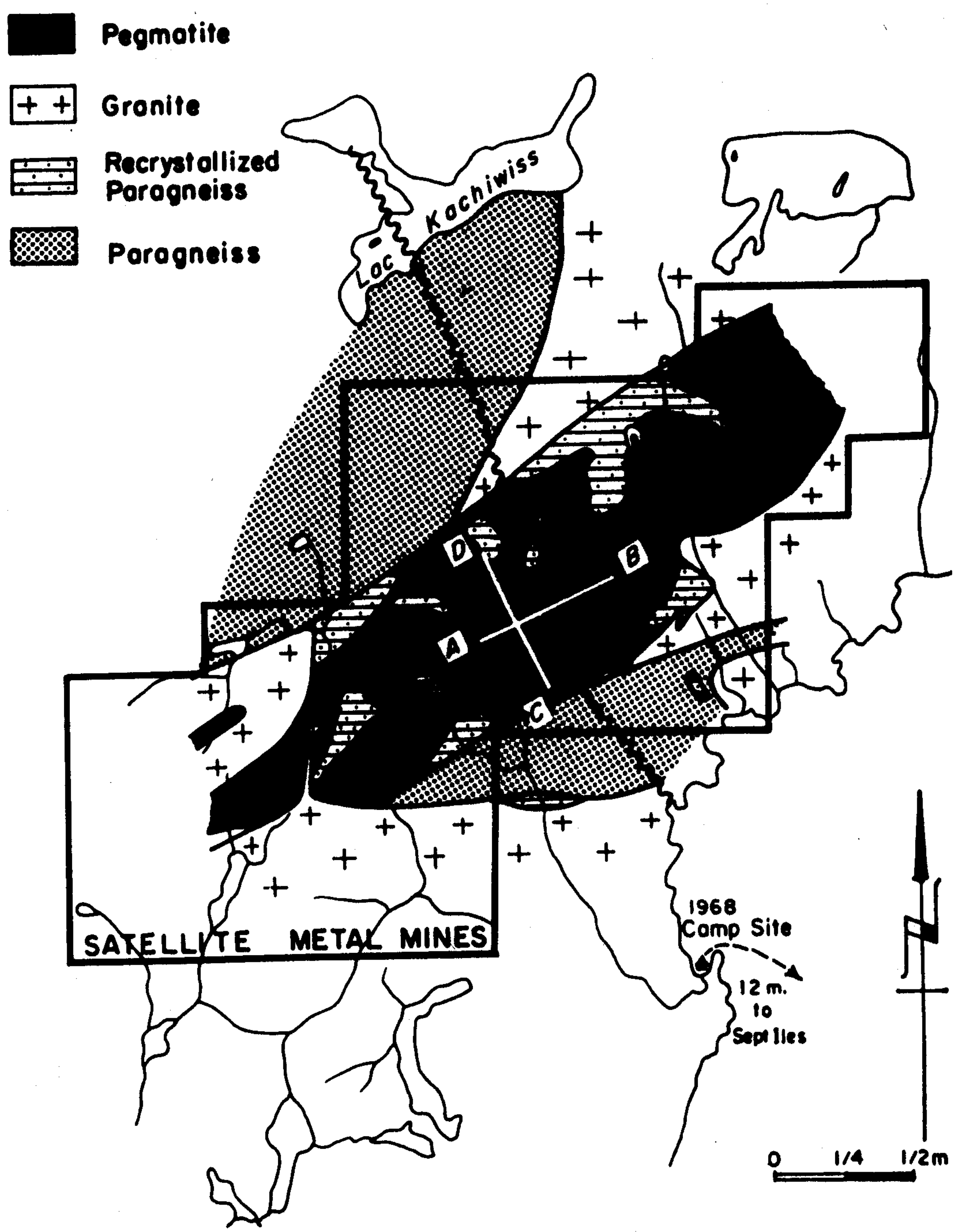
Radioactive mineralization occurs in an albite granite or tonalite sill that is locally pegmatite (Shaw, 1958). The country rock is migmatitic. The principal rocks exposed in the area are hornblende schists, coarse granite, and migmatites.

The major constituents of the mineralized granite are quartz and altered oligoclase with minor chlorite, magnetite, zircon, apatite, and radioactive minor minerals. Fergusonite is the major radioactive mineral, but some uraninite and allanite are present. The feldspar is stained brick red when close to radioactive minerals.

Section 2.4.6 Sept Iles

Radioactive pegmatites crop out in a high-grade metamorphic terrain underlain by Grenville paragneisses and granite gneiss in the Sept Iles area (Baldwin, 1970). Detailed geologic studies of this area indicate four major rock units: paragneiss, recrystallized paragneiss, augen granite, and pegmatite (Figure A-20). Pegmatites invade recrystallized paragneiss along a 0.8 km-wide, NE-trending zone and consist of potash feldspar and lesser amounts of quartz, plagioclase, and biotite. Magnetite and several radioactive minerals, including uraninite, uranothorite, monazite, uranophane and allanite are erratically distributed in the pegmatites. Preliminary data yield a grade of 0.4-0.8 lbs/ton U for samples from several trenches.

Figure A-20



Geological Map of the Sept-Iles Area, Quebec.

After Baldwin (1970); Can. Min. Met. Bull.

Section 2.5 Mont Laurier

Section 2.5.1 Location

The Mont Laurier area is located in the province of Quebec: Mt. Laurier, Kempt Lake, and Cabonga areas.

Section 2.5.2 Geology

The geologic history of the Mt. Laurier area has been described elsewhere in this volume (Chapter 3) in a discussion of an excellent paper by Wynne-Edwards (1969). The local terrane is underlain by biotite gneisses, calc-silicate rocks, marble, metabasalt, and quartzites of the pre-Grenville and Grenville Group (Allen, 1971; Kish, 1975). A number of massive, pink, sheetlike bodies of granite or quartz monzonite intrude the metasediments. Aplites form sparse, thin veins in the margins of the monzonite and thicker masses at the margins of the monzonite; these aplites may be quench phases of the monzonite. Contact relations between the intrusive rocks and the metasediments are generally conformable. Injection gneisses (migmatites) occur in both the Grenville and pre-Grenville gneisses. The uranium deposits occur in pegmatites, which are described in the following section.

Section 2.5.3 Host rocks

The pegmatites that host the uranium mineralization were probably not formed in the manner implied by classical definitions of the term pegmatite. Kish (1975) notes that, by definition, a pegmatite is "an exceptionally coarse-grained igneous rock usually found at the margins of batholiths and represents the last and most hydrous portions of magma to crystallize." Both Allen (1971) and Kish (1975) propose that the bulk of the pegmatites in the Mt. Laurier area developed from local partial melting of the biotite gneisses. Kish (1975) uses the term "metamorphic pegmatite" to distinguish this variety of pegmatite from "pegmatite proper". The "metamorphic pegmatites" occur from thin migmatitic bands to thicker (up to 18 m) masses of banded pegmatite.

The main features of the pegmatite (Allen, 1971) are:

1. The pegmatite layers are conformable with the metasediments.
2. Banding and foliation of the pegmatite is parallel to that of the metasediments.
3. Inclusions of metasediment in pegmatite have the foliation and structure of the surrounding metasediments; i.e., they are not rotated.
4. The mafic minerals present are the same as those in the adjacent metasediments.
5. Contacts with the metasediments are mostly sharp.

According to Allen (1971), "the process of formation of the pegmatites is envisaged as partial melting of different layers of biotite gneiss to yield melts of slightly differing composition, crystallization temperature, and cooling to give a migmatite with alternating bands of biotite gneiss and pegmatite.. . . Pegmatite has not migrated any great distance . . ." The uranium probably was derived from the biotite paragneisses since "the biotite paragneiss in the central part of the sequence is highly radioactive."

Section 2.5.4 Mont Laurier Uranium Mines

"Metamorphic pegmatites" as defined above are mixed with gneiss (Kish, 1975). These pegmatites contain thorian-uraninite and uranothorite. The common accessory minerals are sphene, graphite, and molybdenite.

In the north area of the property, thorian uraninite and uranothorite crystals are scattered through "dirty" (biotitic and feldspathic) quartzites.

Section 2.5.4.1 Origin of the Ores

The "metamorphic pegmatite" deposits of Mt. Laurier are in considerable contrast to the uraniferous pegmatites of the Bancroft region. The Mt. Laurier deposits lack metasomatic and hydrothermal vein-type mineralization and do not exhibit the wall rock alteration that is seen in Bancroft.

Uranium mineralization in the Mt. Laurier area appears to be a consequence of localized partial melting of uraniferous metasediments. Bancroft deposits, in contrast, are probably the result of crystallization of batholith-sized granitic and syenitic magmas that exsolved an aqueous vapor phase containing dissolved granitic solids and uranium. The Mt. Laurier deposits have many similarities to the Wheeler Basin, Colorado, deposit (Young and Hauff, 1975).

Section 2.5.4.2 Mineralogy

Principal minerals are (Allen, 1971; Kish, 1975):

microcline	amphibole
plagioclase	magnetite
quartz	molybdenite
biotite	hematite (red iron oxide)
diopside	

In the vicinity of calc-silicate rocks, the pegmatites contain the following additional minerals:

- sphene
- scapolite
- apatite
- clinozoisite
- graphite

Uranium minerals in the pegmatites are:

- uraninite

uranothorite

samarskite? (Allen, 1971)

uranophane

Section 2.5.4.3 Ore Guides

1. Geochemical anomalies, radiometric uranium and thorium anomalies, and the locations of known radioactive occurrences fall in areas underlain by amphibolite-grade gneiss of the Grenville Group. In granulite-grade assemblages, radioactive indications were not found.
2. Geochemical uranium anomalies tend to be concentrated in the noses of major folds of the Grenville gneisses and near the contact zone of these gneisses with older rocks.
3. Favorable areas for uranium prospecting are those occupied by "dirty" quartzites and biotite paragneisses of the Grenville Group.

Section 2.6 The Labrador Uranium Area

Section 2.6.1 Location

This region is located in the coastal part of the area delineated on Figure A-21.

Section 2.6.2 General Geology

On Figure A-22 is a map of the area termed the "Labrador uranium area" (Beavan, 1958), which embraces roughly 6400 km^2 between the Atlantic coast and the Seal Lake area. Syngenetic disseminations of uranium minerals occur mainly in the coastal part of this area (Figure A-21). Most of the coastal area is underlain by the Aillik Series, consisting of argillites, slates, limestone, schistose pillowed flows, quartzites, sandstone, conglomerates, and the feldspathic granitized equivalents of the last three rock types.

Intrusive into the Aillik Group rocks are numerous stocks and larger bodies of granite, and a few smaller bodies of gabbro, diorite and syenite. The coastal end of the belt contains a profusion of pegmatite, lamprophyre, diabase and amphibolite dikes. A detailed stratigraphic section of the Makkovik Bay area with radiometric ages of the units is presented on Table A-16. Most of the intrusive granite-gneisses and granites range from 1500 to 1600 m.y.

Section 2.6.3 Ore Deposits

Uranium deposits are classified into four different varieties:

a. mineralization in fracture and shear zones in volcanic rocks;

b. mineralization in sedimentary rocks;

c. mineralized fault zones;

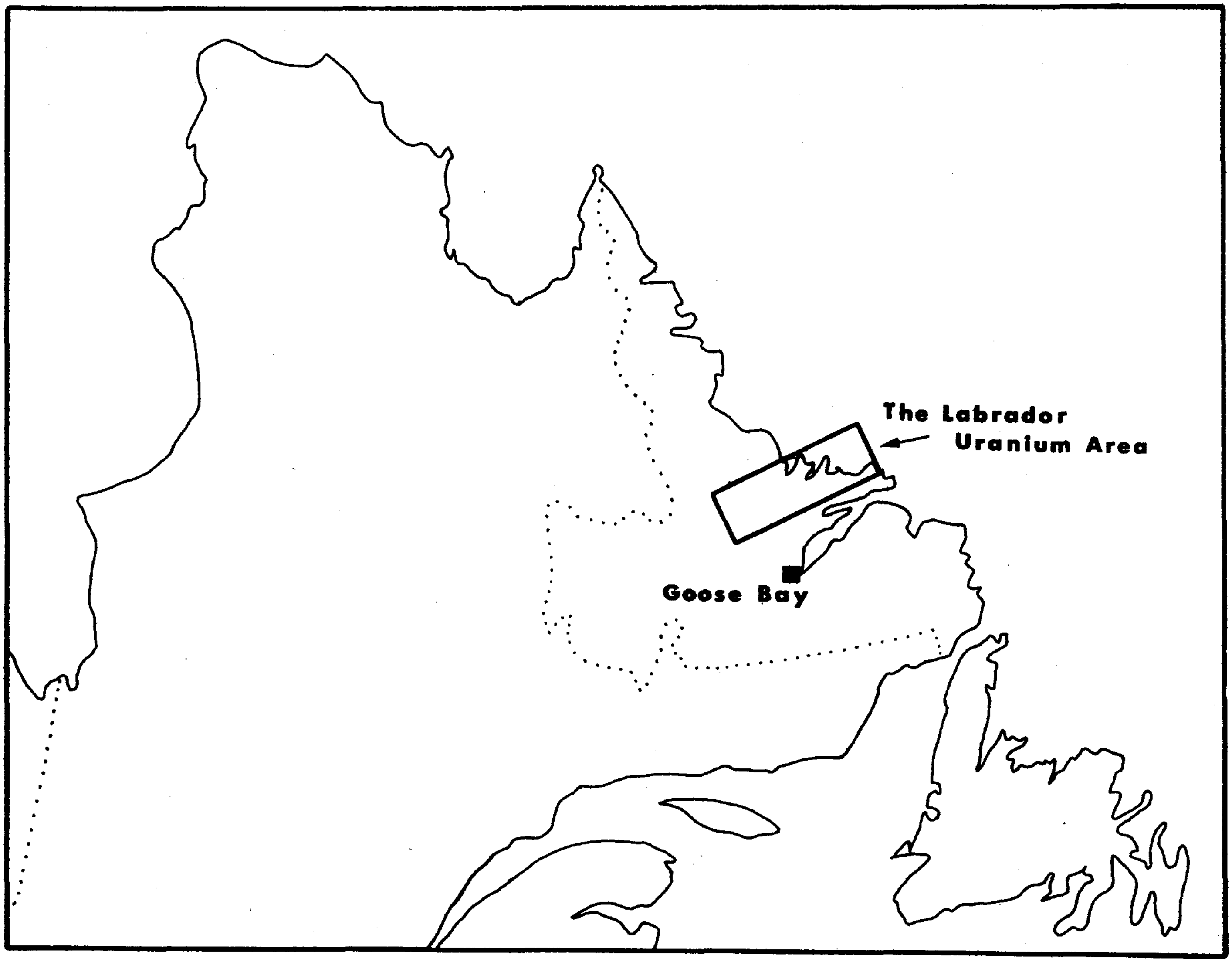
d. radioactive minerals in granitic rocks.

Occurrences of uranium mineralization include:

1. radioactivity associated with patches and streaks of migmatite in simple pegmatites and granites;
2. scattered crystals of allanite and euxenite in small pegmatite dikes; (Accessory minerals may include zircon, garnet, columbite-tantalite, uraninite and pyrochlore-microlite.)
3. uraninite mineralization in biotite-rich zones of migmatite.

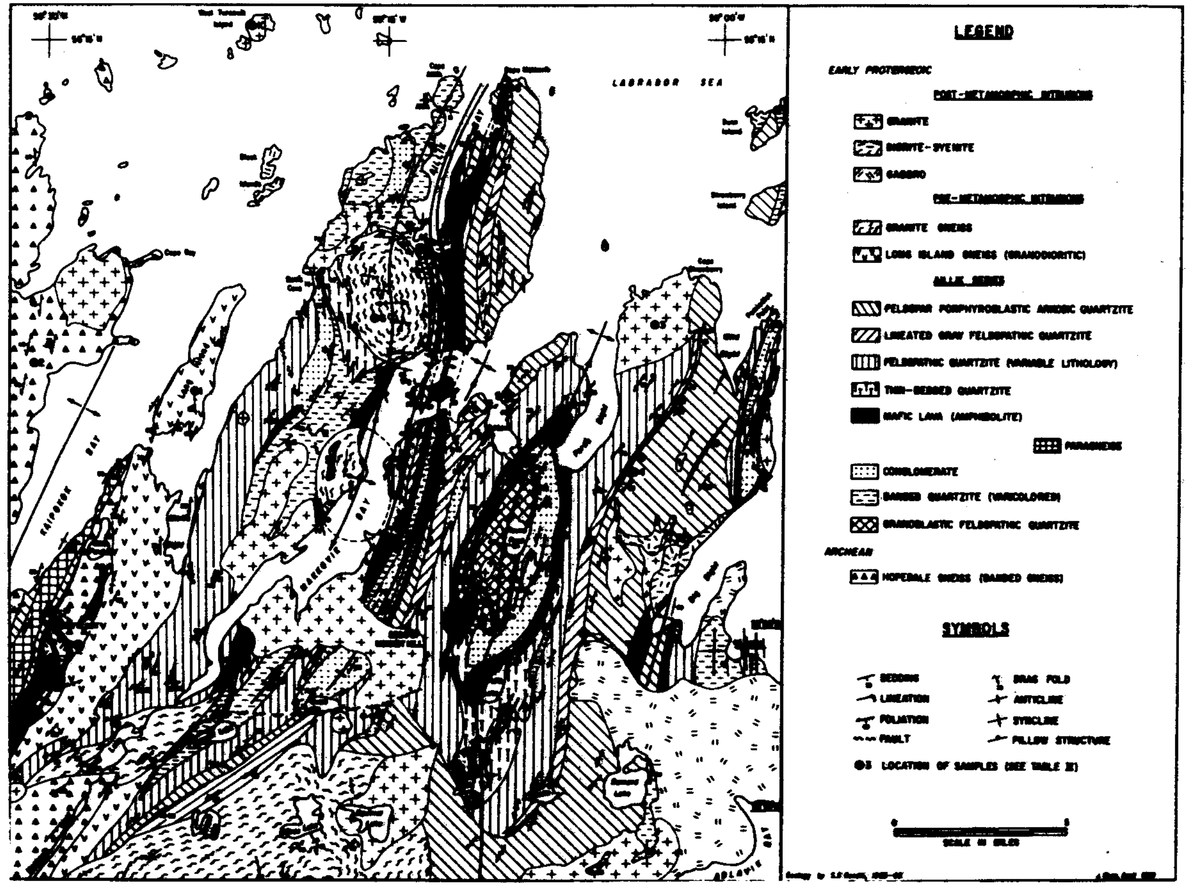
FIGURE A-21

After Beavan (1958); Geol. Assoc. Can. Proc.



The Labrador Uranium Area

FIGURE A-22



Geology of the Makkovik area, the Labrador uranium area,

After Gandhi et al., 1969

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TABLE A-16

TABLE OF FORMATIONS, MAKKOVIK BAY AREA, LABRADOR

After Ganhdi et al. (1969)

CENOZOIC Pleistocene and Recent	Till, gravel, sand, and clay
PALEOZOIC Cambrian	Lamprophyre dikes (500 to 600 m.y.)
PROTEROZOIC Helikian	Diorite and Diabase dikes (950 to 1000 m.y.)
Hudsonian Orogeny (1600 m.y. approximately)	
Aphebian	Post-kinematic Intrusions: Granites: Strawberry type (1600 m.y.) Monkey Hill type Granodiorite-quartz monzonite (1645 m.y.) Related dikes and pegmatites Others (Aphebian?): Adlavik gabbro (lopolith?) Gabbro stocks and dikes Diorite-syenite stocks and dikes Synkinematic Intrusions: Granite gneiss and gneissic granite (1530 m.y.; lenses, domes and a large mass) Pre-metamorphic Intrusions: Amphibolitic dikes (1540 m.y.), Varied felsic and mafic dikes, Long Island gneiss (biotite-hornblende-quartz-feldspar-gneiss; 1830 m.y.) Aillik Series (estimated thickness: 25,000 ft): Feldspar porphyroblastic arkosic quartzite (1545 m.y.) Lineated gray feldspathic quartzite, Feldspathic quartzite (variable lithology) Thin-bedded quartzite Mafic lava (amphibolite; 1500 m.y.) and associated tuffaceous beds Conglomerate; paragneiss Banded quartzite (varicolored) Granoblastic feldspathic quartzite
ARCHEAN (>2390 m.y.)	Hopedale gneiss (mafic banded gneiss, migmatized and much contorted; partially remobilized Archean basement; 1730 m.y.)

