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with Bendix Field Engineering Corporation,
for the U.S. Department of Energy

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URANIUM IN ALKALINE ROCKS

ABSTRACT

Geologic and geochemical criteria were developed for the occurrence of economic uranium deposits in alkaline igneous rocks. A literature search, a limited chemical analytical program, and visits to three prominent alkaline-rock localities (Ilímaussaq, Greenland; Poços de Caldas, Brazil; and Powderhorn, Colorado) were made to establish criteria to determine if a site had some uranium resource potential. From the literature, four alkaline-intrusive occurrences of differing character were identified as type-localities for uranium mineralization, and the important aspects of these localities were described. These characteristics were used to categorize and evaluate U.S. occurrences.

The literature search disclosed 69 U.S. sites, encompassing nepheline syenite, alkaline granite, and carbonatite. It was possible to compare two-thirds of these sites to the type localities. A ranking system identified ten of the sites as most likely to have uranium resource potential.

Further study is needed of the petrology, mineralogy, and geochemistry of sites of known uranium mineralization. Interpretation of these new data will strengthen the important criteria to judge the uranium potential of U.S. alkaline igneous rocks.

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CONTENTS (Continued)

URANIUM IN ALKALINE ROCKS

I. INTRODUCTION

A. GENERAL

Significant reserves of uranium have been identified in alkaline igneous rocks in Brazil and Greenland, and uranium has been mined from peralkaline granite in southeastern Alaska. This project was undertaken to answer the question: Are there other alkaline intrusive occurrences in the United States that are potential sources of uranium?

The overall project objectives are to:

(1) develop criteria by which one can judge the resource potential of uranium in alkaline igneous rocks of the United States; and

(2) identify potential uranium resource areas in alkaline rocks of the United States.

Within the category of alkaline igneous rocks we have included alkaline-peralkaline granites, peralkaline nepheline syenites, and carbonatites. The interrelationship between these categories is discussed in Section II of this report.

To fulfill the objectives the following tasks were accomplished:

(1) Through on-site visits and a search of the literature, we characterized the principal alkaline igneous occurrences of known uranium resource potential.

(2) On the basis of type-localities established from this characterization we developed sets of criteria against which alkaline igneous occurrences in the U.S. could be compared.

(3) From the literature search we identified 69 alkaline occurrences in the U.S. for comparison.

(4) The comparison identified ten localities which warrant further investigation of their uranium resource potential.

In proceeding with these tasks it became apparent that petrologic-geochemical criteria which would be useful in assessing the uranium favorability of domestic alkaline rocks need to be more sharply defined. The phase of the project reported here was based primarily on a literature search, and involved only a limited laboratory geochemical program. Citations in the literature on the distribution and abundance of radioelements in these rocks are sparse. Petrologic, mineralogic, and geochemical studies on samples from known uraniferous alkaline occurrences are required to sharpen these criteria.

In the introductory section of this report we briefly describe the literature search, chemical-analytical program, and resulting comparison of radioelement and companion element abundances. The extensive literature base, encompassing 1441 references, and the chemical-analytical data are included as appendices.

Section II on characterization includes a description of the classification of alkaline rocks and a presentation of the type-localities and criteria used for comparison with U.S. occurrences.

In the third section we tabulate the U.S. occurrences, rank them according to the type-locality criteria, and identify the ten localities that most warrant further investigation.

In the final section we present our conclusions and recommendations for validation studies and further development of criteria.

B. LITERATURE SEARCH

Literature searches were made utilizing several computer data bases. (Dates in parentheses are the time periods covered by each data base.) These included: GEOREF (1967-1977), Nuclear Science Abstracts (1967-1976), Energy Data Base (1974-1977), and Chem. Abstracts (1970 to 4-77). Search of Comprehensive Dissertation Index (1861-1977) was used to discover unpublished theses describing detailed field studies in areas of interest.