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Section 3 Australia

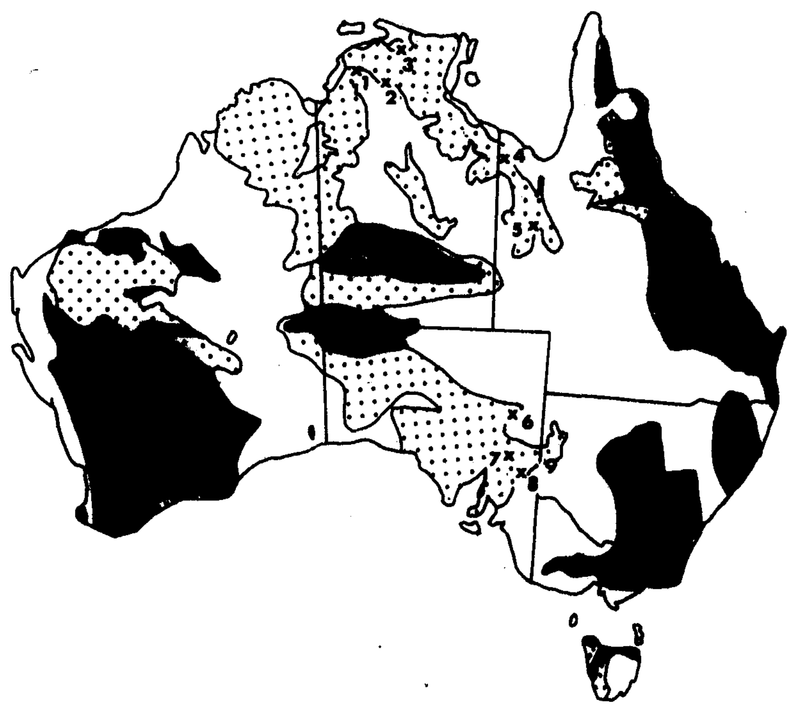
Section 3.1 Introduction

The principal uranium deposits in Australia are located along an arc, concave west, that extends across the continent from near Darwin in the north to near Adelaide in the south (Figure A-23). Although there has been some speculation about whether this "Australian Uranic Arc" constitutes a major tectonic feature that has encompassed much of Australia's geologic history (Raynor, 1960; Willis and Stevens, 1971), it definitely can be characterized as a geochemical province for uranium. Willis and Stevens (1971) have noted that this arc may represent a relatively unstable and comparatively mobile belt that lies to the east of a major shield area and has persisted since Precambrian time. Rayner (1960) concluded that high heat flow values within this belt may be related to abnormally thin continental crust. He further concluded that future uranium exploration might be most fruitful within this arc, which has undergone multiple orogenic cycles since early Precambrian, rather than the persistent shield areas to the west. Within this arc, the principal uranium deposits occur in three major geographic regions: (1) Katherine-Darwin region, Northern Territory; (2) Cloncurry-Mt. Isa, in northwestern Queensland; (3) Olary district, northeast of Adelaide. McLeod (1966) has provided a very brief summary of the major uranium deposits in Australia.

Although many of the major uranium deposits in Australia are apparently in some way genetically related to granitic rocks, very few of these deposits are actually within igneous rocks. For example, uranium mineralization in the Rum Jungle area (Katherine-Darwin Region) is primarily in Lower Proterozoic, sheared, carbonaceous shales and slates (Crohn, 1968; Walpole, 1958; Walpole et al., 1968). These sedimentary rocks flank the Rum Jungle granite complex, which may be the source of the uranium mineralization in the sediments

FIGURE A-23

Major Tectonic Units in Australia
and Principal Uranium Occurrences



Broad Tectonic Units

- **Phanerozoic strata, mainly platform cover**
- **Tasmah orogenic zone**
- **Proterozoic (2300-500 m.y.) mobile zones**
- **Archaean (older than 2300 m.y.) and probable Archaean cratonic blocks**

Major Uranium Deposits

1. **Rum Jungle**
2. **South Alligator Valley**
3. **Nabarlek-Ranger**
4. **Pandanus Creek-Westmoreland**
5. **Mary Kathleen**
6. **Mount Painter**
7. **Crockers Well**
8. **Radium Hill**
9. Broken Hill

(Dodson, et al., 1974). Another example is the famous Mary Kathleen deposit in northwestern Queensland, where uranium mineralization in Lower Proterozoic calc-granulites is apparently associated with intrusion of granitic bodies to the east and west of the deposit (Carter, et al., 1961; Matheson and Searl, 1956; Hughes and Munro, 1965).

There is one region, however, in which there are uraniferous, granitic rocks that have been actively mined for uranium. The association of uranium and granitic rocks in the Olary district, South Australia, is quite common, with the Crocker Well deposit as the best example (Campana and King, 1958; Campana, 1956; Johnson, 1958; Thompson, 1965). This deposit is clearly related to the nearby more well-known Radium Hill mine (Parkin and Glasson, 1954; Sprigg, 1954), which is in vein-type deposits in Archaean gneisses and schists. It is probably related as well to uranium occurrences in granitic rocks at Mt. Victoria (Compana and King, 1958) and in the Thackaringa area, Broken Hill district, New South Wales (Rayner, 1958a and b). All these deposits are within less than 150 km of one another.

As a result, this report on Australian uranium deposits in granite rocks will concentrate on the deposits in the Olary district, South Australia, and only briefly describe uranium occurrences in granitic rocks where there are no proven deposits of economic value.

Section 3.2 Olary District

Section 3.2.1 Location

The Olary district is located in east central South Australia, 500-600 km northeast of Adelaide (longitude 139°30' - 141°00'E, latitude 31°45' - 32°30'S).

Section 3.2.2 Regional Geology

The Western Australian Shield makes up much of the state of South Australia.

In the region near Adelaide this shield has been subdivided into two parts (Figure A-24), the Gawler Platform, and to the east, the Stuart Shelf (Forbes, 1966; Talbot, 1969). East of the Stuart Shelf are the remnants of the old Adelaide geosyncline, which existed from 1500-500 m.y. B.P. (Compston et al., 1956) and contained thick sequences of Precambrian and Cambrian sediments. A major orogeny occurred in Early Paleozoic, affecting all rocks of the Adelaide system, but intermittent compressive folding has occurred into the Cenozoic (Johnson, 1958; Campana, 1955). East of the Adelaide geosyncline, there is a small nucleus of Archaean metasedimentary and Lower Proterozoic granite rocks considered as crystalline basement and called the Willyama Block (Figure A-24). It contains both the Olary District uranium deposits as well as the famous silver-lead-zinc deposits at Broken Hill.

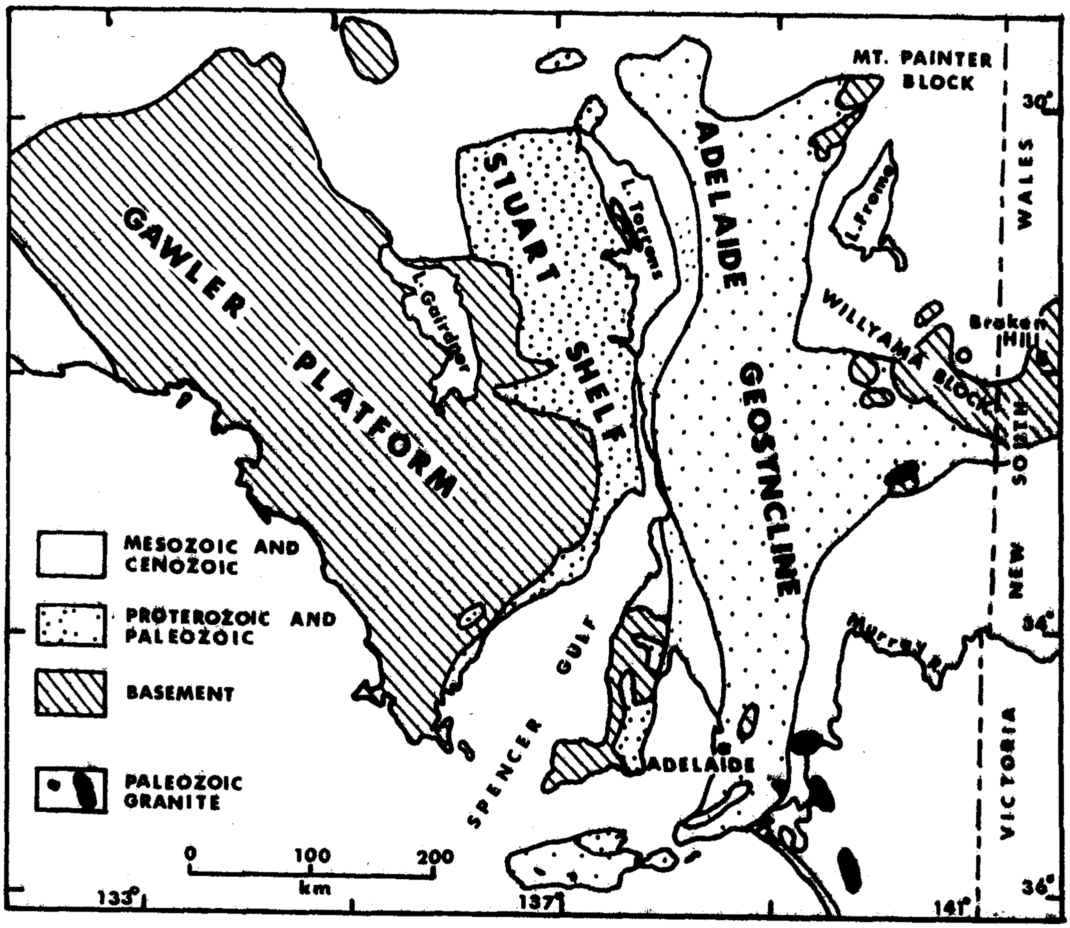
Section 3.2.3 <u>Local Geology</u>

The Olary district is west of the Broken Hill mining district and is made up chiefly of Archaean rocks of the Willyama complex, metasedimentary rocks invaded by granitic rocks, migmatites, and some basic intrusives (Campana, 1956; Campana and King, 1958). Upper Proterozoic rocks of the Adelaide system unconformably overlie those of the Archaean and Lower Proterozoic Willyama complex (Figure A-25). Campana (1955) concluded that the Willyama complex emerged from a geosynclinal trough by deep-seated crustal folding, which he postulated ultimately resulted in the Mt. Lofty-Olary arc. This arc reportedly emerged as a result of diastrophic movements that occurred repeatedly from the Precambrian to the Tertiary. Emplacement of granitic rocks and uranium mineralization apparently took place associated with this deep-seated crustal folding. It seems reasonable that the earliest stages of this continuing orogenic event probably coincided in time with the major unconformity between the Adelaide and Willyama systems, which was

FIGURE A-24

Geology of South Australia

After Forbes (1965), Trans. Roy. Soc. South Australia: and Talbot (1969), Geol. Assoc. Canada.



apparently during the Middle Proterozoic.

There are three main host-rock units for the granitic rocks and uranium mineralization (Campana, 1956; Campana and King, 1958):

Upper: Outalpa arkosic quartzites grading into granitic gneisses, containing variable amounts of feldspar and magnetite, as well as some interbedded mica schist.

Middle: Ethiudna Formation, metadolomites containing tremolite, diopside, and other calc-silicates.

Lower: Weekeroo-Billeroo schists, mica schists, paragneisses, and quartzites.

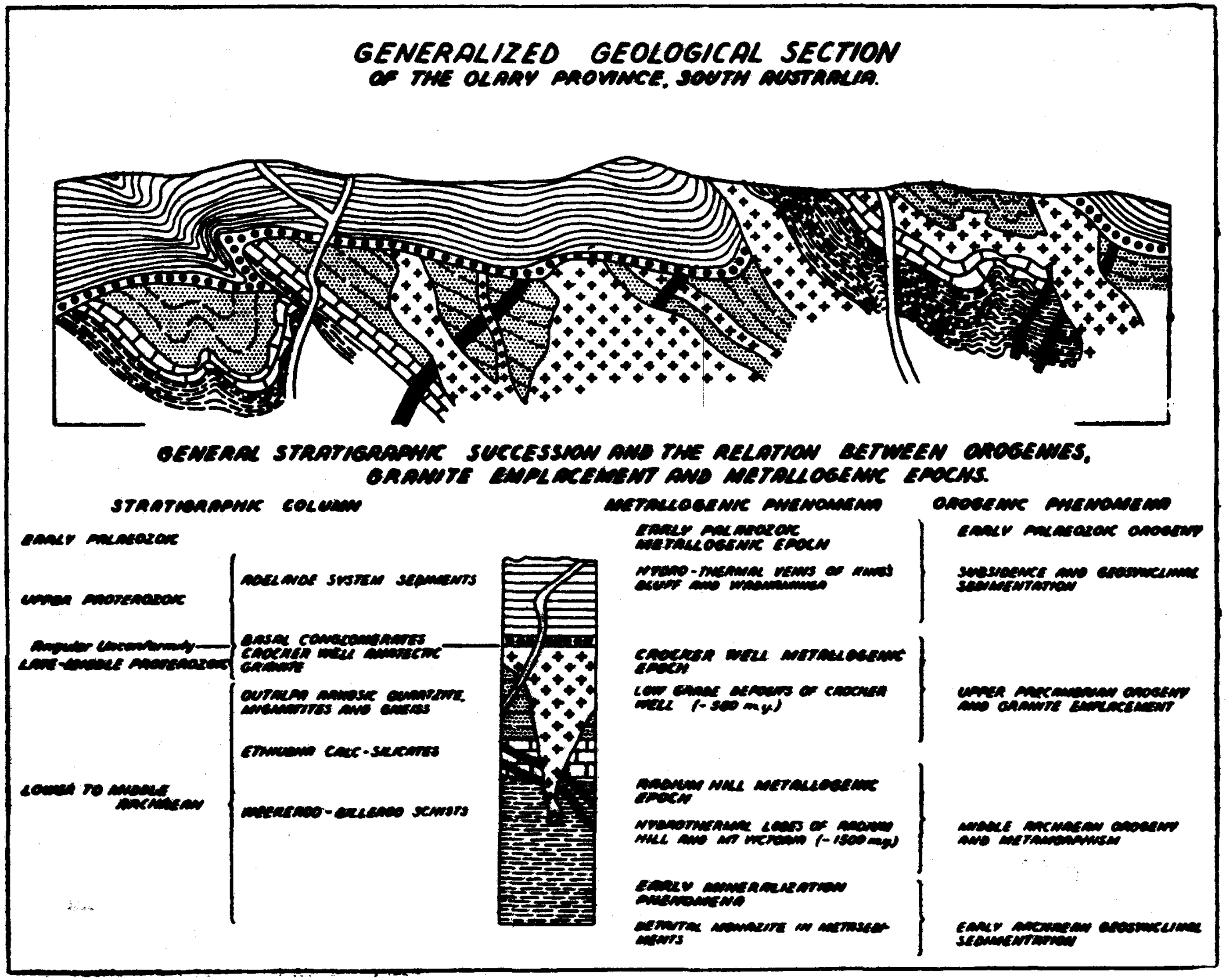
A schematic stratigraphic section is shown in Figure A-25. The entire sequence represents in excess of 3000 m of geosynclinal sedimentation.

There are at least two and perhaps three metallogenic epochs in the Olary district. The Radium Hill and Mt. Victoria deposits are 1500-1600 million years old, whereas the Crocker Well deposits have been dated at about 600 million years. All these dates are based upon uranium-lead techniques in the uranium mineral and are reported in Campana and King (1958). The older (Middle Proterozoic) event may be coincident with the major unconformity between the Adelaide and Willyama systems mentioned previously. The younger metallogenic epoch is probably related to a major orogenic event as well, an event that took place during the Late Proterozoic-Early Paleozoic and affected rocks of both the Willyama and Adelaide systems (Campana, 1956). There is only indirect evidence for a third epoch. There are bands of detrital radioactive grains in the Outalpa quartzite, implying the possibility of an Early Proterozoic or Archaean metallogenic event.

Uranium mineralization in the Olary area is generally within or associated with granitic rocks. There is considerable evidence that these granitic rocks are of anatectic origin. A typical lithologic sequence consists of

FIGURE A-25

After Campana (1956; Jour. Geol. Soc. Aust.



quartzite and feldspathized schist - banded gneiss - migmatite - massive granite, in that order. Contacts are generally gradational. Much of the granitic complex seems to be developed by either blastic recrystallization of former feldspathic beds, partial melting of metasediments and injection into surrounding rocks (anatexis), or metasomatic transfer of alkalies, silica, etc. (granitization). Pegmatites and alaskites are ubiquitous.

One of the strongest arguments for the anatectic and ultrametamorphic origin of the Olary granitic rocks is the association of most of the large granitic bodies with feldspathic quartzite of the Outalpa Formation, rather than less likely source materials such as calc-silicate rocks or schist farther down the section. Thus, a local source within the Outalpa is implied for the preponderance of granitic rocks.

Section 3.2.4 Ore Deposits

Three deposits will be discussed in the Olary District: Radium Hill, Mt. Victoria, and Crocker Well. As Radium Hill and Mt. Victoria are classified as vein deposits, Crocker Well will be stressed.

Section 3.2.4.1 Crocker Well

Geology of the Crocker Well uranium deposits has been discussed in detail by Whittle (1954a) and by Campana and King (1958). Grade of the ore has been estimated at about 0.4% U and reserves at about 12,000 tons. There are four prospects at the Crocker Well mine. The deposit is referred to as both Crockers Well" and "Crocker Well" in the literature.

Section 3.2.4.1.1 Lithology and Mineralogy

Principal lithologies in the Crocker Well area are coarse-grained, porphyritic granite-pegmatite, fine-to-medium-grained adamellite, migmatite, as well as dikes and irregularly shaped bodies of aplite, pegmatite and alaskite (Table A-17). Screens of Archaean or Lower Proterozoic metasedimentary rocks exist as well. Granitic rocks are considered to be predominantly Upper Proterozoic in age. In general, the porphyritic granite and adamellite form the cores of migmatitic bodies, surrounded by and grading outward into "ungranitized" metasedimentary rocks. A geologic map is given in Figure A-26.

Section 3.2.4.1.2 The Ore

The ore is concentrated primarily in rectangular-patterned fractures and breccia zones in the adamellite. The main ore mineral is brannerite (also called "absite"), a complex, hydrous thorium-uranium-titanium oxide that clearly can be considered of primary, hypogene origin. Secondary uranium minerals are very rare in the area. The ore mineral is confined almost entirely within the adamellite. Ore mineralization is thought to be genetically related to the thin veins of sodium-rich aplite, alaskite, and pegmatite in the fracture system of the adamellite, although relationships between these rocks and the adamellite or barren surrounding metasedimentary rocks are not clear. Davidite, a complex hydrous iron-uranium rare earth titanium oxide, which is the most common ore mineral at both Radium Hill and Mt. Victoria, is also found at Crocker Well. Xenotime and monazite are present in minor quantities as well. Non-radioactive accessories associated with the ore are ilmenite, rutile, and magnetite.

Section 3.2.4.1.3 Origin of the Ore

Genesis of the ore must involve origin of the adamellite. Brannerite has been found disseminated throughout the adamellite, although it is far more common in fractures. Johnson (1958) considered the aplite-alaskite-pegmatite, which is associated with brannerite ore as fracture fillings in the adamellite, to be a "late stage product of the regional granitization."

TABLE A-17

PRINCIPAL LITHOLOGIES AND THEIR MINERALOGY AT CROCKER WELL*

6. granite-pegmatite-coarse-grained feldspar-quartz pegmatite dikes and pegmatite quartz veins, some with coarse black rutile, biotite, and magnetite. The ore mineral, brannerite, is not found in these rocks.

5. granodiorite dikes - oligoclase-biotite-quartz granodiorite dikes that intersect the principal mineralized zones. Accessory minerals are apatite, zircon, rutile, ilmenite, monaecite, and xenotime.

4. alaskite, pegmatite, and aplite -- unstressed phases of the adamellite. They occur in two phases: (1) intrusive into the mineralized areas, and (2) as "replacement kernals in a biotite matrix to produce composite rocks known as pseudobreccia." They consist of equal amounts of subhedral potash feldspar, albite, and interstitial rutilated quartz. Brannerite, rutile, and ilmenite are present as accessories. The ore veins are generally associated with the rocks.

3. adamellite - fine- to medium-grained leucocratic adamellite, with blue opaline quartz. It has a hypautomorphic inequigranular texture. Minerals, in order of abundance, are albite, oligoclase, quartz, biotite, and microcline. Accessories are apatite, monazite, magnetite, and zircon, and minor brannerite. The ore veins are confined within the adamellite.

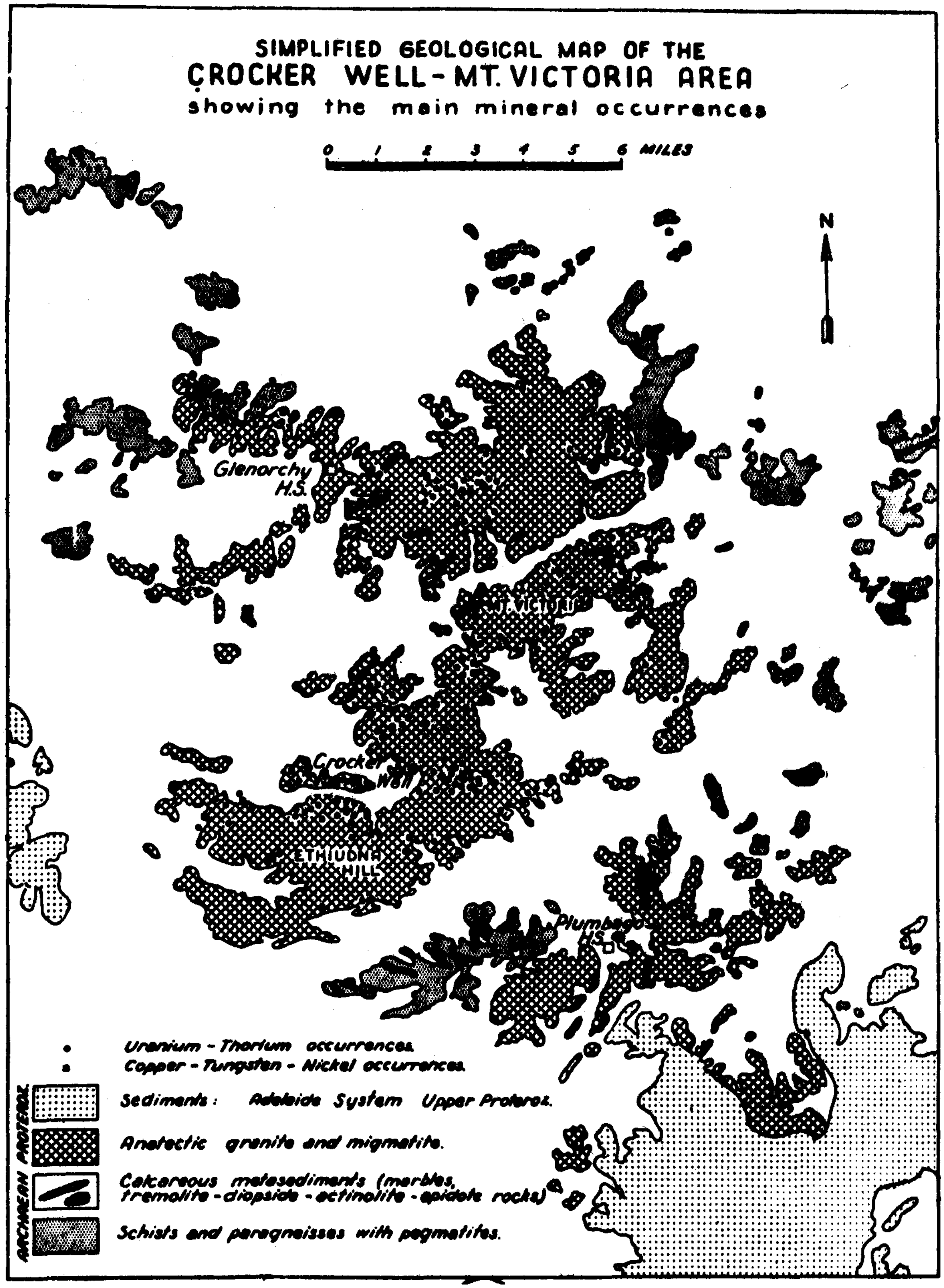
2. grey mafic granodiorite - hybrid granodioritic rocks consisting mainly of albite-oligoclase, quartz, biotite, and magnetite. Interbedded within metasediments and as xenoliths in metasediments. Pyrite is the chief accessory and occurs with biotite in fracture fillings.

1. metasediments - micaceous schists and amphibolitic gneisses grading into migmatites

* arranged from oldest to youngest (after Campana and King, 1958)

FIGURE A-26

After Campana (1956); Jour. Geol. Soc. Aust.



It seems more reasonable that the aplite-alaskite-pegmatite and brannerite ore are late-stage products of fractional crystallization of the adamellite. The brannerite ore was very likely related to supersaturation of the adamellite magma with respect to volatiles and "second boiling point".

Campana (1956) has emphasized that the adamellite is relatively fresh, unstressed, and late tectonic, probably emplaced late in the history of the Late Proterozoic-Early Paleozoic orogenic event that affected the Willyama and Adelaide systems. Field relationships among the granitic rocks and other lithologies in the Olary district discussed earlier indicate that the adamellite is anatectic in origin. Chemical and isotopic analyses are needed to confirm this observation. As previously mentioned, a major unconformity between the Upper and Lower Proterozoic in the Willyama System, in addition to evidence for a metallogenic epoch at Mt. Victoria and Radium Hill 1500-1600 million years ago, suggests an earlier orogenic episode that mobilized uranium.

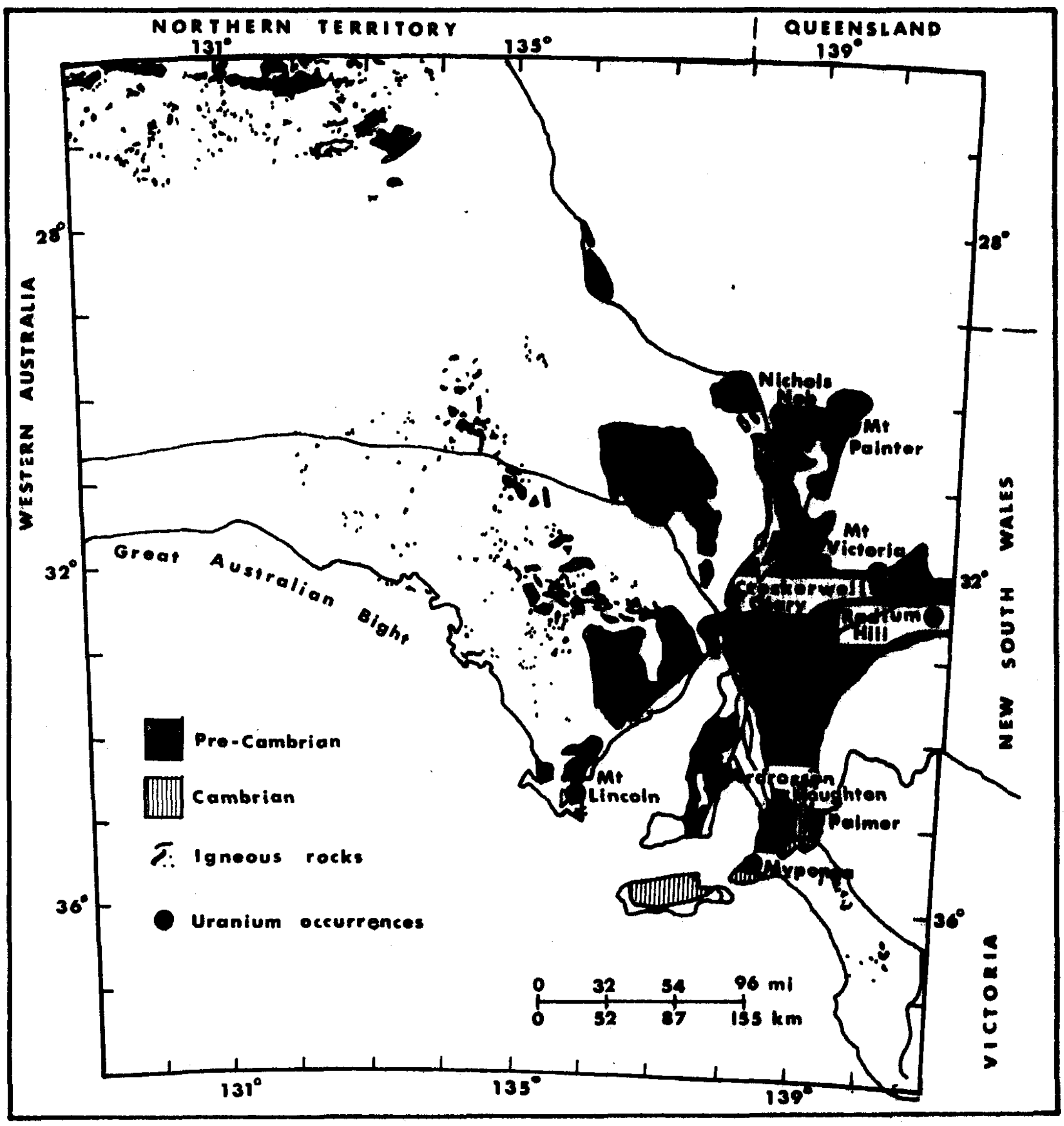
Thus, the granitic rocks and ore from Crocker Well were derived from rocks that have undergone at least two and probably more orogenic cycles. Campana (1956), however, concludes that in this region "granitization and tectonic deformation related to the Proterozoic orogeny have caused a dispersion rather than concentration of metalliferous deposits." Hence, the role of multiple orogenic cycling in the concentration of these ores is not completely clear.

Section 3.2.4.2 Radium Hill

The Radium Hill deposit can be classified as vein-type and is the best known deposit in South Australia (Figure A-27). Uranium mineralization, primarily hypogene davidite, is confined primarily to fractures and shears in Archaean and perhaps Lower Proterozoic metasediments. Davidite is

FIGURE A-27

Geology of South Australia Showing Principal Uranium Deposits
After Johnson (1958)



intimately associated and intergrown with ilmenite and rutile. Gangue minerals are principally bronze biotite and quartz (Parkin and Glasson, 1954; Sprigg, 1954; Whittle, 1954b). The sub-parallel lodes are in fracture planes that are situated near the axial plane of a regional fold. Country rocks are a complex association of amphibolites and gneisses; they have been "highly pegmatized", "highly aplitized", and "highly granitized" (Parkin and Glasson, 1954). Only one chemical analysis of the granitic rock is available (Table A-18), and that confirms the generally highly sodic character of these granitic rocks as reported in the literature. Whittle (1955) reported that uranium mineralization in South Australia is commonly associated with sodic granitic rocks, whereas thorium mineralization is more typically associated with potassic granitic rocks.

The lodes are believed to have been formed by replacement of country rocks along shears and fracture planes by mineralizing solutions associated with the sodic aplites and granites. Enrichment of the ore adjacent to the aplites has been observed. In addition, the lodes become larger and of better grade when the lode shears pass through the amphibolites, thought to be metamorphosed calcareous sediments. As at Crocker Well, gradational contacts exist among granitic and sedimentary rocks, and field relations strongly suggest an anatectic origin for the granitic rocks and a genetic association between the granitic rocks and ore.

Relationships between the deposits at Radium Hill and those at Crocker Well are not completely clear. The principal ore mineral at both is a hydrous uranium titanium oxide, but the davidite at Radium Hill is 1500-1600 m.y. in age compared to brannerite of about 600 m.y. at Crocker Well. Field relationships among granitic and metasedimentary lithologies are similar at both deposits. One may conclude that the main differences between the two

TABLE A-18

CHEMICAL ANALYSIS OF SODA MICROGRANITE FROM RADIUM HILL

From Sprigg (1954, Table 1, p. 27)

SiO_2	71.56
Al_2O_3	17.74
Fe_2O_3	0.30
FeO	0.86
MgO	nil
CaO	0.38
Na_2O	7.54
K_2O	0.78
H_2O+	0.47
H_2O-	0.15
TiO_2	0.38
P_2O_5	0.03
V_2O_5	----
MnO	0.01
Cr_2O_3	----
BaO	nil
CO_2	nil
Cl	nil
SO_3	nil
$FeSO_2$	0.08
Total	100.28

deposits are:(1) the Crocker Well deposit apparently underwent an additional orogenic-metallogenic cycle not undergone at Radium Hill; (2) the Radium Hill deposit is strictly a vein-type deposit in metasedimentary rocks, whereas the ore at Crocker Well occurs primarily in a granitic rock. All gradations exist between these two types at both localities and overall similarities of the two deposits are obvious.

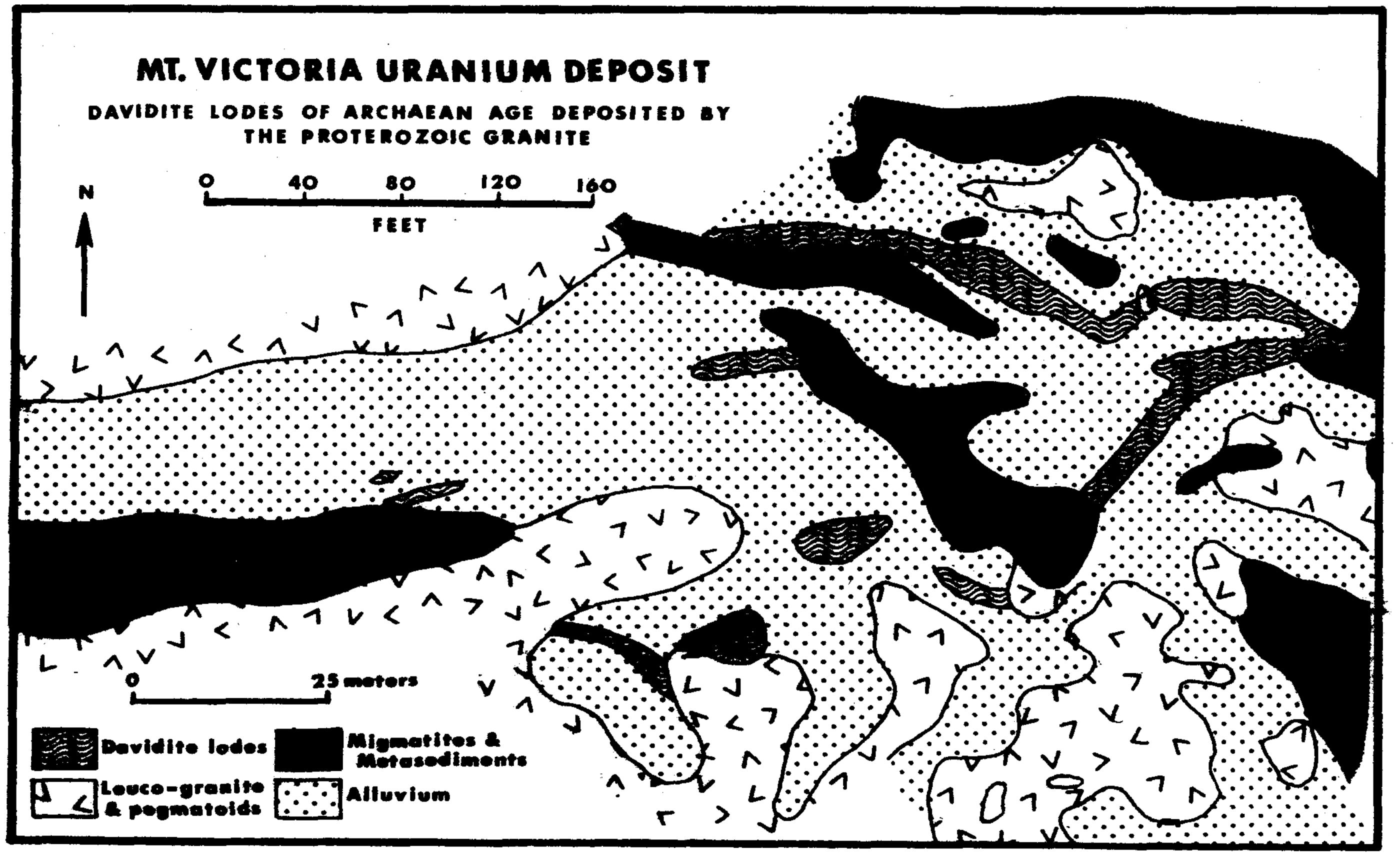
Section 3.2.4.3 Mount Victoria

These deposits are very similar to those at Radium Hill in that they occur in "granitized", Archaean-Lower Proterozoic metasediments (Figure A-26 and Figure A-28); they are of similar age to those at Radium Hill, and the principal ore mineral in both areas is davidite. Johnson (1958) reported that the davidite is not concentrated in shears or veins, but rather is disseminated throughout the lode of quartz-biotite-albitic feldspar schist. Campana and King (1958),however, stated that uranium mineralization is not only disseminated throughout the lode but also concentrated in a system of fracture zones. They believed that the lode was originally granitic in origin and was later fractured and replaced during the mineralizing event. The lodes are lenticular in shape, elongate roughly parallel to the regional foliation. Campana (1956) cited the Mt. Victoria lodes as an excellent example of the disruption of a metalliferous deposit and dissemination of the ore by means of an orogenic event.

Johnson (1958) reported that there is no evidence of replacement of country rock by mineralizing solutions along shears. McLeod (1966), however, summarized the origin of the Mt. Victoria deposits by stating that "davidite occupied fissures which appear to have been formed by brecciation during shearing." Campana and King (1956) considered this deposit to be the pegmatitic-pneumatolytic type.

FIGURE A-28

After Campana (1956); Jour. Geol. Soc. Aust.



Thus, the origin of the Mt. Victoria lodes is not straightforward and seems to possess some features of both the Radium Hill and Crocker Well deposits. Perhaps Mt. Victoria represents an intermediate stage between a classic vein-type deposit at Radium Hill and the granitic type at Crocker Well.

Section 3.3 Other Granitic Uranium Deposits in Australia

Section 3.3.1 Broken Hill District

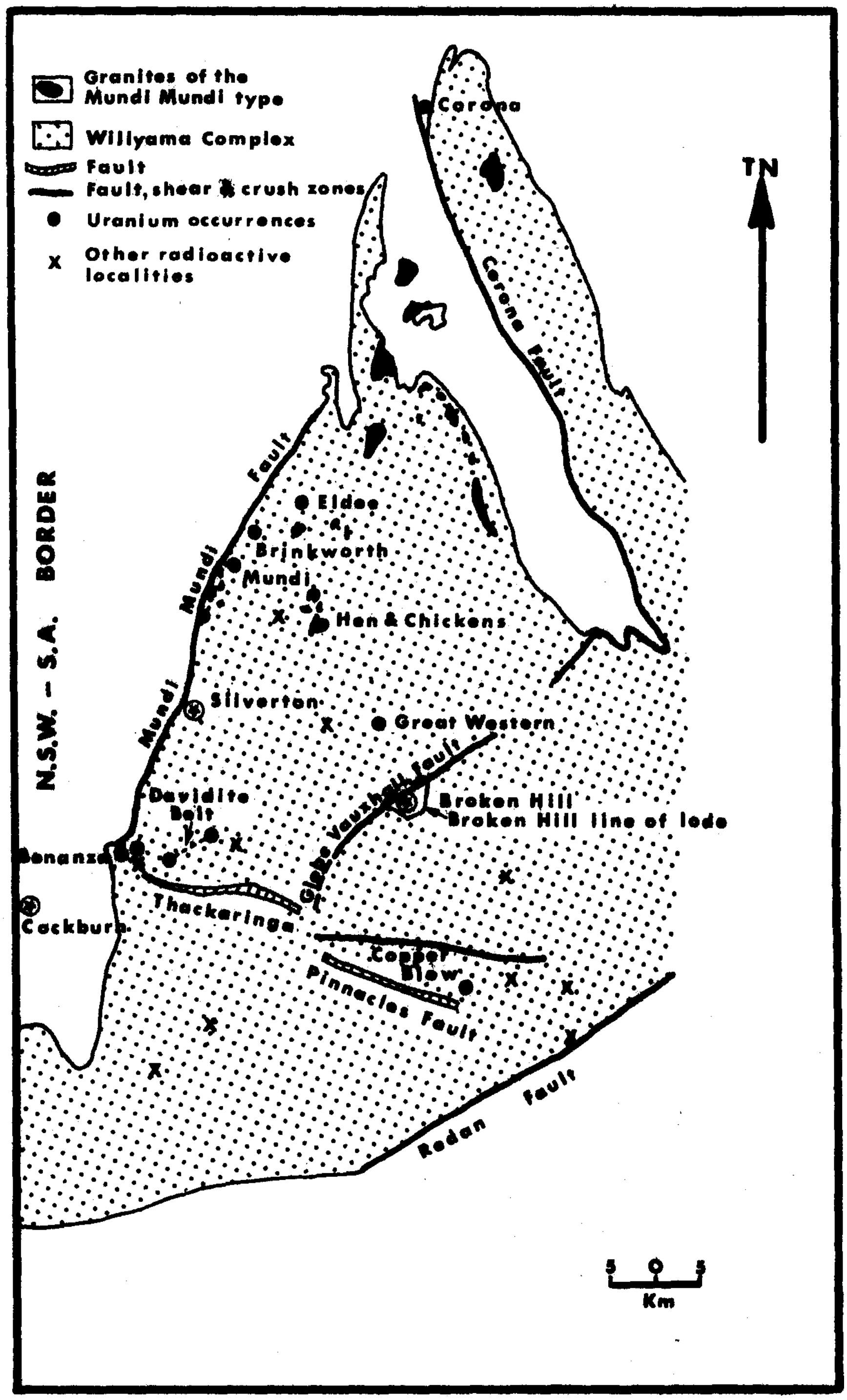
The region that is geographically closest and geologically most similar to the Olary district is the Broken Hill mining district. Both areas are within the Willyama block and primarily contain Precambrian rocks of the Willyama System (Figure A-29). The Broken Hill mining district is famous for its production of lead-zinc-silver ores; however, uranium is associated with some of the base metal deposits (Rayner, 1960; Willis and Steven, 1961). Uranium mineralization is thought to be associated with the Mundi-Mundi type alaskitic granites, which occur in small bosses, dikes, and sills in the area (Figure A-28). Of particular interest is the Thackaringa davidite belt, only about 60 km northeast of Radium Hill, where davidite occurs in pegmatites, aplitic granites, quartz veins, and shear zones associated with the metasediments of the Willyama System (Figure A-29). As in descriptions of the Olary district, the country rocks in this region have been "granitized, aplitized, and pegmatized."

The davidite is commonly intergrown with rutile, ilmenite, hematite, or magnetite. It occurs as disseminated individual grains, augen, pods, lenses, and veins in the pegmatites, aplites, and quartz veins.

Field relations suggest that the granitic rocks are anatectic in origin and the deposits are probably genetically related to those in the Olary

FIGURE A-29

Geology of the Broken Hill Area Showing Principal Uranium Occurrences
After Willis and Stevens (1971)



district. They are apparently of similar age to the Mt. Victoria-Radium Hill deposits (Raynor, 1960; Pidgeon, 1967) and contain similar mineralogy.

Section 3.3.2 Mount Painter

Uranium mineralization of doubtful economic importance has been reported in granite breccia, somewhat similar to the breccia at Crocker Well, along shear zones in Archaean metasedimentary country rocks (Johnson, 1958; Figure A-27). There are two types of granites in the area: a red, sheared variety and a younger, white, unsheared type. Uranium mineralization, principally torbernite (hydrated-copper-uranium phosphate) is primarily secondary and is apparently associated with the red granite. Davidite has not been reported, and primary uranium minerals are very rare. The Mt. Painter deposit is primarily known for its production of copper.

Section 3.3.3 Adelaide Hills

Small, uneconomic deposits of davidite and pitchblende in apparent association with anatectic granite rocks and sodium metasomatism can be found at several localities near Adelaide (Johnson, 1968; Figure A-27). These are known as the Houghton, Myponga and Palmer-Sanderton occurrences. They are quite small and the information on them in the literature is quite meager, but they do show that the "Australian Uranic Arc" and the uranium-titanium geochemical province extend as far south as Adelaide.

Section 3.3.4 Cloncurry-Mount Isa District

This district, north of Broken Hill and Olary along the "Australian Uranic Arc" (Figure A-23), is probably contiguous with these southern regions (Rayner, 1960). There is considerable evidence to suggest that the Cloncurry and Willyama blocks are comparable and perhaps co-extensive (Rayner, 1960; Willis and Steven, 1971).