Descriptors used in the various searches fell into four categories:

1) general terms

alkaline rocks
peralkaline rocks
intrusive complexes
pegmatites
geochemistry
concentration
minerals
ores
rocks
deposits

2) rocks

nepheline syenite
carbonatite
trachyte
phonolite

3) minerals

monazite
zircon
sphene
allanite
epidote
eudialyte
rinkite
steenstrupine
pyrochlore
thorite
baddeleyite

4) chemical elements

uranium
zirconium
niobium
beryllium
rare earths
thorium
lithium
fluorine
fluorides

A typical request was: Find all papers dealing with the occurrence of uranium, thorium, and rare earths in alkaline rocks.

As study emphasis shifted to specific sites, diligent hand searches were done using Mineralogical Abstracts, Geological Society of America abstracts, and the bibliographies contained in various papers and reports. The bibliographies contained in "The Alkaline Rocks" (Sørensen, 1974) were used extensively. In this manner, literature coverage was extended back to the earliest paper in the report (Weed, 1896). Each item selected for inclusion in the bibliography was carded and indexed by geographical location. Subsequently, the 1,441 items in the bibliography were entered into a computer data base using the Berkeley Data Management System at Lawrence Berkeley Laboratory.

During the course of the study, we have borrowed, duplicated (with permission), or purchased copies of almost half of the citations in the bibliography. These copies have formed the working library for the study.

The working bibliography is included as Appendix D. The total bibliography is included as Appendix E on microfiche (see pocket inside back cover).

Table 1 lists the original language in which the papers in the bibliography were published, and the number in each language. The largest number of reports were in English. Papers published originally in Russian made a sizeable contribution. There are English translations of the text or abstracts for almost all of these papers.

Table 2A gives the number of papers published describing alkaline intrusive occurrences by continent and country. Table 2B gives the analogous information on United States occurrences by state.

Examination of the world's literature on alkaline, peralkaline, and carbonatitic rocks has identified seventeen principal localities outside of the United States. These, together with prominent U.S. occurrences, (discussed in Section III), are shown on the map, Figure 1. Principal among the foreign occurrences, not in Soviet Bloc coun-

TABLE 1

Original language	Number
English	974
Russian	368
French	34
Portuguese	13
German	13
Ukrainian	8
Spanish	5
Italian	6
Bulgarian	4
Swedish	3
Rumanian	3
Japanese	3
Czech	2
Danish	1
Polish	1
Finnish	1
Korean	1
Afrikaans	1

TABLE 2A

Continent	Country	Number
Europe		
	General	12
	Austria	1
	Bulgaria	3
	Czechoslovakia	2
	Finland	5
	France	17
	Germany	3
	Italy	15
	Norway	21[a]
	Poland	1
	Portugal	4
	Romania	6
	Scotland	2
	Spain	4
	Sweden	3
	Switzerland	3
	Yugoslavia	1
	Greenland	62[b]
	Iceland	1
	Azores	1
	Canary Islands	2
USSR		269[c]
Asia		
	General	1
	Taiwan	1
	India	27
	Andhra Pradesh	8
	Kashmir	1
	Madras	2
	Rajasthan	4

TABLE 2A
(continued)

Continent	Country	Number
Asia (continued)		
	Japan	4
	Nepal	1
	Turkey	1
	Australia	6
	Fuerte Ventura Island	1
	New Zealand	1
	Tahiti	1
	Tenerife	1
	Antarctica	1
Africa		
	General	28[d]
	Angola	2
	Zaire	5
	Cameroon	1
	Egypt	4
	Ethiopia	3
	Gabon	3
	Guinea	2
	Kenya	7
	Liberia	1
	Malawi	6
	Morocco	1
	Niger	8
	Nigeria	13
	Rhodesia	3
	South Africa	21
	Southwest Africa (Namibia)	12
	Tanzania	5
	Uganda	5
	Cape Verde Islands	2

TABLE 2A
(continued)