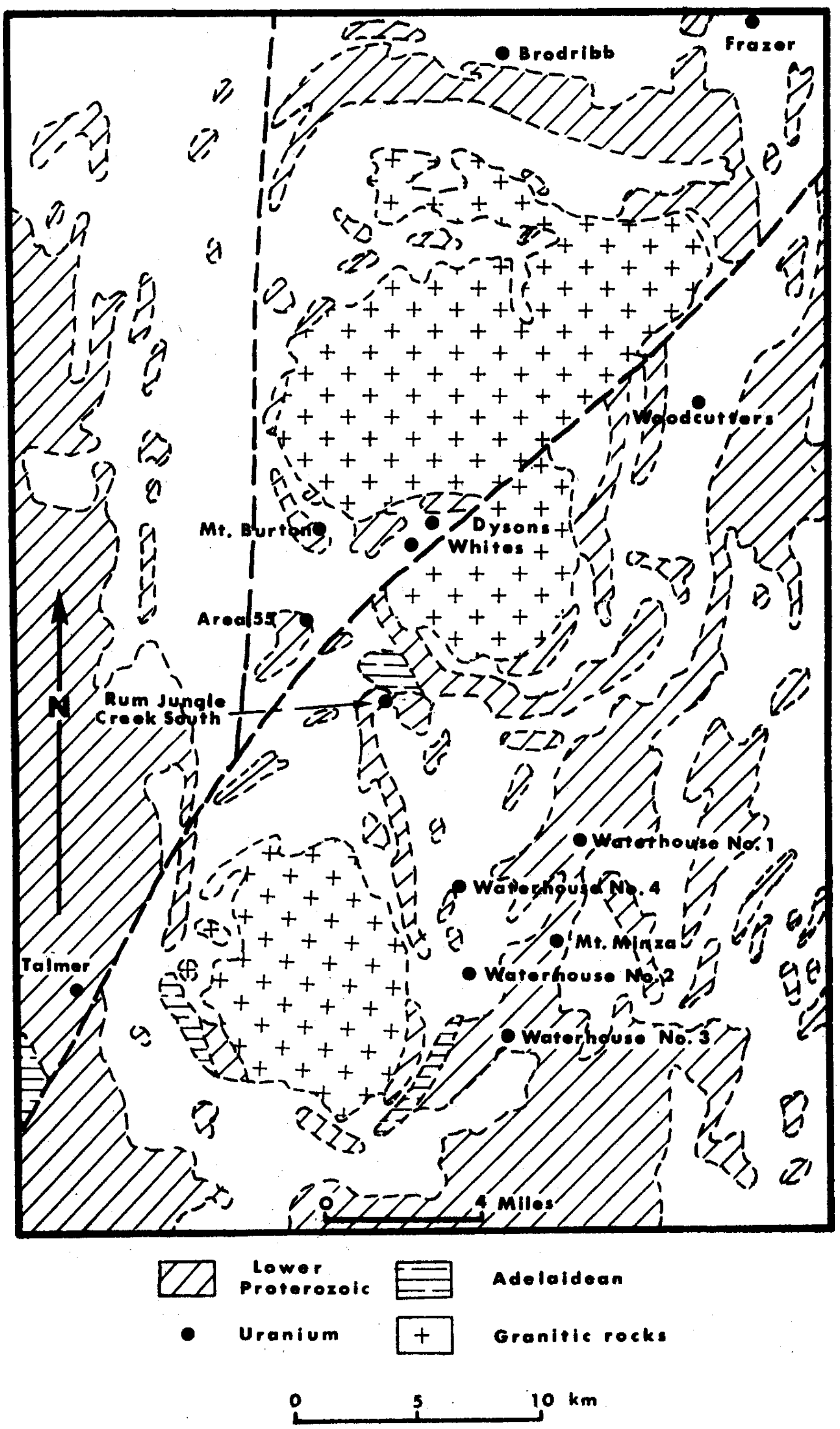
As stated earlier, the best-known uranium deposit in this district, Mary Kathleen, is apparently associated with, but not in, granitic rocks (Brooks, 1958, 1960; Lawrence, 1955; Carter et al., 1961; Matheson and Searl, 1956; Hughes and Munro, 1965). There is one area, however, in which there are davidite-type uranium deposits, similar to those at Thackaringa (Broken Hill) and the Olary district. This is known as the Six Kangaroos deposit, too small to be an important source for uranium, but important in that it demonstrates that the uranium-titanium geochemical province mentioned previously extends as far north as northwestern Queensland (Figure A-23). The davidite, disseminated in calcareous Archaean schist and gneisses of the Corella Formation, is associated with nearby outcrops of granite, pegmatite, and alaskite (Lawrence et al., 1957; Carter et al., 1961; Brooks, 1958). The davidite is commonly enclosed in black calcite; its age is unknown but probably is similar to Radium Hill and Mt. Victoria. Lawrence et al., (1957) considered davidite to be formed by contact metasomatism of the metasedimentary rocks by mineralizing solutions emanating from the granitic rocks.

Section 3.3.5 Katherine-Darwin Region

The two best known uranium deposits in this area are those at Rum Jungle and South Alligator River. Neither is in granitic rock, although as stated earlier, uranium mineralization in the carbonaceous-dolomitic rocks of the Rum Jungle area is apparently associated with the Rum Jungle granite complex and the Waterhouse granite (Crohn, 1968; Dodson, et al., 1974; Walpole, et al., 1968). Granites of the Rum Jungle complex average 10.3 ppm uranium (Heier and Rhodes, 1966), and their diapiric intrusion into the Pine Creek geosyncline in Middle Proterozoic appears to be responsible for the widespread domal structures in this region (Stephansson and Johnson, 1976; Figure A-30).

FIGURE A-30

Geology of the Rum Jungle Area Showing Principal Uranium Occurrences



From Walpole et. al. (1968); Australia Bur. Min. Res., Geology, and Ge. physics

Although uranium mineralization is almost completely confined to the Lower Proterozoic sediments of the Pine Creek geosyncline, mobilization of uranium in the granites during regional metamorphism probably provided a source of uranium in the sedimentary rocks (Heier and Rhodes, 1966; Dodson, et al., 1974).

Of particular interest in the Katherine-Darwin area are the anomalously radioactive granitoid rocks of the Nimbuwah Complex, Alligator River area. The classical development from incipiently migmatized schists on the periphery of the granitoid bodies to completely homogenized anatectic granites in the center is observed (Dodson, et al., 1974). A rubidium-strontium isochron yielded an age of 1840 m.y. for the anatectic granites (Dodson, et al., 1974). The anomalously radioactive pink biotite granites, apparently anatectic in origin, are apparently younger than the 2450 m.y. Waterhouse granite (Compston and Arriens, 1968), and are probably comagmatic with the Edith River volcanics, thought to be the source rocks for the South Alligator River metasedimentary uranium deposits (Ayers and Eadington, 1975).

Unfortunately, no information is available in the literature concerning the concentration of uranium in anatectic granites of the Nimbuwah Complex. Ayers and Eadington (1975) report that the Malone Creek granite in the South Alligator River area contains 15 ppm uranium. It is clear that the entire Katherine-Darwin region represents a uranium geochemical province in the granitic as well as the metasedimentary rocks, although there is some doubt whether the granitic rocks contain sufficient uranium to be of economic interest.

An interesting observation is that within the "Australian Uranic Arc", only the deposits in the Katherine-Darwin area reportedly contain no davidite and apparently are not part of the overall uranium-titanium geochemical province. This observation may be real or simply may be explained by the fact that very little detailed work has been done on the granitic rocks in this region.

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Section 4 Africa

Section 4.1 Rössing, South West Africa (Namibia)

Section 4.1.1 Location

The Rössing uranium deposit occurs about 50 km northeast of Swakopmund, South West Africa (22°25'S, 15°01'E; Figure A-31).

Section 4.1.2 Regional Geology

The deposit occurs within the Damaran orogenic belt and consists primarily of low-grade uranium mineralization disseminated within a migmatitic granite. Descriptions of the Rössing deposit itself are scarce (see Von Backström, 1970; Armstrong, 1974; and Berning *et al.*, 1976). Descriptions of the general geology of the Damaran belt are somewhat more numerous, and the ones most pertinent for understanding the regional geology of the Rössing area are Smith (1965), Jacob (1974) and Armstrong (1974). A copy of the report written by one of the present writers (JJWR) after a visit to South West Africa is included in this report as Appendix 3.

The Damaran orogenic belt extends in a northeast-southwest direction and consists largely of older igneous and sedimentary rocks metamorphosed and remobilized about 600 to 500 m.y. ago. The stratigraphic section is shown in Figure A-32. Exact ages are not available for most rocks, but ages of 510 m.y. have been obtained for some uranium minerals.

Section 4.1.3 Local Geology

The Rössing deposit is one of the series of G_4 granites, all of which were probably formed by anatexis during the latest orogeny. The G_4 granites occur only within outcrop areas of the Nosib Group (Figure A-33), although

FIGURE A-31

Location of Rössing Uranium Deposit

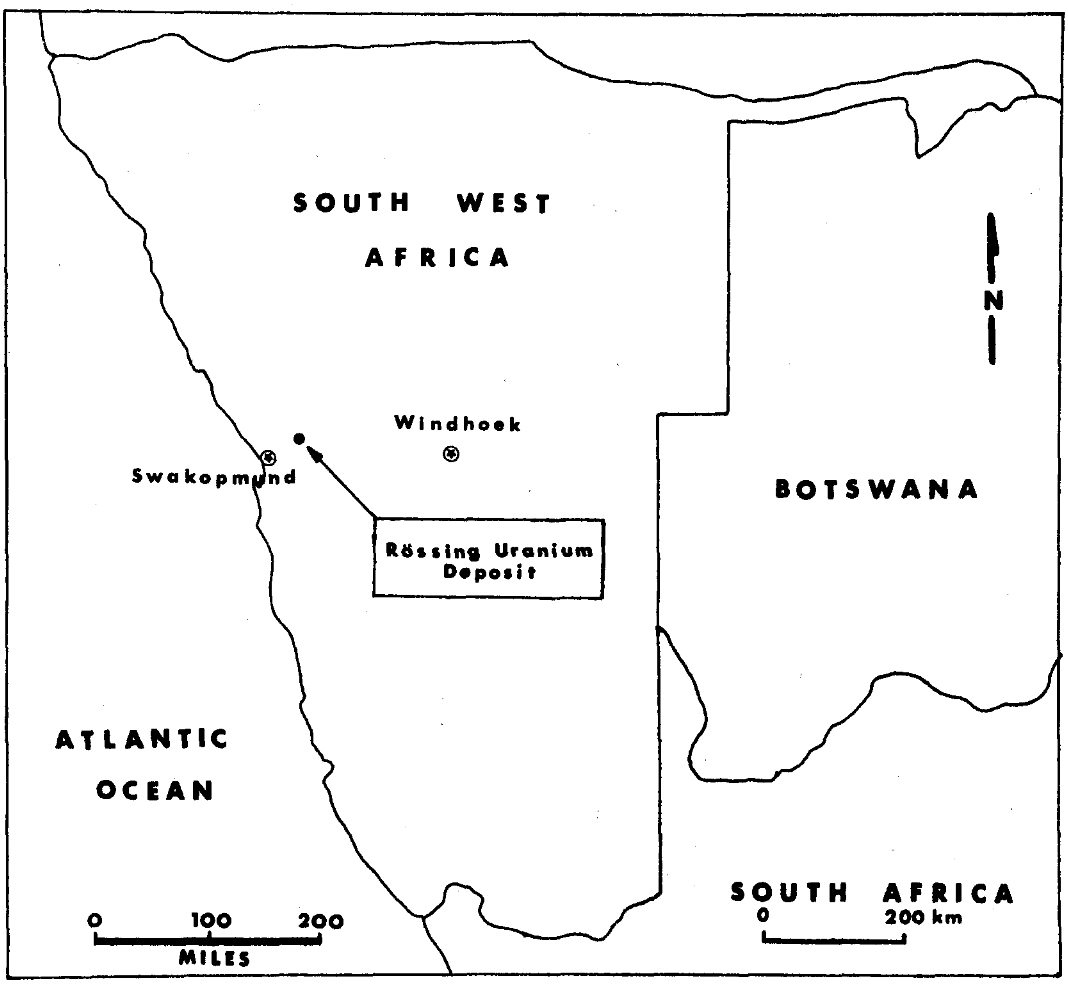


FIGURE A-32

Stratigraphic Section of Units in the Rössing Area

Damara Group:	
Khomas Subgroup:	
in northwestern portion of the orogen - highly variable schist, gneiss, marble, quartzite, and migmatite	contains Salem Granites
Rössing Formation:	
schist, gneiss, marble, quartzite, local calc-silicate hornfels	
Nosib Group:	
Khan Formation:	
hornblende- and biotite-bearing schists and gneisses	contains G_4 Granites
Etusis Formation:	
quartzitic and arkosic gneisses, migmatite, metaconglomerate	
Basement:	
Abbabis Formation:	
very highly metamorphosed; gneiss, augen gneiss, schist, quartzite	possibly includes Red Granite Gneiss (Gn_1)

FIGURE A-33

Geology around the Rossing uranium deposit, after Smith (1965)

Recent deposits. Sand, gravel and surface limestone.

Dolerite dike.

Damara System

Khomas Series. Biotite-cordierite-garnet and quartz-biotite schist.

Hakos Series

Upper Stage. Blue marble, white marble and quartz-biotite schist.

Chuos tillite.

Lower Stage. Marble bands with quartzite facies.

Nosib Fm.

Upper Stage. Calc granulite, schist and quartzite.

Lower Stage. Quartzite and quartz-biotite schist.

Syntectonic

Pegmatite and pegmatitic granite.

Quartzofeldspathic rocks. Granite-gneiss and granite with sedimentary remnants.

F — Fault

U — Uranium

Cu — Copper

M — Mica

Scale: 0 – 1 mi; 0 – 1.6 km

they cause contact metamorphism in the overlying limestones of the Rössing Formation. The granites are broadly conformable with the general northeast-southwest grain of the country rocks, but detailed cross-cutting relationships indicate mobility of G_4 fluids. Contacts are gradational only over a few cm, and contact metamorphism is absent between the G_4 granites and the schists and gneisses of the Nosib Group.

The principal characteristics of the whole suite of G_4 granites are:

1. A very felsic composition. Commonly they have been described as alaskites, although the term has been used differently by different writers. In general, the only mafic mineral is biotite, which constitutes less than 5 percent of the rock. Thus, the mineral assemblage is almost exclusively quartz-microcline-sodic plagioclase.

2. A highly variable texture. The granites are generally coarse-grained, partly pegmatitic, but finer-grained portions are distributed in apparently random patterns.

3. The intricate interleaving of granite and metamorphic wall rock creates a migmatitic appearance. There is no evidence of derivation of the granites by differentiation from the surrounding rock (e.g., no mafic residual borders).

4. The various bodies are highly variable in size and shape. The map of the Rössing deposit (Figure A-33) shows a typical example of a large body and also indicates the difficulty of defining and describing the exact size and shape. The maximum area of exposure of any identifiable body is about 2.5 km^2, and separable bodies range down to a few square meters in size. The Rössing deposit contains a G_4 granite body with an outcrop area of about 1.2 km^2.

5. Joint patterns are not well developed, and the mineralization is apparently not affected by the limited joints that are present.

6. Although the G_4 granites in the Damaran belt are certainly associated with the last major deformation at about 500 to 600 m.y. ago, none of the G_4 bodies themselves have been dated. Thus, it is not possible to assign an exact age to the rocks in which the Rössing uranium occurs. Furthermore, no published data is available on the age of either the primary or secondary minerals.

7. Diapiric granites and diabasic and other dikes occur in the Rössing area and are clearly younger than the G_4 granites. The influence, if any, of these younger bodies on the uranium distribution is unknown.

Section 4.1.4 <u>The Ore Deposit</u>

The mineralized zone at Rössing has an outcrop area of 640 m in diameter, and values of uranium of 1-11 lbs/ton extend to an explored depth of 460 m. The average concentration of the minable ore is 350 ppm, with a total estimated reserve of several million tons of 1 lb./ton uranium ore.

Section 4.1.4.1 <u>Mineralogy</u>

The major minerals of the deposit (Von Backström, 1970b) are:

quartz (smoky)

microcline, perthite and microcline

biotite-minor

plagioclase (An 0-20) - a minor constituent

accessory minerals

zircon

monazite

pyrite

chalcopyrite (altered to covellite and digenite)

molybdenite

ilmenite (altered to leucoxene)

magnetite

fluorite

hematite

Uranium minerals include:

uraninite (55% of all the radioactive minerals)

davidite

rossingite

metatorbernite

meta-haiweeite

uranophane

beta-uranophane

carnoitite

thorogummite

gummite

An average mode of uraninite ore pegmatite is:

quartz	36.08
k feldspar	53.15
plagioclase	10.61
biotite	0.27
accessories	trace

Section 4.1.4.2 Ore Guides

1. The uraniferous zone of enrichment is present along biotite-rich selvages of the alaskite.
2. Economic mineralization is confined to alaskites which intrude the

pyroxene garnet gneiss/amphibole unit, and the amphibole-biotite schist/lower marble/lower cordierite - biotite gneiss unit.

3. The mine is at a limb of a synclinorium.
4. Uranium mineralization is confined to unzoned pegmatites.
5. Abundant secondary uranium minerals are found in pegmatites that are jointed, fissured and fractured.
6. Uraninite displays a preferential association with biotite and zircon.

Section 4.1.5 Origin of the Deposit

The origin of the Rössing deposit and similar, although smaller, concentrations in neighboring areas, has been a matter of speculation. As discussed in Appendix 3, the uranium is clearly associated with the formation of anatectic granites in an area that has undergone multiple tectonic, sedimentary, and igneous recycling. Although the G_4 granites are clearly anatectic, their source materials (either Nosib or pre-Nosib rocks) are not exceptionally rich in uranium; thus, the high uranium concentrations cannot be explained simply by derivation from uranium-rich source material. Information is also not available on whether the uraninite in the G_4 is a primary crystallization product from the granite magma or a later, perhaps hydrothermal, addition.

The question of supergene enrichment at Rössing is an important one. The Namib Desert, in which Rössing occurs, is a site of heavy dews in an otherwise arid environment, and supergene processes are presumably very likely. The secondary minerals, however, are not clearly related to the present surface or any other erosion surface, and it is possible that most of the secondary mineralization is hypogene.

Section 4.1.5.1 The Alaskitic Pegmatites

Several hypotheses for the origin of the radioactive occurrences are presented below. All investigators agree that the alaskites crystallized from an anatectic melt; however, the source parental sediments of the alaskites have not been unequivocally identified.

1. "The (alaskitic) pegmatite is of syntectonic age and partly of metasomatic origin as is evident from its partial replacement of biotite schist and biotite quartzite. . ." (Smith, 1965)

2. "The formation which is most highly radioactive on a regional scale is the Red Granite Gneiss. This rock is the protore of the uranium deposits in the Alaskitic pegmatitic granites. The Red Granite Gneiss is interpreted as being partly of pre-Nosib age and partly the result of anatexis of Nosib group metasediments. . ." It is proposed that uranium was incorporated into early granitic melts and solutions during progressive anatexis of pre-Nosib and Nosib rocks at the time of the Damaran metamorphism; these melts eventually crystallized as alaskitic pegmatite granite. (Jacob, 1974b).

3. "The alaskitic material was derived from a deep-seated juvenile source where syntectic processes were active." It is suggested that the alaskites crystallized from anatectic melts of the underlying Etusis and Abbabis Formations (part of the Nosib and pre-Nosib group). (Berning et al., 1976)

Magmatic-metasomatic solutions participated in the growth and mineralization of the alaskites. Two views on the origin and role of these solutions are presented below:

1. "Metasomatic activity, associated with the final stages of crystallization of alaskite melts has produced skarns. The metasomatizing fluids,

derived through second boiling have carried uranium in solution into the carbonate rocks. . . In pegmatites, uranium derived from the same source as the pegmatite forming fluids remained in solution until late in the crystallization history, before being finally incorporated into complex minerals as uraninite. . . Where mineralisers like fluorine were present, uranium was probably held in solution as fluoride complexes until a very late stage when it was finally precipitated during hydrothermal and greisening processes." (Jacob, 1974b).

2. "Passive nonviolent metasomatic emplacement of the alaskite can be inferred from the fact that the strike and dip of the ghost layering observed in the alaskite are identical not only to that of the surrounding country rock but also to that of the xenoliths pendant in the alaskite. . . (Alaskite) dikes were progressively widened by metasomatism to eventually form large irregular masses of aplite. . ." (Berning et al., 1976)

Section 4.1.5.2 Secondary mineralization

The abundant secondary uranium mineralization in alaskites is a unique feature of the Rössing deposit, and the climatic conditions of the Namib desert may provide favorable conditions for the precipitation of secondary uranium minerals.

"The climate of the Namib desert is arid and the water table is either non-existent or very low. Heavy dew, which condenses almost nightly on bare rocks percolates downwards and extracts uranium from the pegmatite. Where conditions are favorable, uranium is precipitated in the form of secondary uranium minerals. . ." (Von Backström, 1970)

Section 4.2 Kaffo Valley (Liruei complex), Nigeria

Section 4.2.1 Location

The Kaffo Valley deposits are located in the Liruei-n-Kano Hills, 10°45' N, 8°45' E, Nigeria (Fig. 1; Bowden and Turner, 1974).

Section 4.2.2 Geology

The Kaffo Valley albite riebeckite granite is part of the Liruei complex (Figure A-34) and is situated in a province of numerous high level, nonorogenic, Jurassic-age granitic ring complexes. The Liruei complex is subcircular in outline, approximately 15 km in diameter, and contains five main rock types, which in order of intrusion are:

1. granite porphyry ring dikes
2. quartz pyroxene fayalite porphyry
3. rhyolite and quartz porphyry
4. riebeckite granite porphyry
5. biotite granite porphyry

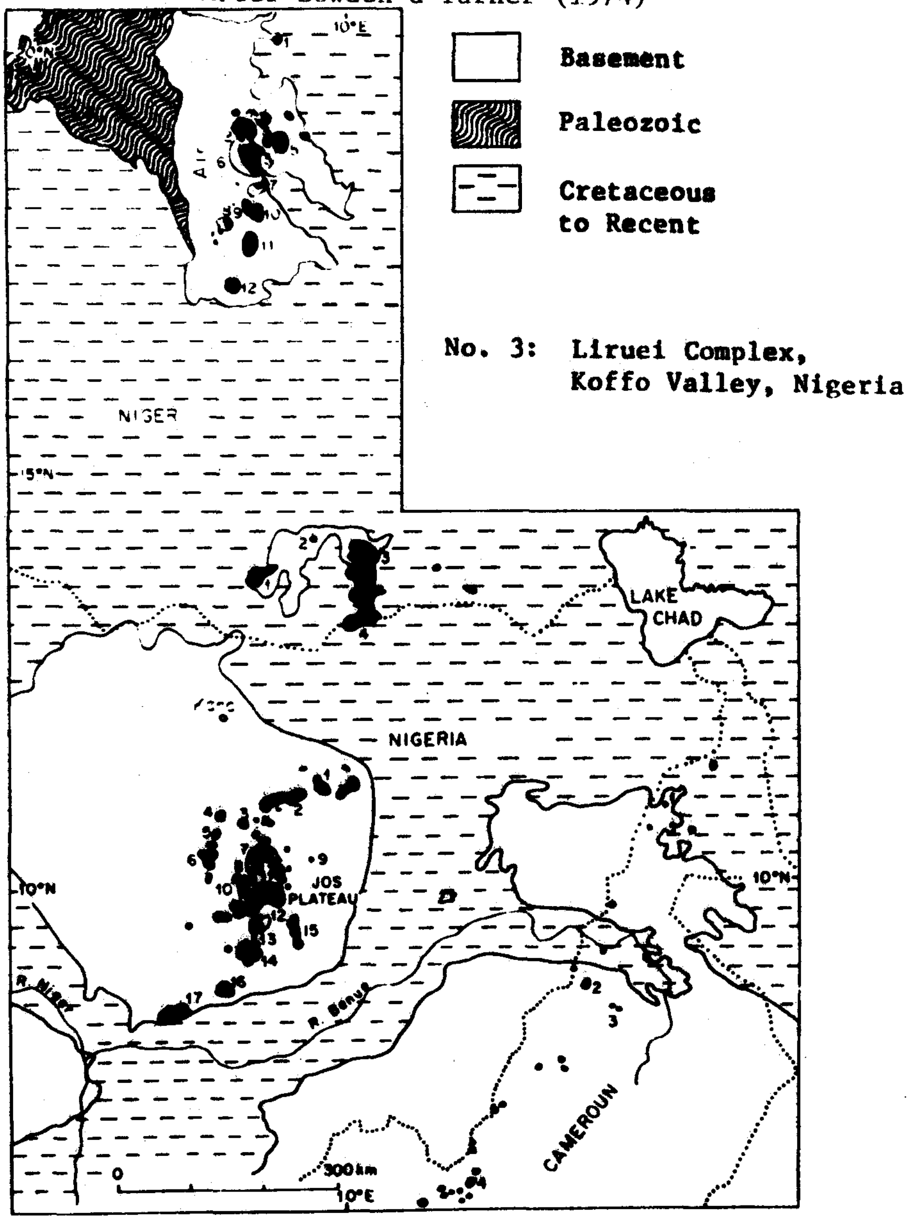
Other similar ring complexes occur throughout the Jos Plateau region to the south of Kaffo Valley; however, the Kaffo Valley intrusive is the only body of known uranium potential. All of the granitic ring complexes are Mesozoic in age and are termed "younger granites."

Section 4.2.3 Host rocks

The albite-riebeckite granite crops out between the biotite granite and riebeckite-aegerine granite facies of the complex (Figure A-35) and has an areal extent of about 1.2 km^2. The texture is somewhat porphyritic, and the essential minerals are quartz, orthoclase-perthite, abundant albite, riebeckite and aegerine. Fluorite, topaz and cyrtolite are accessory minerals.

FIGURE A-34

Geology of the Jos Plateau Area
After Bowden & Turner (1974)

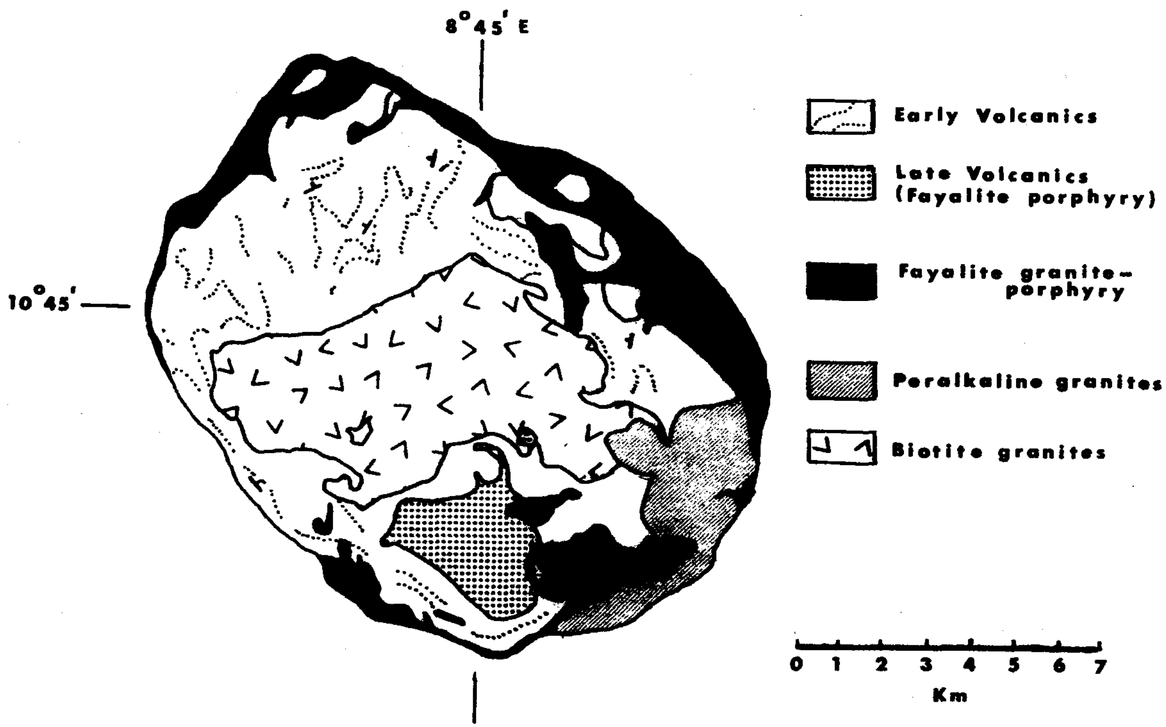


No. 3: Liruei Complex, Koffo Valley, Nigeria

From Bowden and Turner (1974); in The Alkaline Rocks, published by John Wiley and Sons.

FIGURE A-35

Geology of the Lireui Complex
After Bowden and Turner (1974)



From Bowden and Turner (1974); in The Alkaline Rocks, published by John Wiley and Sons.

Albite forms a fine-grained matrix for larger quartz and perthite grains. Contacts of the granite have a noticeable development of a pegmatitic facies. The uranium content of rocks in an area of 0.8 km^2 in the albite-riebeckite granite zone averages 0.01% U. The niobium content in this area averages 0.26%. Most of the uranium in the bulk-rock sample is derived from pyrochlore, which contains an average of 2.6% U, 2.9% Th and about 30% $(Nb, Ta)_2O_5$.

MacKevett (1963) notes petrographic, mineralogic and chemical similarities between the Kaffo Valley peralkaline granites and the Bokan Mountain peralkaline granite, which hosts the Ross Adams deposit.

Section 4.2.4 Geochemistry and Origin

The albitized, peralkaline granites have several unusual geochemical characteristics that contrast them from other granites in the area:

1. An unusually low K/Rb ratio (25)
2. High fluorine content
3. High Nb, U, Rb, Li, Y, and Sr
4. A high agpaitic coefficient:

$$\frac{(NaO + K_2O)}{Al_2O_3} = 1.33$$

5. Σ REE is exceptionally high. Typical analyses are given in Table A-19.

Bowden and Turner (1974) suggest that the high trace element content of the granites is directly attributable to the effects of post-magmatic albitization rather than extreme fractionation as proposed by Butler (1972).

Isotopic studies of the peralkaline and non-peralkaline granites of the Jos Plateau are in compliance with an origin of these rocks by crustal fusion. A Sr^{87}/Sr^{86} initial ratio of 0.7212 for the granite of the nearby Amo complex (Bowden and Turner, 1974) is much higher than initial ratios

TABLE A-19

MAJOR AND TRACE ELEMENT CONTENTS OF ALBITE-RIEBECKITE GRANITES, KAFFO VALLEY, NIGERIA

	(1)	(2)	(3)		(4)
SiO_2	70.04	71.31	71.38	Li	575
Al_2O_3	10.53	13.97	12.34	Rb	1400
Fe_2O_3	3.00	1.46	1.96	K/Rb	25
FeO	4.61	1.14	0.91	Ga	55
MgO	tr	0.13	0.16	Zr	2160
CaO	0.27	0.50	0.17	Agpaitic coeff	1.33
Na_2O	5.00	7.67	7.17	La	185
K_2O	4.36	3.83	4.17	Yb	75
H_2O^+	0.20	0.06	0.30	Y	535
H_2O^-	0.61	0.08	0.12	Nb	1500
CO_2	0.07	0.02	-	Sn	150
TiO_2	0.20	0.08	0.07		
ZrO_2	0.25	-	-		
P_2O_5	tr	0.02	0.01		
MnO	0.09	0.02	0.05		
BrO	-	tr	-		
LiO_2	tr	-	-		
Cl	-	tr	0.30		
F	0.41	-	1.05		
S	tr	0.01	-		
	100.05	100.30	100.05		

1,2: Beer (1952)
3: Jacobson (1958)
4: Bowden and Turner (1974)

of magmas inferred to have formed from a mantle source. Bowden (1976) argues that the similarity of lead isotopes in older granites, younger granites (Jurassic granitic ring complexes) and pegmatites implies that all of these rock types formed by fusion of local crustal materials.

As mentioned, MacKevett (1963) noted geologic similarities between the Nigerian peralkaline granites and the Bokan Mountain peralkaline granites. Some additional similarities are:

1. In the Kaffo Valley deposit, uranium is enriched in the Na-rich albite riebeckite granite compared to potassic riebeckite granite. At Bokan Mtn. the uranium deposits are in a relatively potassium-poor, sodium-rich, albite riebeckite granite.
2. Nb, Zr, and rare earths are higher in the uranium-rich portions of both deposits.
3. Albitization is a conspicuous feature in the Bokan Mtn. (in surrounding country rocks) and Kaffo Valley (a late or post-magmatic mineral in the albite-riebeckite granites) deposits.
4. The uranium-rich portions of both peralkaline granites are enriched in F relative to the uranium-poor rock types.

Section 4.3 Red Sea Hills, Egypt

Section 4.3.1 Location

The uranium deposits are located about 500 km southeast of Cairo (approximately 26°N-34°E).

Section 4.3.2 Geology

The Red Sea Hills of Egypt consist of Precambrian rocks uplifted along the margin of the rift that has now become the Red Sea. The location and a highly generalized stratigraphic section of the area are shown in Figure A-36 and Table A-20. Adequate dates are scarce, but the Younger (pink) Granites yield fairly consistent ages of 500 to 600 m.y. (Hashad et al., 1972; El Shazly et al., 1973). The general geology is summarized by papers in Said (1972) and the map of El Ramly (1972).

Uranium is mostly associated with Younger Granites, although the exact date of uranium mineralization is unknown and not necessarily the date of intrusion of the granites. Very little published information is available on the uranium occurrences; a short summary is provided by Hussain et al. (1970), and many of the observations in this report are from personal study by one of the writers (JJWR) and discussions with Dr. E.M. El Shazly and Dr. Ibrahim El Kassas.

The principal characteristics of the Younger Granites are:

1. Diapiric intrusions cutting discordantly across all older rocks.

2. Highly felsic, with high contents of quartz and high potassium feldspar/plagioclase ratios. Mafic minerals are scarce, with the principal one being biotite.

3. Massive intrusions, with flow structures generally absent. Joints are common, but regional patterns have not been determined.

4. Generally coarse-grained, in some places pegmatitic. Textural variability is common, with finer-grained areas apparently randomly distributed within the plutons.

5. Plutons generally have a diameter of a few miles.

6. Inclusions are scarce.

7. Contact metamorphism of wall rocks is generally limited.

8. Pegmatites and other dikes associated directly with Younger Granites are rare. Dike sets, including pegmatites, are associated with the Older Granites, but these rocks do not show uranium mineralization. Some very

FIGURE A-36

Location of Uranium Deposits in the Red Sea Hills Area

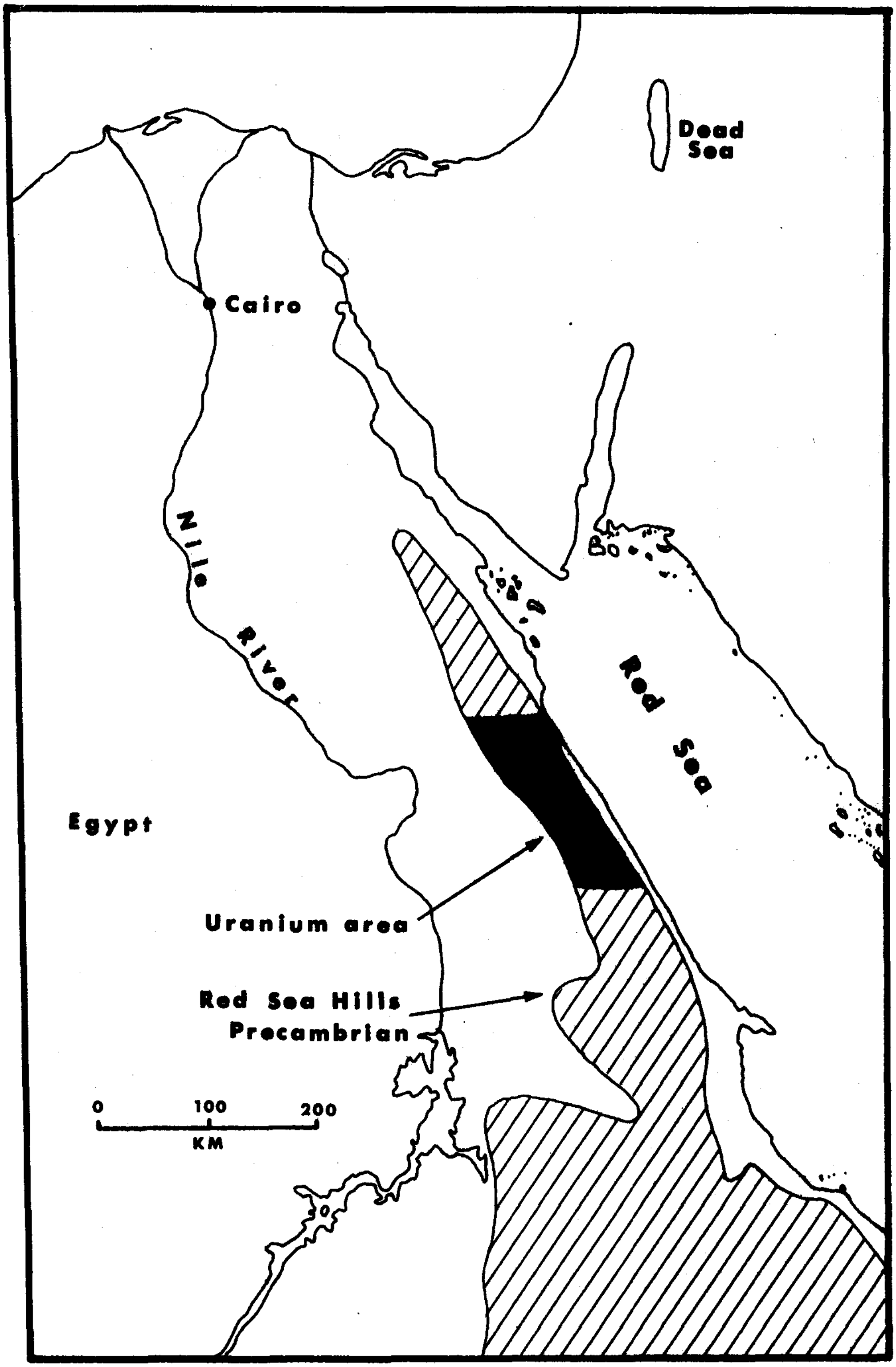


TABLE A-20

STRATIGRAPHIC SECTION OF EASTERN EGYPT

shallow intrusions (ring dikes, mafic dikes, bostonites, etc.)

Younger Granites

Hammamat conglomerates, sandstones, and siltstones

Dokhan silicic volcanics

Older Granites (gray)

metasediments, metavolcanics, and other mafic rocks

gneiss

young mafic and other dikes post-date the Younger Granites, but their relationship to uranium mineralization is also unknown except for the close association of uranium and some bostonite dikes and sills.

Section 4.3.3 Uranium in the Younger Granites

The relationship between uranium and the Younger Granites is complex. Although the uranium occurs primarily in the area of Younger Granite intrusions, as shown by airborne gamma-ray spectrometry, the mineralization is clearly not restricted to the granites themselves. The principal characteristics of the occurrences are:

1. Uranium concentrations are approximately twice the normal background concentration and average 10 ppm in the granites.

2. The uranium is disseminated, with recognizable veins and other concentrations being scarce.

3. The mineralogy is not well known, but most of the uranium in the granites appears to be in primary uraninite. The uranium-bearing minerals in the wall rocks are unknown.

4. The Th/U ratio of the granites is low (approximately 2) in comparison with the normal ratio of 4 or more for such differentiated rocks. This low ratio indicates that uranium has not been lost from the intrusions into wall rocks, and thus implies that the source of the mineralizing fluids is presumably release of hydrothermal solutions from depth. The relationship with the Younger Granites may be largely structural, with intrusion of the granites causing areal weakness that permits invasion of the granites and wall rocks by the fluids.

5. Limited evidence suggests that the finer-grained, less reddish, portions of the intrusions contain the highest concentrations of uranium.

6. Local structures, such as joints, are apparently not important in controlling the distribution of uranium.

7. The prospects for large, moderately rich, uranium deposits cannot be evaluated at the present time.

The Red Sea Hills are extremely dry. There is little evidence of supergene activity in the present areas of uranium concentration and no reason to expect that it has been important in forming the present high uranium values. The uranium in the area appears to be the result of soaking of structurally favorable regions in mineralized fluids at least once, and possibly several times, since the emplacement of the Younger Granites.

Section 4.3.4 Uranium in the Bostonites

In addition to the uranium associated with the Younger Granites, significant concentrations have been found associated with the suite of bostonite dikes and sills that occur in great abundance in one portion of the Red Sea Hills (Hussein and El Kassas, 1970; Hussein et al., 1972). Throughout an area of approximately 2500 km^2, numerous plugs, dikes, and sills of bostonite intrude a variety of wall rocks. These bodies range up to several thousand meters across, are discordant, and cause minor contact metamorphism. A Mesozoic age is likely but not clearly established. The bostonites consist of an equigranular, fine-grained, assemblage of quartz and potassium feldspar with minor plagioclase and mafic minerals. The uranium-bearing minerals are largely unknown.

Uranium concentrations range up to 2000 ppm at some places (particularly the contact zone of the large sill at El Atshan). Such extreme concentrations, however, are very localized in pencil-shaped bodies partly related to fracturing in the contact zone. Average uranium concentrations in the mineralized zones are about 50 to 100 ppm over a distance of 3 m extending into both wall rocks and bostonites. The uranium is presumably derived from fluids associated with the bostonite magmas and is disseminated through local zones of fracturing near the contacts.

Section 4.4 References on Africa

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Section 5 Miscellaneous Deposits

Section 5.1 Currais Novos, Brazil

Section 5.1.1 Location

The deposits are located on the Rio Grande Del Norte, Serido, Brazil (about 40°W,5°S; Figure A-37).