Continent	Country	Number
North America		
	General	2
	Canada	130[e]
	United States	424 (see Table 2B)
	Mexico	6
South America		
	General	4
	Brazil	28[f]
	Venezuela	1

a) The sixteen papers on Norway deal primarily with the Fen area.
b) Greenland - 62 papers, report primarily studies of Ilímaussaq and other alkaline intrusives.
c) USSR represented by 269 papers covering the Kola Peninsula with Lovozero and Khibiny alkaline massifs, the Ural Mountains and a large area near Lake Baikal, as well as many other intrusives.
d) Africa has several well studied areas, the East African Rift Zone, the Jos Plateau in Nigeria, Pilanesberg and Palabora in southern Africa.
e) Canadian papers deal with the Ottawa-St.Lawrence area of Quebec and Ontario as well as a number of other intrusives scattered across Canada.
f) Twenty-eight Brazilian papers deal with the deposit at Poços de Caldas and other less well explored areas.

TABLE 2B

State	Number
United States	
General	53
Alaska	23
Arkansas	18
Arizona	14
California	25
Colorado	56
Connecticut	8
Idaho	20
Illinois	2
Kentucky	1
Maine	10
Maryland	1
Massachusetts	12
Michigan	2
Minnesota	7
Mississippi	2
Montana	35
Nebraska	1
Nevada	4
New Hampshire	18
New Jersey	7
New Mexico	13
New York	3
North Carolina	5
Oklahoma	6
Oregon	2
Pennsylvania	2
Rhode Island	3
South Carolina	1
South Dakota	4
Texas	19
Utah	10
Vermont	4
Virginia	9
Washington	6
Wisconsin	3
Wyoming	15