Section 5.1.2 Geology

The uraniferous occurrences are located in the Serido geosyncline, which is a Precambrian complex of metasediments intruded by granites (Ebert, 1969; Ramos and Fraenkel, 1976). The geosyncline is comprised of the Ceara Series, which is stratigraphically subdivided into two groups:

a) Caico Group: A lower Precambrian age group of migmatites, gneisses para-amphibolites, meta-arkoses and limestones.

b) Serido Group: Upper Precambrian age, discordantly overlying the Caico Group. Includes quartzites, metaconglomerates, gneisses, schists, tactites and phyllites

Four petrographic types of Precambrian granitic rocks are recognized:

a) Conceicao type granodiorites

Concordant, intrusive, synorogenic gray granodiorites

b) Itaporanga granites

Late orogenic, porphyritic, leucocratic, microcline granites with minor biotite, hornblende and garnet

c) Itapetim granites

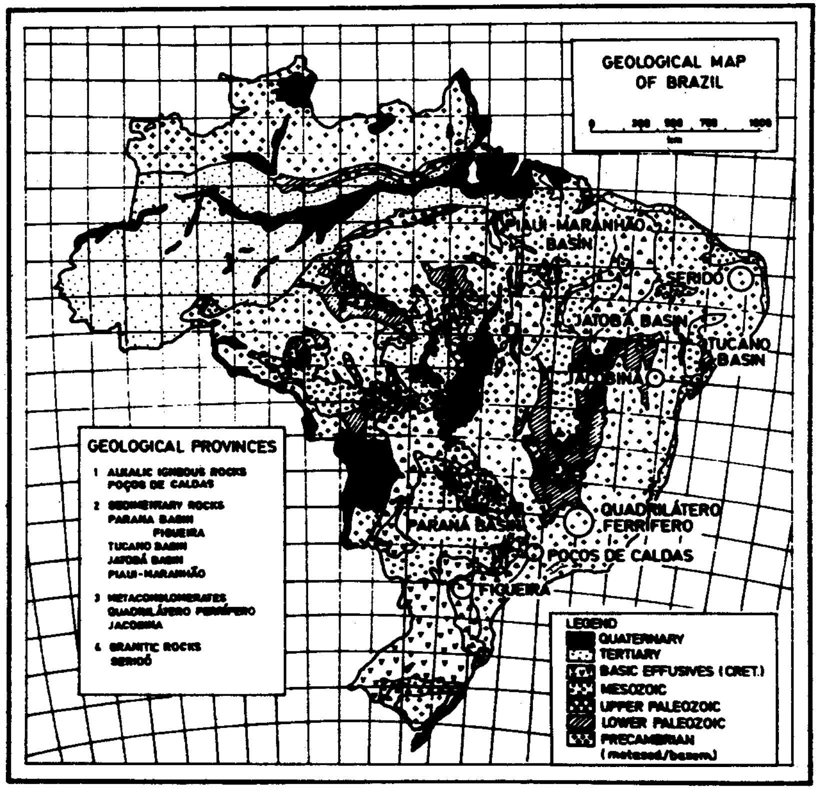
Intrusive, late orogenic, fine-grained, equigranular granite dikes similar to type (b) but lacking hornblende

d) Catingueira type granites

Alkaline, leucocratic fine-grained granite dikes containing albite, quartz, microcline, titanite, zircon and magnetite.

FIGURE A-37

Geologic Map of Brazil and Major Uranium Deposits
The Currais Novos deposits are located in the Serido area.



After Ramos an:' Fraenkel (1974); from Formation of Uranium Deposits, published by International Atomic Energy Agency.

Tertiary to Precambrian sills and dikes cut these units and Cretaceous and Tertiary sandy sediments.

Section 5.1.3 The Ore Deposits

Geological and radiometric surveys in the Serido geosyncline revealed numerous radioactive anomalies. The radiometric anomalies show a distinct relation to the local tectonic pattern and align along a NNE-SSW zone of intense tectonism (Figure A-38).

Two types of uranium mineralization are present:

1. disseminated uranium mineralization in synorogenic granites and pegmatoid granite as well as in biotite schists, meta-arkoses, and tactites
2. vein-type mineralization in localized fractures

The disseminated mineralization is restricted to the intermediate facies between the granite and pegmatite that typically occur in or near anticlinal axes. Secondary mineralization occurs to depths up to 90 m. Granites in the mineralized zone average 400 ppm; pegmatites contain 180 to 1500 ppm. Vein-type mineralization is located along shears and fracture zones in the vicinity of major anticlinal axes.

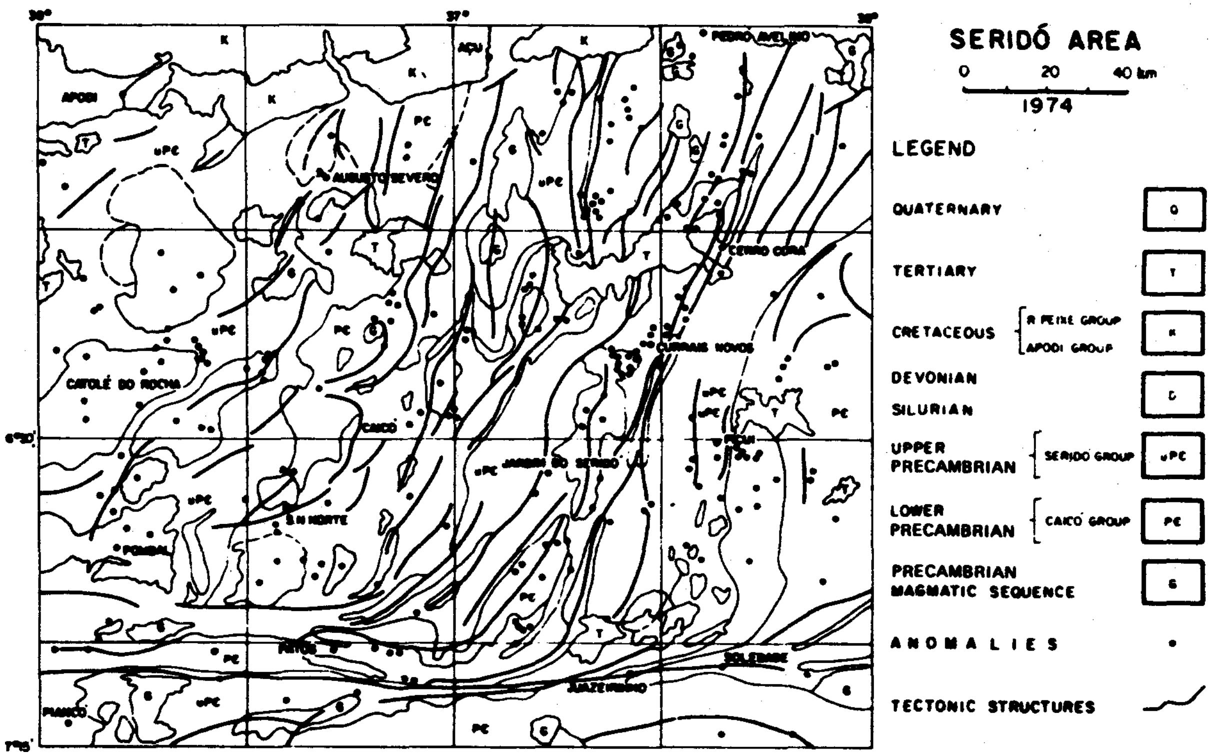
Section 5.1.4 Mineralogy

Mineralogy of the main rock types is as follows (Favali, 1973; Ramos and Fraenkel, 1974):

Granites	Granite Pegmatites
microcline	microcline
quartz	quartz
oligoclase	biotite
biotite	magnetite
magnetite	metatorbernite
chalcopyrite	meta-autunite

FIGURE A-38

Geologic Sketch Map of the Serido Area



After Ramos and Fraenkel (1974); from Formation of Uranium Deposits, published by International Atomic Energy Agency.

Granites (cont.)

molybdenite

sphene

fluorite

Intermediate Facies between Granite and Pegmatite

microcline	quartz
plagioclase	biotite
titanite	zircon
pyrite	molybdenite
uraninite	uranothorianite
beta-uranophane	metatorbernite
francolite	

Hydrothermal Veins	Biotite Schist with Quartz Boudins
quartz	biotite
feldspar	quartz
diopside	zircon
stilpnomelane	
siderite	ilmenite
uraniferous opal	hematite
pyrite	monazite
uraninite	wavelite
traces of Ni and Co	autunite
presence of Cu and Cr	torbernite

Section 5.1.5 References on Currais Novos

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Section 5.2 India

Most Indian deposits of uranium in igneous rocks are localized in mobile belts. Other than the vein uranium deposits associated with granites in the Singhbum area, there is no major production of uranium from igneous host rocks.

A number of references to igneous occurrences are provided in the reference list. Notes on three specific areas are given below.

Section 5.2.1 Salem, Madras State Granites

Quite extensive deposits of uraniferous granite occur in the Kullampatti area of the Salem district (Parameshara Rao and Majundar, 1960) The main uranium minerals are uraninite and fergusonite, and the bulk uranium content of the granite is 0.067% U_3O_8. An approximate mode is as follows:

quartz	51%	zircon, uraninite	4%
feldspars	23%	fergusonite and tourmaline,	
mica	2%	others	10%
garnet	5%	(iron oxide, rutile)	

Section 5.2.2 The Bhunas Pegmatites

They are located in the Bhilwava district of Udaipur, Rajastan ($25^o13'30''N$, $74^o22'30''E$). Zoned, uraniferous pegmatites intrude mica and hornblende schists at Bhunas (Udas, 1958). These pegmatites are a source of commercial quality ruby mica; among the uranium minerals in the pegmatite are uraninite, autunite, cyrtolite and meta-torbernite. Intergrown uraninite and cyrtolite crystals weigh up to 18 kg. Bulk ore samples have an average grade of 0.08% U with local variations between 0.04 and 0.3 U.

Section 5.2.3 Sarguia (Madhya Pradesh)

Uranium concentrations of 0.08-0.21% U occur in a syenite porphyry within granite in an eroded anticline of quartzites and marbles (Dar, 1972). Uranium minerals and fluorite are confined to the matrix of the porphyry.

Section 5.2.4 References for India

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Section 5,3 Western Spain

Figure A-39 denotes uranium occurrences in the Iberian Peninsula. Most of the deposits are in the Hercynian belt of granites and metamorphic rocks. Hercynian and Variscan granites in western and Central Europe are the locus of numerous vein uranium deposits that are described in Rich et al's (1976) compendium. Pegmatite uranium deposits in the Hercynian and Variscan belts are small and uneconomic. Two igneous uranium occurrences from western Spain are briefly noted below, and a number of references to other igneous occurrences in Spain are provided in the reference list.

Section 5.3.1 Sierra Albarrana

Section 5.3.1.1 Location

The pegmatites are located in Cordoba, southwestern Spain (locale no. 1 on Figure A-39; Arribas, 1974).

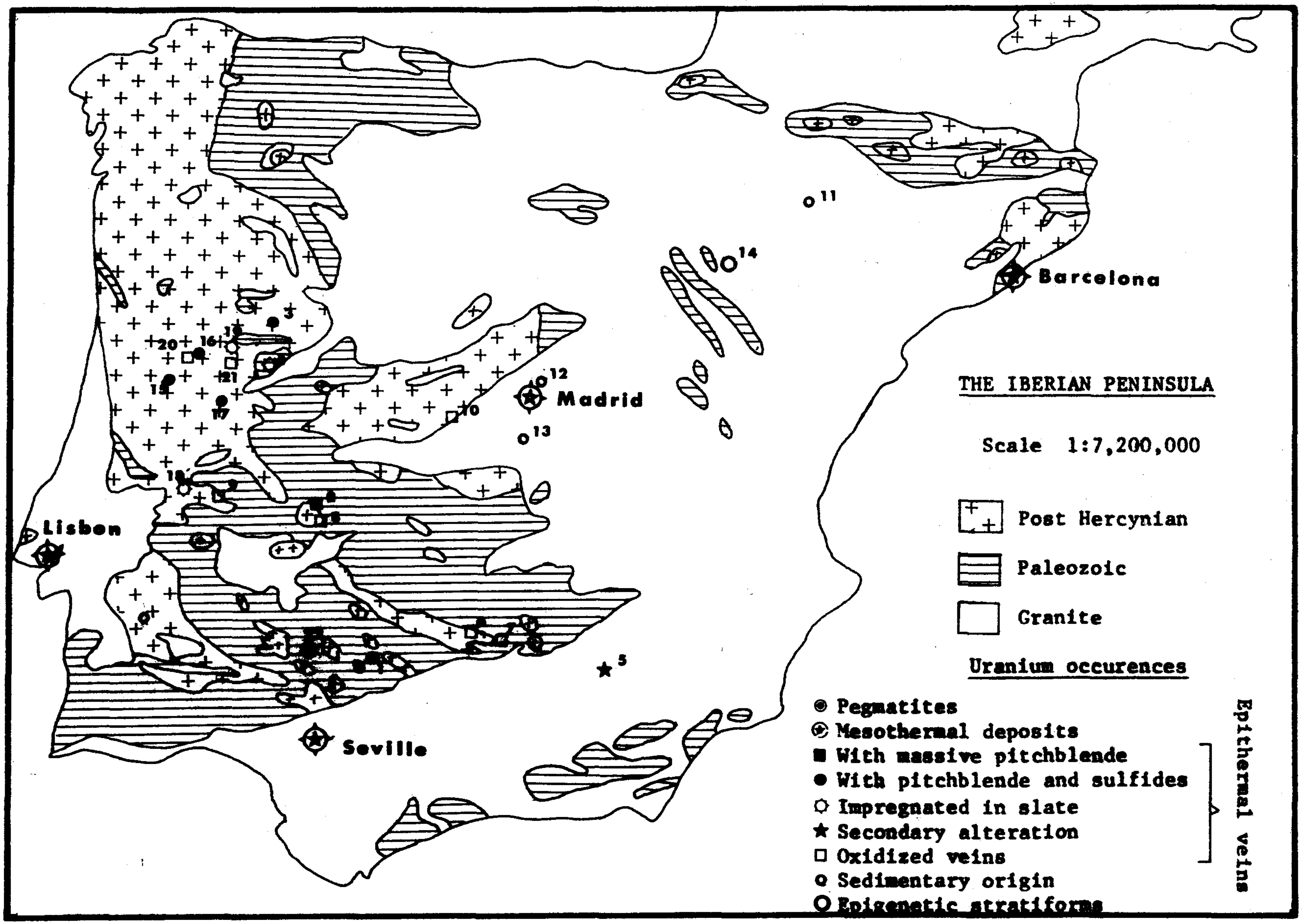
Section 5.3.1.2 Geology

The uraniferous pegmatites of Sierra Albarrana occur as dikes and masses in highly metamorphosed sediments which form the cover of a granitic batholith cropping out to the east. Country rocks include biotite-plagioclase-gneiss, alkaline biotite gneiss, amphibolite gneiss and amphibolite.

Three morphological types of dikes are recognized: (1) dikes; (2)irregular masses; and (3) "chimneys." Uranium and beryl are mutually exclusive minerals in the pegmatites, and nearly the whole of the uranium extracted is from potassic pegmatites of the "irregular mass" type. The pegmatites allegedly formed by the differentiation of granite and syenite magmas. Several types of secondary uranium minerals are reported in these pegmatites in addition to the primary assemblage.

The age of the deposits is Hercynian (250 ± 15 m.y.).

Uranium Deposits in the Iberian Peninsula
After Arribas (1960)



Section 5.3.1.3 Mineralogy

Radioactive minerals in the pegmatites are:

1. uraninite
2. brannerite
3. monazite
4. becquerelite
5. autunite
6. torbernite
7. gummite

Other minerals in the pegmatites include subequal amounts of:

1. quartz
2. feldspars
3. muscovite
4. biotite

Accessories include:

1. ilmenorutile
2. ilmenite
3. magnetite
4. chalcopyrite
5. pyrite
6. tourmaline
7. beryl

Section 5.3.2 Villanuwa del Fresno

Section 5.3.2.1 Location

The occurrence is located in Badajoz Province, southwestern Spain (locale no. 4 on Fig. 1., Arribas, 1974).

Section 5.3.2.2 Geology

A minor occurrence of davidite in a lens of sodic microsyenite is reported in a sodic gneiss terrane. The microsyenite contains albite, quartz, pyrite, davidite, biotite, and hematite. Segregations of biotite are localized at the contact between the radioactive rock and the soda gneiss, which is highly tourmalinized in the vicinity of the deposit. Petrographic features suggest a magmatic origin for the microsyenite; however, a metamorphic origin has not been ruled out.

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APPENDIX 2

ROCKS WITH URANIUM CONCENTRATION IN EXCESS OF 10 PPM

U.S.A.

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	no. analyses	References
Darby Pluton S.E. Seward Penn	Quartz Monzonite	Early Tertiary	11.2	5.2	13	Miller & Bunker (1976)
Conway granite New Hampshire	Biotite-alkaline	175 m.y.	11.5	4.8	?	Hurley (1956)
Front Range Colorado	Bostonite dikes	60 m.y.	43.6 regional 139 single dike	3.2 2.8	? 15	Phair & Gottfried (1964)
Sussex Co. New Jersey	Bostonite dike	? late Mesozoic-early Cenozoic	22	?	?	Butler & Schnabel (1955)
Outlet Neck New Mexico	Minette	Tertiary	11.9	2.3	?	Shoemaker (1955)
Bennett Peak New Mexico	Minette	Tertiary	12.3	2.5	?	Shoemaker (1955)
Mitten Rock New Mexico	felspathic	Tertiary	10.6	4.7	?	Shoemaker (1955)
Augusta Co. Virginia	Nepheline syenite dikes	Tertiary	14.8	3.8	11	Gottfried, *et al.* (1962)
Big Bend Nat. Park, Texas	Riebeckite granite	Tertiary	19.3	2.3	4	Gottfried, *et al.* (1962)

U.S.A. (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	no. analyses	References
Graniteville Missouri	Granite	1,350 m.y.	13.7	3.6	4	Malan (1972)
Quincy Mass.	Granite	425 m.y.	10.0	3.2	35	P. Tillman, pers. comm.
Chelmsford Mass.	Granite	? lower Paleozoic	10.3	?	7	Phair & Gottfried (1964)
Rocky Mt. Park Colorado	Rhyolite glass	Tertiary	10.9		3	Larsen & Phair (1954)
Ruby Mt. Colorado	Rhyolite	Tertiary	15.0	3.6	2	Rosholt, et al. (1971)
Nevada (?)	Comendite tuff	Tertiary	20.2	4	?	Rosholt, et al. (1971)
Nevada (?)	Pantellerite tuff	Tertiary	36.5	5.2	2	Rosholt, et al. (1971)
Central Front Range Colorado	Empire syenitic (undersat.) stock	Tertiary	11.8	3.6	10	Phair & Jenkins (1975)
Idaho Springs Colorado	Sodic syenite	Tertiary	10.5	3.0	2	Phair & Jenkins (1975)
Wet Mountains Colorado	Rhyolite-Quartz porphyry	Tertiary	16.5	2.2	5	Phair & Jenkins (1975)

U.S.A (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	no. analyses	References
Cripple Creek Colorado	Phonolite	Tertiary	19.2	?	3	Phair & Jenkins (1975)
Big Falls Wisc.	Granite	1,400 m.y.	26.7	2.3	?	Malan & Sterling (1969)
Republic Michigan	Granite	1,700 m.y.	14.7	8.0	?	Malan & Sterling (1969)
Stevens Co. Washington	Quartz Monzonite	Cretaceous	12.0	?	?	Nash & Lehrman (1975)

CANADA

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	no. analyses	References
SW, Baffin Islands, N.W.T.	Granite	Churchill Prov.	200-300	?	?	Padgham (1973)
Cape Dorset, Baffin Island	Biotite Paragneiss	Churchill Province	500	?	?	Padgham (1973)
Johan Beetz, Quebec	Granite Pegmatite	Grenville	70	?	?	Little (1970)
Hardisty Lake, N.W.T.	Granite Rocks	Bear Province	13.1	4.1	20	Eade & Fahrig (1971)
Southwest Saskatchewan	Porphyritic biotite granite	Precambrian	24.1	3.4	3	Rosholt _et al._, (1967)
Mt. Pleasant,	Granite	?	12	?	1	Ruzicka (1971)

CANADA (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	no. analyses	References
Mt. Laurier Canada	White Pegmatite	Grenville?	118	3.1	1	Kish (1975)
Lake Nippising Ontario	Carbonatite	?	450	?	?	Rowe (1955)
Quirke Lake	Fresh Granite	pre-Huronian	30	1.8	1	Roscoe & Steacy (1958)

AUSTRALIA

Northern Territory,
South Alligator Rivers

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	no. analyses	References
Edith River volcanics	Rhyolite	1750 m.y. Compston & Ahrens (1968)	8.35	2.5	?	Ayres and Eadington (1975)
Malone Creek granite	Granite	Middle Proterozoic	35	1.4	1	Ayres and Eadington (1975)
Pul Pul rhyolite	Rhyolite	Middle Proterozoic	10	4.2	1	Ayres and Eadington (1975)
Coronation member	Rhyolite	Middle Proterozoic	20	2.8	1	Ayres and Eadington (1975)
Nimbwah complex	Biotite	1840 m.y.				Dodson *et al*. (1974)

AUSTRALIA (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# analyses	References
<u>Rum Jungle, N.T.</u>						
Rum Jungle Complex	Granites and Gneisses	2600 m.y.	10.3	4.4	32	Heier & Rhodes (1966)
Rum Jungle	"younger" Granites	1700 m.y.	10.6	4.3	14	Heier & Rhodes (1966)
<u>Western Australia</u>						
Kellerberrin 117°18' E, 31' 40'S	foliated medium grained granite	Archaean	10	7	23	Hyndman et al. (1968)
<u>South Australia</u>						
York Peninsula	granitic gneisses	Archaean?	24	1.6	4	Bunker <u>et</u> <u>al</u>. (1975)
	Moonta Porphyry	Archaean (Glaessner & Parkin, 1958)	65	1.2	4	Bunker <u>et</u> <u>al</u>. (1975)
<u>Tasmania</u>						
Heemskirk granite	red granite facies	354 m.y.	8.9	5.6	5	Heier& Brooks (1966)
Heemskirk granite	white granite facies	354 m.y.	19.9	1.7	13	Heier& Brooks (1966)

AFRICA

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# analyses	References
Liueri Complex						
Kaffo Valley Nigeria	Albite-riebeckite granite	Jurassic	100	?	37	McKay & Beer (1952)
East African Rift						
Kenya, Tanzania, Uganda	nephelinites (average)	Neogene-Quaternary	10.4	1.8	13	Polyakov & Sobornov (1971)
Mt. Hanang	melanite-nephelinite		10.1	1.6	2	Polyakov & Sobornov (1971)
Oldinyo-Lengai	melilite-nephelinite		10.7	1.4	2	Polyakov & Sobornov (1971)
Mt. Kenya	Kenyte		10.9	1.7	1	Polyakov & Sobornov (1971)
Oldinyo-Lengai	carbonatite		46.1	0.2	1	Polyakov & Sobornov (1971)
Holma massif	carbonatite		27.0	2.0	1	Polyakov & Sobornov (1971)
Mt. Kilimanjaro	rhomb porphyry		10.1	2.9	1	Polyakov & Sobornov (1971)
Cedar Hill, Kenya	Pantellerite		19.0	1.7	1	Polyakov & Sobornov (1971)
Lake Narvasha, Kenya	Comendite		22.0	2.0	1	Polyakov & Sobornov (1971)

AFRICA (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# analyses	References
Palabora Complex, N.E. Transvaal	Carbonatites	2060 m.y.	40	?	?	von Backstrom (1974)
Atakor, Hoggar Plateau	phonolite		11		9	Cheminee (1973)
Atakor, Hoggar Plateau	hyperalkaline phonolite		13		3	Cheminee (1973)
S. Africa	kimberlites, soft micaceous var.		11.9	?	2	Kresten (1974)
Pilansberg, S. Africa	tinguaite and foyaites		50-220		?	von Backstrom (1974)
Tweerivier, S. Africa	carbonatite		20-50	15-30?	?	von Backstrom (1974)
Glenover, S. Africa	carbonatite		100-500	?	?	von Backstrom (1974)
Ondurakorume, S.W. Africa	carbonatite		20	1.5	?	von Backstrom (1974)
Eastern Egypt	bostonite dikes	(Mesozoic?)	50-100	?	?	this report

EUROPE

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# Analyses	References
Aar Massif, Switz.	Guiv syenite (avg.)	270-300 m.y.	22.1	3.2	44	Labhart & Rybach (1971)
Aar Massif, Switz.	core zone		15	3.7		
Aar Massif, Switz.	rim		28	2.8		
Aar Massif, Switz.	fine grained facies		30.8	2.7	11	
Aar Massif, Switz.	porphyritic		19.2	3.4	33	
Langesund, S. Oslo region, Nor.	Nepheline pegmatites	?	50	?	?	Siggerud (1955)
Iddejfjord, Oslo region	alkali granite	900 m.y.	9.9	5.1	134	Kileen & Heier (1975)
SW England	granite (avg.)	282 m.y.	10.4	1.7	50	Tammemagi & Smith (1975)
SW England	Bodmin Moor		9.8	1.4	5	
SW England	Carnmenellis		10.8	1.6	5	
SW England	Lands End		11.4	2.0	9	
SW England	St. Austell		10.8	1.4	9	
Kaiserstuhl Complex, Germany	phonolites "dolomites barytiferes"	post upper oligocene to Miocene	19	1.2	?	Wambeke *et al*. (1964)
Urgeirica district, Portugal	unaltered granite	Hercynian	45	1.5	2	von Backstrom (1974)
	sericitized granite	Hercynian	31	1.0	2	
St. Sylvestro massif, West-central France	two mica granite	Hercynian	14-22	?	?	Barbier & Ranchin (1969)
De Mortagne massif, Nantes, France	granite	Hercynian	up to 23	?	?	Roubault & Coppens (1960)

EUROPE (contd.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# Analyses	References
Brame, France	granite	Hercynian	10.5	?	39	Moreau et al.(1965)
Ambazac, France	granite	Hercynian	10.81	?	295	
Lachaux, France	granite	Hercynian	9.9	?	22	
Auvergne, N. Central France	phonolites, rhyolites, basalts		9-14.5	?	68	Imbo et al. (1968)
Vendee, France	granite	Hercynian	3.6-23.6	?	29	Roubault & Coppens (1960)
N. Cantal, France	phonolites, trachytes	Quaternary	16	3.1	6	Varet (1969)
Mt. Dore, France	rhyolite	Pliocene	10.3	4.1	26	Cheminee (1973)
Aigoun and St. Guiral-Leroi Massif, France	granite and marginal rocks	Hercynian	12	?	6	Didier (1973)
Vesuvius, Italy	trachyte	10,000 yr.	13	6.1	4	Cheminee (1973)
Strombol, Italy	basalt	May, 1963	11	1.2	12	Cheminee (1973)
Strombol, Italy	trachyte	Sept, 1963	10.8	1.2	15	Cheminee (1973)
Strombol, Italy	trachyte	Oct., 1963	11	1.3	14	Cheminee (1973)
Latera volcano, Italy	latite	Quaternary	16	6.3	7	Locardi & Mittempergher (1967)
	trachyte		21	4.2	11	
	alkali trachyte		24	4.3	7	
Vico volcano, Italy	trachyphonolite (tephritic)	Quaternary	27	4.3	30	Locardi & Mittempergher (1967)
	trachyte		37	5.5	3	
	latitic trachyphonolite		47	4.4	15	
	trachyphonolites		50	4.4	30	

EUROPE (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# Analyses	References
Lipari Island, Italy	not given		11.1	3.9	23	Cheminee (1973)
Volcano Island, Italy	not given		12.0	4.2	10	Cheminee (1973)
Sabatini Volcano, Italy	alkali trachytes to rhyolites	Quaternary	18	5.6	5	Locardi & Mittempergher (1967)
Sabatini Volcano, Italy	undersaturated trachytes		24.5	4.7	16	
Valture, Italy	basalts, tephrites, phonolites	?	24-55	1.4-2.4	11	Imbo *et al*. (1968)
Etna, Sicily	andesites, basaltic andesites	Quaternary	11-17	1.0-1.7	9	Imbo *et al*. (1968)
Ischia Island, It.	latites to phonolites	?	7-33	2.0-5.4	23	Imbo *et al*. (1968)
Roccamonfina,	leucitites, tephrites, latites	?	5-43	1.3-3.2	32	Imbo *et al*. (1968)

U.S.S.R.

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# Analyses	References
Lovozero massif, Kola Peninsula	Differentiatal Complex	266 m.y.	12.5	5.6	24	Vlasov (1968)
Lovozero massif, Kola Peninsula	Poikilitic syenite	266 m.y.	7.6	12	10	Vlasov (1968)

U.S.S.R. (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# analyses	References
Lovozero massif, Kola Peninsula	Eudialite lujaurite	266 m.y.	2.0	2.5	5	Vlasov (1968)
Lovozero massif,	Massif avg.	266 m.y.	14.7	4.4		Vlasov (1968)
N. Caucusas	rhyolite	300 m.y.	53.0	0.3	5	Afanosyev *et al*. (1972)
N. Caucusas	granophyre felsite	300 m.y.	16	0.8	10	Afanosyev *et al*. (1972)
N. Caucusas	alkalic granite	10 m.y.	21.6	1.7	4	Afanosyev *et al*. (1972)
N. Caucusas	rhyolite	4 m.y.	14.7	3.1	3	Afanosyev *et al*. (1972)
N. Caucusas	granite	2 m.y.	15.0	1.5	6	Afanosyev *et al*. (1972)
N. Caucusas	granite	260 m.y.	17.0	2.7	1	Afanosyev *et al*. (1972)
N. Caucusas	alaskite	320 m.y.	44.0	2.4	3	Afanosyev *et al*. (1972)
Ognitskii Complex, Eastern Sayan Mts.	riebeckite granites	Middle Paleozoic	10	11	4	Kovalenko *et al*. (1964)
Ognitskii Complex Eastern Sayan Mts.	albitized granite with hematite	Middle Paleozoic	13.5	6.6	3	Kovalenko *et al*. (1964)
Ognitskii Complex Eastern Sayan Mts.	albitized granites	Middle Paleozoic	11.8	3.3	8	Kovalenko *et al*. (1964)
Ognitskii Complex Eastern Sayan Mts.	alaskite	Middle Paleozoic	11.2	4.2	6	Kovalenko *et al*. (1964)
Ognitskii Complex Eastern Sayan Mts.	quartz albitites	Middle Paleozoic	12.3	7.1	3	Kovalenko *et al*. (1964)
Northern Kirgizia	alaskite granites	Upper Permian-Triassic	15		4	Turovskii (1957)

U.S.S.R. (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# Analyses	References
Northern Kirgizia	granosyenites	Upper Permian-Triassic	23		4	Turovskii (1957)
Northern Kirgizia	granosyenites	Variscan	18		8	Turovskii (1957)
Northern Kirgizia	syenite	Variscan	14		97	Turovskii (1957)
Northern Kirgizia	quartz porphyry	Caledonian	13.5		3	Turovskii (1957)
Matcha and Turpi Massifs, Southern Tien-Shan	altered alkalic syenites and albitites	Variscan	14.9	2.9	6	Leonova (1964)
Sakharioki Massif Kola Peninsula	nepheline syenites	Hercynian	16	1.6	?	Gerasimovsky (1968)
Turiy Peninsula, Murmansk region	carbonatites	Caledonian	13.4	0.5	?	Bulakh et al. (1973)
Turiy Peninsula, Murmansk region	magnetite carbonatites	Caledonian	52	0.2	?	Bulakh et al. (1973)
Perzhanskii-Peraga Rudnaya	silicified granite	Archaean?	25.0	4.4	12	Ushakova (1961)
Kovolensk Complex, Ukranian shield	alkali granites	1100-1800 m.y.	15.1	2.8	?	Tolstoy et al. (1973)
Western Transbaik-aliya	biotite granites	Lower Paleozoic	10.0	3.5	21	Smirnov (1962)
Northern Kazakhstan	subvolcanic epileucite series	?	18.3	2.0	9	Lebedev-Zinovyev (1965)

U.S.S.R. (cont.)

Locality	Host Rock Type	Age	Concentration (PPM)	Th/U	# Analyses	References
Northern Kazakhstan	amphibole nepheline syenites	?	21	2.1	15	Lebedev-Zinoyev (1965)
Northern Kazakhstan	amphibole-melanite-nepheline syenites	?	11.1	4.0	2	Lebedev-Zinoyev (1965)
Northern Kazakhstan	biotite nephaline syenite	?	14.7	1.3	3	Lebedev-Zinoyev (1965)
Northern Kazakhstan	aegerine-nephaline-syenites	?	16.6	2.6	13	Lebedev-Zinoyev (1965)
Northern Kazakhstan	juvites	?	31.7	2.2	22	Lebedev-Zinoyev (1965)
Northern Kazakhstan	pseudoleucite tinguaites	?	19.3	2.0	4	Lebedev-Zinoyev (1965)
Bureinsk massif	granites	early Paleozoic	11.6	3.5	21	Putintsev et al. (1972)
Kzyl-Ompul Massif, Northern Tien-Shan	syenites	Variscan	13.7	4.5	6	Leonova et al. (1961)
Kzyl-Ompul Massif, Northern Tien-Shan	massif average		9.7	5.8	16	Leonova et al. (1961)
Borovskoe Complex, Northern Kazakhstan	leucocratic granites	lower Paleozoic	10	3.6	4	Smylsov (1958)
Yantsev Massif, Middle Dnepr region	albitized,silicified pegmatoid granites, aplites	1900-2000 m.y.	9.9	2.4	?	Fillipov & Komlev (1959)

U.S.S.R. (cont.)

Locality	Host Rock Type	Age	Concentration (ppm)	Th/U	# Analyses	References
Tokovskii Massif, Middle Dnepr region	porphyritic granite	1700-1800 m.y.	9.3	10.4	101	
Ural Mts.	Albitized miaskites	295 $\pm$ 15 m.y.	14.5	27	?	Yeskova et al. (1962)
U.S.S.R., unspecified	glassy ignimbrites	Hercynian-Kimeridgian	21	2.7	21	Shatkov et al. (1970)
U.S.S.R., unspecified	semiglassy ignimbrites	Hercynian-Kimeridgian	13.5	4.3	12	Shatkov et al. (1970)
U.S.S.R., unspecified	sanidine liparites (volcanol)	Hercynian-Kimeridgian	12.6	4.2	23	Shatkov et al. (1970)
U.S.S.R, unspecified	sanidine liparites (volcanoz)	Hercynian-	12.0	3.7	12	Shatkov et al. (1970)
		MISCELLANEOUS				
Ilimaussaq Complex, Greenland	lujavrites	1020 m.y.	>100, locally 400	?	?	Sørensen (1970)
Ilimaussaq Complex	average		62	0.6		Sørensen (1970)
Cercado and Agosinho deposits, Pocos de Caldos, Brazil	nepheline syenites	63-80 m.y.	1800	2-6		de Andrade Ramos & Fraenkel (1974)
Salem district, India	granite, pegmatite	Precambrian	500			Rao and Majumder (1960)

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APPENDIX 3

PRELIMINARY REPORT ON VISIT TO SOUTH WEST AFRICA

John J. W. Rogers

In connection with our investigation of the occurrence of uranium in igneous rocks, I have recently been able to visit areas of considerable interest in South West Africa. My trip also enabled me to confer with geologists in South Africa who are experts on the geology and uranium potential of South West Africa. I would like specifically to acknowledge the following persons, all of whom showed great kindness to me and provided information both in the office and field on which much of this report is based: J. von Backström, Atomic Energy Board, Pelindaba; R. Jacob, Rhodes University, Grahamstown; A. Kröner, Precambrian Research Unit, Capetown; and numerous geologists of the Anglo American Corp. in Johannesburg, Windhoek, and Swakopmund, including Messrs Coetzee, Gewald, Main, Smith, Versfeld, Waggener, Wilson, and Woodhouse. Much of the success of the trip is based on the great assistance provided by the Anglo American Corp. The following notes are a summary of my impressions concerning the Damara orogen and the occurrence of uranium in its igneous rocks. No investigation has been made of the calcrete deposits in the same area. Any errors in these interpretations are my own and not the responsibility of the persons mentioned above.

The portion of South West Africa visited extends from Windhoek, on a high plain of moderate vegetation, to the Namib Desert, on the coast. Uranium deposits occur in the desert portion of the Damaran orogen, which extends NE-SW through South West Africa. A number of geologic studies have been carried out in the area; the ones most commonly consulted in preparing this report are those of Smith (1965), von Backström (1970), Jacob (1974), Armstrong (1974), and Berning et. al. (1976).

The stratigraphic section in general use in the Damaran orogen is attached, and although some modification has been proposed, this terminology has been retained in this report. The metasedimentary units overlie basement (Abbabis Formation); a series of gneisses designated as the Red Granite Gneiss (Gn_1) also appear to be older basement in some places, but not all relationships are clear. The metasediments are intricately intruded by a variety of catazonal-type granites, including the uranium-bearing G_4. A number of late, diapiric granites are also present.

The Damaran orogen is a NE-SW-striking belt most recently deformed in Pan African time (about 500 m.y. ago). It extends between older cratons to the southeast and northwest and may connect with the similar Katangan belt to the northeast, although the correlation of the two belts is obscured by younger cover in the Kalahari region. The belt is approximately 300 miles wide, and the regional trend is NE-SW in all portions. The southeastern one third of the width of the belt is a graywacke assemblage (Khomas Schists) showing multiple deformation, moderate metamorphism, and an absence of intrusive or basement rocks. The schist belt may be ensimatic, but evidence of suturing between the cratons on either side has not been found within the exposed portions of the belt.

The northwestern two thirds of the Damaran orogen is quite different from the Khomas trough. The northwestern portion is characterized by the same NE-SW trend but contains a wide variety of rock types. The entire area appears to be underlain by sialic basement, now exposed at numerous places as mantled gneiss domes. The basement is overlain by quartzites, arkoses, marbles, and other shallow-water sediments that have now been metamorphosed to moderate- to high-rank gneisses and schists. The belt appears to pitch to the northeast, thus exposing lower levels of the orogen toward the southwest, near the coast. High uranium concentrations occur in the southwestern, more deeply exposed, portions of the orogen, where basement rocks, high-rank metasedimentary rocks, and anatectic granites are closely intermingled.

The principal evidence that many of the granites in the deeply eroded portion of the Damara belt are anatectic and/or syntectic is the stratigraphic restriction of two of the major intrusive types. One of the older granites (G_4) is the major host of uranium deposits and is restricted primarily to the Nosib Group, with some metamorphism of marbles in the overlying Rössing formation and minor intrusion into younger metasedimentary rocks. The development of skarns along contacts of G_4 and the Rossing marbles, plus the conformity of overlying metasediments with the Rossing Formation, indicates that G_4 post-dates most of the sedimentation in the area, and thus its restriction to the Nosib Group is presumably the result of very local anatectic derivation of the G_4 melt. In similar fashion, the restriction of the Salem granites to the upper part of the Damara Group, above the Rossing Formation, also indicates local derivation of the Salem magmas.

These anatectic granites have a readily distinguishable set of properties. They are variable in grain size, anastomose and grade into surrounding metamorphic wall rocks, lack chilled contacts, and contain abundant screens and inclusions of the wall rocks. They are thus distinct from the post-tectonic, diapiric granites that intrude all of the metamorphic rocks of the orogen as massive, easily distinguishable units. The diapiric granites generally do not contain significant uranium concentrations.

One of the problems in the Damaran orogen has been the recognition of older basement underlying the metasediments. Some basement (Abbabis Formation) has been identified since the time of early geologic investigations in the area. Controversy exists, however, over a rock type referred to as Red Granite Gneiss (Gn_1); Gn_1 has been variously designated as either a higher rank equivalent of Nosib metasediments or a basement on which Nosib quartzites and quartz conglomerates were deposited. Variability in lithologic character of the Gn_1 makes the determination difficult. Furthermore, some Gn_1 "basement" may have been remobilized and injected into overlying metasediments. Limited recent dating indicates ages up to 1700 m.y. in some apparent Gn_1 equivalents.

High uranium concentrations are associated with the G_4 granites. These granites consist primarily of quartz and alkali feldspars with minor biotite. Mafic minerals are sufficiently scarce in most samples that the G_4 has been referred to as an alaskite. Anhedral textures predominate, and the grain size is highly variable, becoming pegmatitic in many places. There is no readily discernible pattern of grain size variation. The granite has irregularly invaded the Khan Formation without visible contact metamorphic effects, but the contacts with marbles of the Rossing Formation are extensively converted into calc-silicate skarns. Apophyses of the G_4 in the Khan Formation are not surrounded by residual mafic aureoles and, therefore, are apparently not derived by anatexis of the Khan Formation. Outcrops of the G_4 generally show the regional NE-SW strike and occur primarily in antiforms. Because the G_4 melt is not derived from the Khan Formation, and does not intrude significantly above the Rossing Formation, the G_4 has presumably been derived from lower Nosib or pre-Nosib basement rocks.

The uranium in the G_4 granite is very irregularly distributed. Uranium values range upward from 30 ppm to 1,000 ppm or more. High concentrations are particularly noted near contacts with the biotitic schists of the Khan Formation, and in some contact zones uranium has been added to the Khan Formation by fluids from the granite. Much of the high-uranium granite contains slightly higher concentrations of biotite than the remainder of the granite. Particularly high concentrations of uranium are commonly associated with smoky quartz because of the development of the smoky appearance by radiation damage. Uranium is also commonly associated with reddish, ferruginous zones, although it is not clear whether these discolorations are caused by magmatic or weathering processes.

Reported mineralogy at Rössing indicates that about 60 percent of the uranium is in primary minerals (chiefly uraninite) and 40 percent in a large variety of secondary minerals. The extent to which the variability of uranium concentrations in the various granites is caused by primary or by secondary processes is unknown. Furthermore, there is no clear evidence to indicate whether the secondary uranium mineralization is hypogene or supergene. Most of the uranium values in the Khan Formation near its contact with the G_4 are in secondary minerals, instead of uraninite, and thus it seems likely that at least some of the secondary distribution is caused by late magmatic processes.

The nature of the Namib Desert, in which the uranium deposits occur, is of particular importance in connection with the possibility of supergene enrichment of the uranium. This desert is extensively developed in a narrow zone, about 50 to 100 miles wide, along the southwestern coast of Africa as a result of a cold, northerly-moving current of Antarctic water along the coast. The desert is likely to have been in existence for some tens of millions of years, allowing ample time for supergene processes to occur. Although rainfall is sparse, the morning dews are very heavy, leading to the evolution of the peculiar Welwitchia plant, which lives on collection of the dew. Furthermore, although the water table is generally several hundred feet below the surface, the desert shows abundant evidence of stream sculpturing and is clearly not as dry as the more wind-dominated Sahara and Arabian deserts. Thus, the water balance in the Namib desert may be highly favorable to downward percolation of ground water and prolonged supergene activity.

I have drawn a number of preliminary conclusions concerning the abundance of uranium in the Rössing area, but the tentative nature of these conclusions must be emphasized. The principal conclusion is that the high concentrations of uranium in South West Africa are the result of the geologic history of the Damaran belt rather than any peculiar petrology of the rocks with which the uranium is associated. The G_4 granites and associated wall rocks are not unique to the Damaran orogen and, in fact, exhibit lithologies and structural relationships that can be found in igneous-metamorphic complexes throughout the world. Most of these other occurrences, however, are not strikingly enriched in uranium, and it seems logical to conclude that there is some factor in the development of the Damaran orogen that is responsible for the high uranium concentrations.

This controlling factor is likely to be the continual recycling that rocks in the orogen (at least the northwestern portion) have undergone. The materials have clearly passed through several stages of metamorphism, at least one sedimentary cycle, and at least one stage of anatexis. The result of all of these processes is apparently the continued concentration of uranium until the final, anatectic, G_4 granites contain upwards from 30 ppm uranium. This conclusion is highly generalized but is somewhat supported by the attached preliminary statement of R. Nishimori to the effect that uranium-rich granites are commonly catazonal and apparently anatectic. There are, however, many anatectic granites in the world that are not rich in uranium, and the precise reason for high concentration in some granites is not clear.

A second conclusion is that the exceptional concentrations of uranium in the Rössing area may be related to the climatic characteristics of the Namib Desert. The extent to which the secondary mineralization at Rössing and in related deposits is caused by supergene or by hypogene activity is uncertain. As mentioned above, the Namib Desert should be an area favorable to supergene processes, and it may be that similar conditions are necessary for the extreme concentrations found in the granites of the area. Even without secondary enrichment, however, the G_4 granites are exceptionally rich in uranium as a result of some primary process.