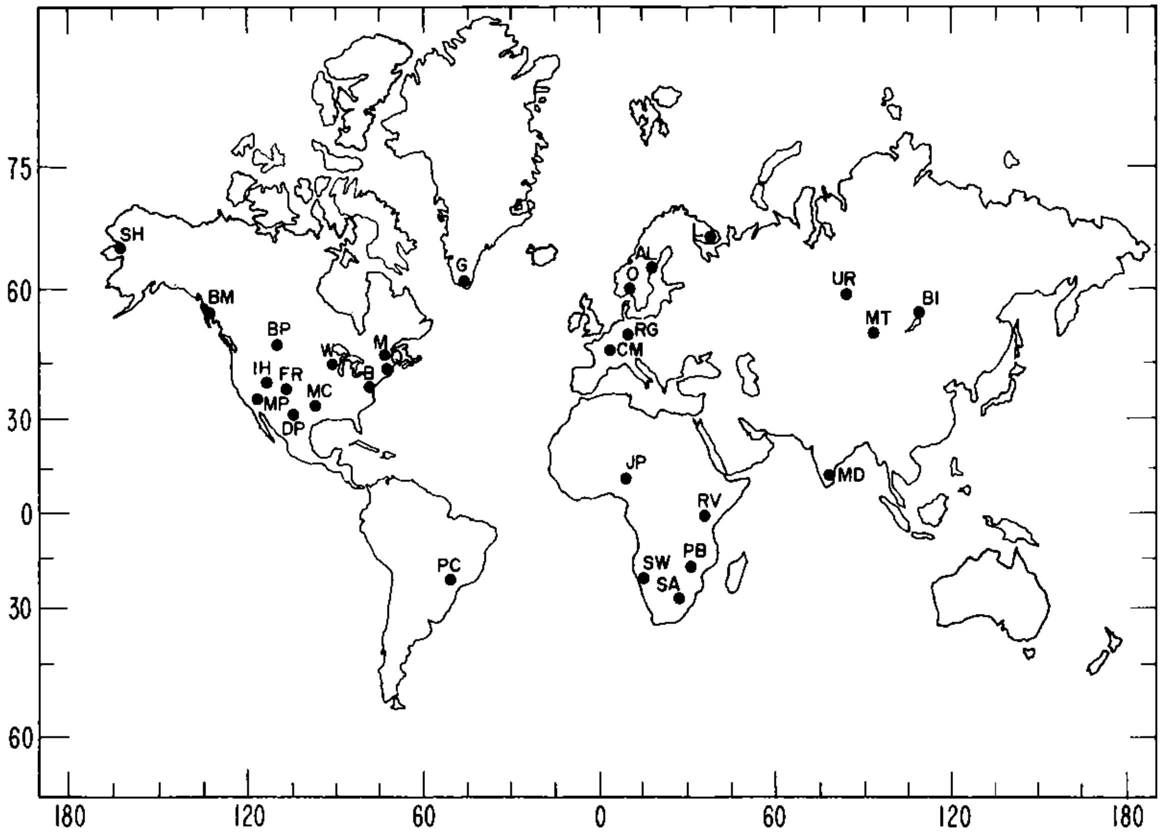

Fig. 1. Prominent world occurrences of alkaline, peralkaline and carbonatitic rocks; symbols are identified on accompanying map key. (XBL 782-2384)

MAP KEY AND CITATIONS

Al Alnö Island, Sweden (Von Eckerman, 1948, 1966)

B Beemerville, New Jersey (Aurousseau, 1922; Maxey, 1976; Wilkenson, 1946

BI Baikal, Soviet Union (Khomyakov, 1974)

BM Bokan Mountain, Alaska (Mackevett, 1958, 1963; Lanphere, 1964b)

BP Bearpaw Mountains, Montana (Pecora, 1962)

CM Central Massif, France (Poty, 1974)

DP Diablo Plateau, Texas (Barker, 1977)

FR Front Range, Colorado (Lovering, 1950; Nash, 1973)

G Gardar Province, Greenland (Sørensen, 1970)

IH Iron Hill - Powderhorn, Colorado (Temple, 1965)

JP Jos Plateau - Aïr, Nigeria (Bowden and Turner, in Sørensen, 1974)

L Lovozero, Kola Peninsula, Soviet Union (Gerasimovsky et al., in Sørensen, 1974)

M Monteregian Hills - Ottawa Graben, Canada (Philpotts, in Sørensen, 1974)

MC Magnet Cove - Potash Sulphur Springs, Arkansas (Nesbitt, 1977; Stone, 1964)

MD Madras, India (Rao and Majumdar, 1960)

MP Mountain Pass, California (Olsen, 1954)

MT Mongol-Tuva Province, Soviet Union (Pavlenko, in Sørensen, 1964)

O Oslo Graben, Norway (Killeen and Heier, 1975)

PB Palabora, South Africa (Heinrich, 1970c; Staatz, 1973)

PC Poços de Caldas - Goiás Belt, Brazil (Wedow, 1967; Ulbrich and Gomes (in press))

Q Quincy, Massachusetts (Chute, 1966)

RG Rhine Graben - Kaiserstuhl (Wimmenauer, 1966; and in Sørensen, 1974)

RV Rift Valley, East Africa (Gerasimovsky and Polyakov, 1972)

SA South Africa - Pilanesberg, Vredefort (Tilley, 1960; Mathias in Sørensen, 1974)

SH Selawik Hills, Alaska (Patton and Miller, 1968)

SW Southwest Africa - Cape Cross - Brandenberg (Verwoerd, 1967; Mathias in Sørensen, 1974)

UR Ural Mountains, Soviet Union (Eskova, et al., 1962)

W Wausaw, Wisconsin (Emmons, 1953)

tries, are the peralkaline intrusives at Ilímaussaq, Greenland and Poços de Caldas, Brazil. At each of these sites reserves well in excess of ten thousand tons of uranium oxide have been identified. Ilímaussaq and Poços de Caldas are described individually in Section II B, and reports of visits to them are included in Appendix A.

C. ANALYSES OF SAMPLES FROM UNIVERSITY OF CALIFORNIA COLLECTIONS

A laboratory geochemical program analyzed selected samples of peralkaline rocks from collections of the University of California, Berkeley. Specimens included those from the northern rim of the Poço de Caldas massif; a ring intrusion near Nemegos, Ontario; a dike in nepheline syenite near Montreal; the Magnet Cove area, Arkansas, and Ilímaussaq, Greenland. Descriptions of the samples, along with their analyses, are listed in Appendix B.