Obviously, there are still a large number of unanswered questions concerning the igneous uranium deposits of the Damaran orogen. A few of the most pertinent ones are as follows:

1. In the granites in general, how much of the uranium is primary and how much is secondary?

2. Is the inhomogeneity of distribution of the uranium largely the result of variability in abundance of the secondary minerals? In similar fashion, does the secondary process cause more or less uniformity in the distribution of uranium values?

3. Is the secondary process dominantly supergene or hypogene?

4. What part of the recycling process in the Damaran orogen is largely responsible for the concentration of uranium? Can the effects of sedimentary processing be separated from the effects of partial melting by the study of such ratios as U/Rb, U/Sr, U/Th, U/Zr, etc.?

5. Are the climatic conditions of the Namib Desert an important factor in the development of the very high uranium concentrations?

The answers to many of these questions may be important in using the information gained from the Damaran orogen in predicting broad areas of the United States in which economic concentrations of uranium may occur in igneous rocks.

Generalized Stratigraphy in the Western Part of the Damaran Orogen

Note: This stratigraphic section is merely a summary of terms referred to in the accompanying text and is not to be considered a complete stratigraphic section for any part of the Damaran orogen.

Post-tectonic intrusive rocks (diapiric granites, dikes, etc.)

Damara Group:

Khomas Subgroup:

in northwestern portion of the orogen - highly variable schist, gneiss, marble, quartzite, and migmatite — contains Salem Granites

Rossing Formation:

schist, gneiss, marble, quartzite, local calc-silicate hornfels

Nosib Group:

Khan Formation:

hornblende- and biotite-bearing schists and gneisses — contains G_4 granites

Etusis Formation:

quartzitic and arkosic gneisses, migmatite, metaconglomerate

Basement:

Abbabis Formation:

very highly metamorphosed; gneiss, augen gneiss, schist, quartzite — possibly includes Red Granite Gneiss (Gn_1)

SUPPLEMENT TO ROGERS' REPORT

Richard Nishimori

The preceding report describes an occurrence of uranium mineralization in a granitic terrane; the Rossing deposit has been described as a prototype of ore deposits termed "porphyry uranium deposits" by Armstrong (1974). Such "granitic" deposits are in clear contrast to uranium deposits associated with primary magmatic (as opposed to anatectic or migmatic) alkaline rock complexes. Unlike the Rössing deposit, uranium occurrences in alkaline complexes (Pocos de Caldas, Brazil; Ilimaussaq, Greenland) are the result of crystallization and differentiation of intrusive alkaline magmas and are accompanied throughout by abnormally high concentrations of rare earth elements, niobium, zirconium, and other large cations or "incompatible elements". The high concentrations of these elements plus alkalies plus uranium are commonly inferred to be an indigenous feature of the parental magmas of these alkaline complexes.

The Rossing deposit, in contrast, owes its existence in part to the process of anatexis--the mobilization and refractionation of older (uranium rich?) crustal rocks producing uraniferous granites with ore concentrated in the pegmatitic or alaskitic phase of these anatectic granites. The Rossing deposit is similar, in a general way, to other catazonal granite complexes occurring in the Olary Province, South Australia; Wheeler Basin, Colorado; Charlebois Lake, Saskatchewan; the Bancroft area, Ontario; and Currais Novos, Rio Grande del Norte, Brazil. These occurrences are briefly discussed below:

Crocker Wells, Olary Province, South Australia

The Crocker Wells uranium deposit is hosted by an adamellite variety of granitoid rock. Davidite (dated at 580 m.y.) and absite are the most important uranium-bearing minerals. The actual ore mineralization is most closely associated with the intrusion of the alaskitic and aplitic phases of the adamellite which are in an intimate relationship with both the enclosing migmatites and granitic rock.

The granitic formations of the Olary province are classified by Campana (1957) as anatectic because metamorphic strata show all transitions from feldspathized schists and quartzites to migmatites and massive granites. The fertile adamellite rock in this area is considered to be a mobilized phase of the regional granitization process which affected the area. Johnson (1958) describes the adamellite as "the cores of several migmatized masses, garlanded by ungranitized sediments".

Campana (1957) speculates that the Crocker Wells uranium deposits are the result of anatexis of older, uranium-rich sediments, citing that Archaean metasediments in the area (Outalpa arkosic quartzites) contain radioactive minerals as detrital grains. Furthermore, Campana cites the Radium Hill metallogenic epoch (1600 m.y.) as evidence for a previous history and source of U metallogeny in this area, supporting the allegation that the Crocker Wells deposit could also result from the remelting and mobilization of older crystalline rocks and their related mineral deposits.

Wheeler Basin, Colorado

Young and Hauff (1975) report an occurrence of disseminated uraninite in Wheeler Basin, Colorado, in Precambrian migmatized gneiss, mixed gneiss, and pegmatite. They allege the origin of this deposit to be the remobilization and concentration of elements during metamorphism as a consequence of the intrusion of the Silver Plume granite. The highest concentrations of disseminated uraninite are confined to those segments of the host gneisses, pegmatites and migmatites that are richest in biotite; Rössing shows a similar but somewhat weaker correlation of uranium concentration to biotite concentration. The pegmatite host rocks of the uraninite-rich biotite concentrations of this deposit "consist mostly of pink perthite, quartz, and much smaller amounts of biotite and muscovite" and are therefore, by definition, alaskitic pegmatites.

It is prudent to note that the Colorado Front Range is a region wherein "bedrock enrichment in radioactive constituents can be demonstrated on a crustal scale of many thousands of miles (Phair and Gottfried, 1965)". Refractionation of uraniferous older crustal rocks is thus a reasonable petrogenic model for the origin of the uraninite in this occurrence. Young and Hauff (1975) compare this deposit favorably to Rössing.

Carlebois Lake, Saskatchewan

The Charlebois Lake uranium deposits may be considered one of several groups of similar uranium deposits in the province of Saskatchewan. The oldest rocks in this area are highly metamorphosed Archaean sediments (Tazin group), which grade into granitic gneisses, which in turn pass into more massive granites. The uraninite deposits are in migmatite zones bordering granite masses. These migmatites are composed of calcium-rich metasediments intruded and replaced by fine-grained white pegmatite. The radioactive mineralization occurs in facies of the fine-grained pegmatite and in some of the related injection gneisses. Mineralogically, the fine pegmatite ranges from a light gray to white rock, predominantly composed of feldspar, to a dark gray or gray rock composed principally of mica and smoky quartz. The varieties richest in quartz and biotite contain the greatest amount of uraninite. The ages of the granites in this area correspond with the timing of the Hudsonian orogeny (approx. 1800 m.y.). Mawdsley (1951, 1952, 1958) notes that the metasediments in the Charlebois Lake area are practically devoid of radioactivity and thus doubts that the radioactive minerals in the pegmatites and migmatites are genetically related to the Tazin sediments.

Bancroft area, Ontario

The batholiths of the Bancroft area, Ontario, occur in a high-grade terrane containing marbles, amphibolite schists, gneisses, metagabbro, metadiorite gneiss, paramphibolite and paragneiss. Emplacement of the granites and syenites into this amphibolite terrane was accompanied by lit-par-lit injection, granitization and syenitization resulting in the formation of large areas of granitic gneiss and syenitic gneiss of hybrid origin. The mixed gneiss or paragneiss which surrounds many of the granitic and syenitic gneiss plutons is the chief host rock of the uraninite- and uranothorianite-rich granitic and syenitic pegmatites, which comprise the previously mined uranium deposits of this area (Satterly, 1957; Robinson and Hewitt, 1958; Robinson, 1960). The age of the uraninite is approximately 1,000 m.y.

Other occurrences of uranium mineralization in this area are metasomatic deposits in marble, metamorphic pyroxenite, and granitic gneiss, and also in uranium-bearing calcite-flourite-apatite veins.

Currais Novos, Rio Grande del Norte, Brazil

Only limited information is available concerning the Currais Novos deposit. Recent reconnaissance in the Serido geosyncline (Maciel and Cruz, 1973; Favali, 1973; Ramos and Fraenkel, 1974) indicates that disseminated uranium mineralization occurs in granite and pegmatoid granite in the form of uraninite, uranothorianite, and allanite. Uranium mineralization is also found in biotite schists, migmatite and meta-arkose in this area. The mineralized pegmatites and granites, which are related to the Itaporanga type granites, occur in the migmatites (paragneisses, meta-arkoses) of the Caico group of lower Precambrian age; the Caico group discordantly overlies the Archaean basement. Maciel and Cruz (1973) consider the Currais Novos ore deposits to be quite similar to the Rössing deposits.

Discussion

If there is a single unifying environmental factor among these various deposits, it must be that the features of their granitic host rocks ally these deposits with the "catazone". These disseminated uranium deposits occur in terranes where concordant contact relations predominate over discordant features; migmatization and granitization are ubiquitous features in these terranes. The ore deposits themselves occur predominantly in mixed rock or migmatitic zones and are hosted primarily by pegmatite and/or alaskite dikes which are the latest and most felsic (evolved) phases of the genetically related granites.

It is tempting to speculate that all of these deposits are a consequence of mobilization and refractionation of older crustal materials that were at least moderately enriched in uranium. However, broadly circumstantial evidence supports this notion for only two of the deposits (Crockers Well and Wheeler Basin). The source of uranium for these deposits is thus enigmatic.

Uranium (as well as other incompatible elements) would be expected to occur in low concentrations in the deepest (granulite facies) parts of the mobile belts. At shallower levels (amphibolite or less), however, it is possible that uranium in metasediments could be mobilized and concentrated by metamorphic processes, as Narayan Das et. al. (1971) have shown for pelitic schists from the Kulu Himalayas. Subsequent anatexis of such sediments would further reconcentrate uranium into the latest fraction of the anatectic granites, i.e., in the pegmatites and alaskites and perhaps veins. In the Singhbum shear zone, India, Banerji (1962) has demonstrated that uranium (vein) deposits are closely related to zones of migmatization. Alternative to the hypothesis of mobilization of moderately uranium-rich crustal rocks would be the repeated remobilization and reworking of ordinary crust to produce the desired concentrations of uranium.

Comparison to Beaverlodge, Canada

The term "catazonal" embraces several styles of granite formation, and it is judicious to note that the previously mentioned examples of catazonal granite are of a type that were associated with the formation of magmatic granite (e.g., mixed gneiss, migmatites, lit-par-lit injection, massive granites). One may contrast the previous examples of uranium deposits in granites with the uranium deposits of the Beaverlodge area, Saskatchewan. Buddington (1959) terms the origin of the granitic complexes in this area as one of "Batholithic development of pseudo-igneous granite in (the) catazone". Beaverlodge area granites were formed by metasomatism and replacement (Christie, 1953; Robinson, 1955) with very minor development of magmatic granite. Few and minor syngenetic deposits of uraninite in pegmatite and granite have been discovered despite intensive prospecting. However, the epigenetic uranium deposits of the Beaverlodge area are frequently near areas of heavily granitized mixed rocks, and Tremblay (1972) considers the granitized areas to have been the immediate source of uranium for the epigenetic deposits. He notes that the granites or granitized rocks have a higher uranium content (5.4 ppm) than the other rock types in the area. The model set forth by Tremblay (1972) for the origin of the Beaverlodge area uranium deposits is as such:

1. Deposition of uranium-bearing sediments (Tazin formation)
2. Mobilization of uranium and its concentration during granitization
3. Remobilization of uranium and its concentration during mylonitization
4. Remobilization and concentration during late fracturing following the same zones of weakness as (3); episodes 3 and 4 produced the workable deposits.

A primary feature of this model is that it emphasizes the role that granitization plays as a vehicle for the concentration of uranium from older crust. In this case, subsequent redistribution and concentration took the form of epigenetic rather than syngenetic deposits. Nonetheless, the point of contrasting Beaverlodge to Rössing-type deposits is to suggest the notion that the evolution of syngenetic uranium deposits in granitic rocks may, in part, be a consequence of the mode of granite formation, specifically:

1. Catazonal granites that are solely of replacement origin may be an unfavorable host for the extensive development of Rössing-type deposits but may play a role in the formation of epigenetic deposits.
2. A case for resemblance between Rössing and other deposits can

be based on the similarity of their host rocks--catazonal granites that show an interval of magmatic granite development.

Conclusions

The Rossing deposit appears to be broadly kindred to other uranium deposits that are separated from it in both time and space. One is faced with several questions in explaining the genesis of these so called "porphyry uranium deposits", namely:

1. What is the ultimate source of the uranium concentrate? Are these concentrations a consequence of repeated reworking or are they the result of a single mobilization of originally uranium-rich crustal rock? Alternatively one must invoke (purely ad hoc) a uranium-rich mantle source, i.e. deep mantle plumes or chemical plumes.

2. Within these granitic uranium deposits, some pegmatites prove to be barren while others are mineralized. Is there a set of geochemical, environmental, structural or host rock controls which dictate the distribution of uranium in these deposits?

3. And, a question closely related to (1) and (2): Other anatectic granites occur in the Precambrian and rocks of other ages; is there a reason why these complexes do not have similar uranium deposits?

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APPENDIX 4

REPORT ON FIELD EXCURSIONS TO EASTERN CANADA

by

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In conjunction with Energy Resources and Development Administration contract E(05-1)-1661, several deposits of uranium in pegmatites were visited in the Grenville province of Canada. During the course of this trip, visits were made to the Madawaska mine and several other deposits in the Bancroft district, Ontario; the Lac Kachwiss prospect near Sept Iles, Quebec; and deposits in the vicinity of Lac Patibre in the Mont Laurier district, Quebec. We wish to thank G. Reilly and R. Bujas of Getty Oil Ltd., Z. Hasan and B. Lowe of Imperial Oil Ltd., and D. Wilson and R. Alexander of Madawaska Mines for their kind assistance in both the field and the office and for extending or arranging permission for us to examine their uranium properties. The statements in this report are believed to be accurate; however, any errors are attributable to misinterpretations by the authors rather than any of the geologists consulted.

Bancroft-Madawaska Mines

Detailed descriptions of some 125 radioactive mineral occurrences in the Bancroft district can be found in Satterly (1957); pegmatite, vein and metasomatic deposits of uranium are represented in the Bancroft district. Mining and refining of uranium was carried out in this area until 1964, with most production coming from four pegmatite deposits (Greyhawk, Dyno, Faraday, and Bicroft mines). One of these mines, the Madawaska (formerly the Faraday Mine) reopened this summer (1976) for the first time since 1964. Over the past year, the Bancroft district has experienced an increase in the intensity of prospecting. Many of the previously known deposits are being re-evaluated in light of the anticipated high demand for uranium to fuel nuclear power plants.

A general review of the geology of the Bancroft district with appropriate references is included in our contract report (Appendix 1) and will not be repeated here. There are, however, some pertinent details concerning more recent activity at Bancroft uranium properties. At the Madawaska mine, ore is currently being mined at depth levels in excess of 300 meters. Grade control, as has been the case in the past, is difficult due to the spotty distribution of uranium mineralization. The average grade of ore mined is approximately 0.12% U, while the economically extractable grade of uranium is 0.04% U. This latter figure represents the break-even point with respect to operating expenses and does not include allowances for the initial capitalization of the mill. Approximately 1000 tons of ore are processed per day, and production is expected to increase to 1500 tons per day in late fall, 1976.

The radioactive minerals, principally uraninite and uranothorite, occur in dikes of pink, syenitic pegmatite that intrude the Faraday metagabbro unit. A nearby granite sheet, the Faraday granite is probably genetically related to the uraniferous pegmatites. There are no universal guides to high grade ore, but red coloration (hematite stain), smoky quartz, and an abundance of biotite and/or magnetite often accompany better grades of ore. Pale pink, coarse-grained pegmatites are typically low grade (less than 0.04% U) compared to aplitic and medium grained varieties of the "pegmatite." A common, but not ubiquitous, feature of the uraniferous pegmatites is the concentration of uranium at the hanging ore footwalls of pegmatite ores. Some uranium is also found in metasomatic or alteration halos in the metagabbro surrounding ore-grade pegmatites. The most salient feature of these halos is the presence of pink to red feldspars which do not occur in "unaltered" metagabbro.

An outstanding characteristic of the ores is the erratic distribution of uranium within individual pegmatite dikes. Uranium concentration frequently varies up to two orders of magnitude over a scale of a few tens of centimeters within individual dikes. Such variation is typically not correlatable to a megascopic difference in rock mode or texture.

Numerous uranium deposits of hydrothermal origin occur in the Bancroft district. An unusual occurrence of uraninite in calcite-fluorite-apatite veins was visited at the Cardiff Uranium prospect in Cardiff township. This deposit probably formed due to replacement of limey rocks by solutions derived during the crystallization of the local granites and syenites. Uraninite also occurs in skarns, and a deposit examined at Bryan's road in Monmouth township apparently formed by metasomatism of limestone. Pink to reddish-pink calcite is characteristic of higher grades of uranium.

In general, the greatest economic potential for uranium in the Bancroft district resides in pegmatite deposits. Current exploration strategies must be dictated by the costs of mill capitalization. Exploitation of many of the small deposits will be catalyzed by the development of one or more deposits large enough to pay for the high costs of initiating production.

Sept Iles

The uranium potential of the Lac Kachwiss prospect has been briefly review by Baldwin (1970). This deposit comprises pink K-feldspar-rich syenitic pegmatites that range in texture from aplitic to phaneritic to pegmatitic. The close association and concordant relationships between the pegmatites and a monzonitic to syenitic gneiss unit suggests that the pegmatites are anatectic melts of these gneisses. Uranium concentration ranges from 0.5 to 100 ppm in the syenitic to monzonitic gneiss. Higher concentrations of uranium in the pegmatites show weak correlations with the presence of smoky quartz, hematite stains, and biotite-rich zones. As of yet, the principal uranium-bearing mineral has not been identified. Erratic variations in the concentration of uranium in drill cores, as is seen at Bancroft, characterize the distribution of uranium in the Lac Kachwiss prospect. An important factor for the potential development of this prospect into a mine is the nearness of the deposit to a major shipping and population center (the city of Sept Iles). If the prospect proves to be economic, open pit mining methods will be utilized.

Mont Laurier

Descriptions of the regional geology (Wynne-Edwards, 1969) and uranium deposits (Allen, 1971; Tremblay, 1974; Kish, 1975) in the Mont Laurier district have been reported in some detail previously. Uraniferous pegmatites near Lac Patibre are apparently ultrametamorphic in origin and were derived by partial melting of uraniferous biotite gneisses. Two types of pegmatites can be distinguished in the Mont Laurier area; white, uraninite-bearing pegmatites and comparatively uranium-poor pink pegmatites. Both types of pegmatite are approximately granitic in composition. Magnetite is a ubiquitous accessory mineral in the pink pegmatites, while graphite, molybdenite, pyrite and pyrrhotite predominate over oxide minerals in the white pegmatites. Red alteration is conspicuously absent in the white pegmatites. White pegmatite lenses up to 10 meters wide average up to 2 or 3 lbs/ton uranium, but as is the case for most other pegmatite uranium deposits, uranium is distributed heterogeneously throughout the pegmatites.

An active drilling and geological program is currently being executed in the Mont Laurier district.

Conclusions and Impressions

Our field observations and discussions in Canada have amplified several points on the economic concentration of uranium in pegmatites:

1. The problem of the origin of pegmatite uranium deposits is necessarily related to the origin of granitic magma and structural controls on emplacement of the pegmatite ore bodies. There is evidence at each of the deposits visited that suggests that the pegmatites were ultimately derived by fusion of metasediments to form melts of uraniferous granite. At Mont Laurier, anatexis was extremely localized; sediments were fused to form pegmatite dikes in place. At Bancroft, anatexis produced batholiths which crystallized, differentiated, and injected uraniferous pegmatites into the country rock. Structural traps or zones of weakness such as folds or faults are favorable sites for ore localization.
2. There is no consistency in the mineral associations of uranium deposits in pegmatites. While smoky quartz, hematite, magnetite and biotite sometimes indicate better grades of ore, the applicability of these mineralogical criteria are far from universal. Ore deposits occur in both syenitic and granitic pegmatites and in both red-altered and unaltered pegmatites.
3. In all of the deposits visited, uranium is distributed very erratically throughout the deposit and within individual pegmatites. This makes grade control extremely difficult. From a petrologic viewpoint, the erratic distribution of uranium in pegmatites suggests that the crystallization of uraninite is related to mechanical and geochemical factors which are not entirely the same as those that occasioned the crystallization of the early liquidus minerals of the pegmatites.

4. There are no present dependable geochemical criteria that are acceptable to geologists as prospecting guides, probably because there are not enough quantitative data on the composition of the ores and their host rocks. Further investigations on the relationship between uranium mineralization and Cu, S, P, F, Mo and other trace elements may be fruitful in delineating the possible elemental associations of uranium in igneous terranes.

5. All of the deposits visited are located in amphibolite to upper-amphibolite terranes and are in a province (the Grenville) which has undergone an extensive history of crustal recycling. Igneous uranium deposits in other parts of the world (Appendix 1. in our contract report) appear to be associated with similar environments.

6. The increase in price of uranium in the recent past has stimulated exploration and development efforts for uranium deposits in igneous rocks in the Canadian shield. A minimum lead time of several years lies between discovery and uranium production from this type of deposit, so it is not premature to expand our efforts in this country for exploration of igneous-affiliated uranium.

7. The term "pegmatite" is imprecise and in some cases inaccurate in describing the texture and composition of the ore rocks discussed in this report. The ores discussed range from granitic to syenitic in composition. Texture varies as well; at Bancroft, for example, fine grained aplitic and medium grained varieties of the syenitic "pegmatite" are generally richer in uranium than the truly pegmatitic, coarse grained syenite dikes. Variation in uranium content with texture suggests that crystallization history of the pegmatites, as influenced by rate of cooling, degree of water and volatile saturation and other factors may influence the mobility and deposition of uranium.

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