Samples were selected in the following manner: An initial group was chosen, through examination of hand specimens and thin sections, when available, with the primary objective of obtaining a representative sampling of rock types from each collection. Sample homogeneity and small grain size were used as criteria whenever possible. In a few cases, atypical or non-homogenous samples were selected by virtue of exceptional attributes which could possibly correlate with high U or rare earth (REE) abundances; specimens, for instance, with an abundance of Ti- and Zr-bearing alkali silicates, or specimens cut by late-stage veins.

This group of 80 samples was then tested for approximate uranium and thorium abundance by gamma-ray spectrometry and, on the basis of these preliminary results, the final group of 31 samples--relatively enriched in U and Th--was selected. These rocks were then analyzed for major- and trace-element abundances by X-ray fluorescence and neutron activation analyses.

D. COMPARISON OF RADIOELEMENT AND TRACE-ELEMENT CONTENTS

Radioelement and trace-element contents of intrusive rocks have been compared to identify possible "pathfinders" for uranium. The question was: If no radioelement data exists in the literature on a given occurrence, can one use data on other elements to indicate the presence of appreciable uranium?

Trace-element (Zr,Nb,Be,F, rare earths, Li,Zn,and Mo) contents reported for alkaline and some calc-alkaline intrusives were compared with corresponding uranium and thorium contents of the same rocks. Sources of the data are listed in Table 3. The compilation included data from (a) alkalic granites of Bokan Mountain, Alaska; (b) peralkaline intrusives at Magnet Cove, Arkansas; Ilímaussaq, Greenland; and Lovozero, Soviet Union; and (c) calc-alkalic intrusives of New England and the Sierra Nevada batholith. Concentrations of each element were plotted against uranium or uranium-plus-thorium contents, using available data from the literature.

Table 3

SOURCES OF RADIO- AND TRACE-ELEMENT DATA FOR COMPARISON

Location	Reference
Magnet Cove	Erickson, et al., 1963
Bokan Mountain	MacKevitt, 1963
Ilímaussaq	Bohse, et al., 1974
Ilímaussaq	Sorensen, 1974
Ilímaussaq	Sass, et al., 1972
Ilímaussaq	Ferguson, 1970
Ilímaussaq	Wollenberg, 1971
Ilímaussaq	Hansen, 1968
Lovozero	Gerasimovskii, et al., 1968B
Granites	Ross, 1972
Granites	Dodge, et al., 1969
Granites	Wollenberg, 1968
Granites	Bateman, 1963
Granites	Lyons, 1964

Inspection of the plots, both linear and log-log, indicated that for rocks not excessively mineralized in uranium or trace-elements (essentially the country rocks surrounding the mineralized occurrences), zirconium had the strongest relationship to uranium-plus-thorium. This correlation is illustrated on the log-log plot, Figure 2. The apparent relationships between other trace elements and radioelements were weaker, or data were too sparse to be useful. After zirconium, the next best correlation with U+Th is that of La+Ce*, shown on Figure 3. The lack of good correlation is, in part, the result of trace element data from semi-quantitative analyses.

As seen from Figures 2 and 3, the correlation with Zr is quite apparent, while that with La+Ce is weaker; yet a definite positive trend is indicated.

For comparison, U+Th and La+Ce from analyses done at LBL (Appendix B) on samples of country rock from Pocos de Caldas, Nemegos, and the Magnet Cove are plotted on Figure 4. Here a good correlation is evident between the radio- and rare-earth elements. However, there is essentially no correlation between U+Th and zirconium from the same data base. The reason may be that the minerals which contain Zr are not necessarily those which contain the radio- and rare-earth elements.

In general then, zirconium and rare-earth elements may be qualitative pathfinders for radioelements. However, more petrologic and chemical-analytical work on a more controlled group of samples is necessary before the usefulness of these and/or other pathfinder elements can be confirmed.

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*For several of the data points Ce was calculated, based on the average La/Ce ratio of analyses where Ce was reported.

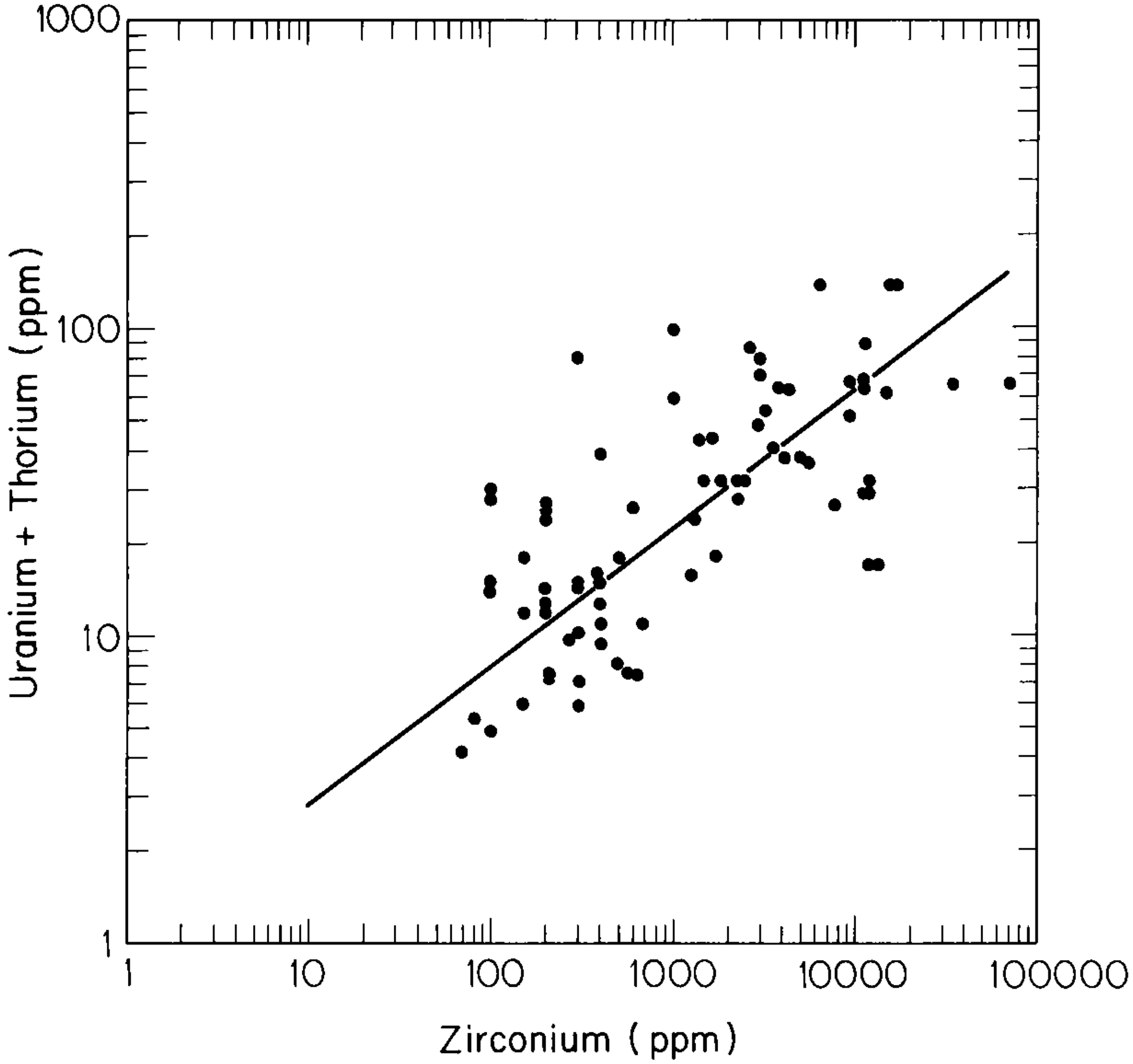

Fig. 2. Zirconium *versus* uranium plus thorium; data from the literature sources listed in Table 3. (XBL 781-124)

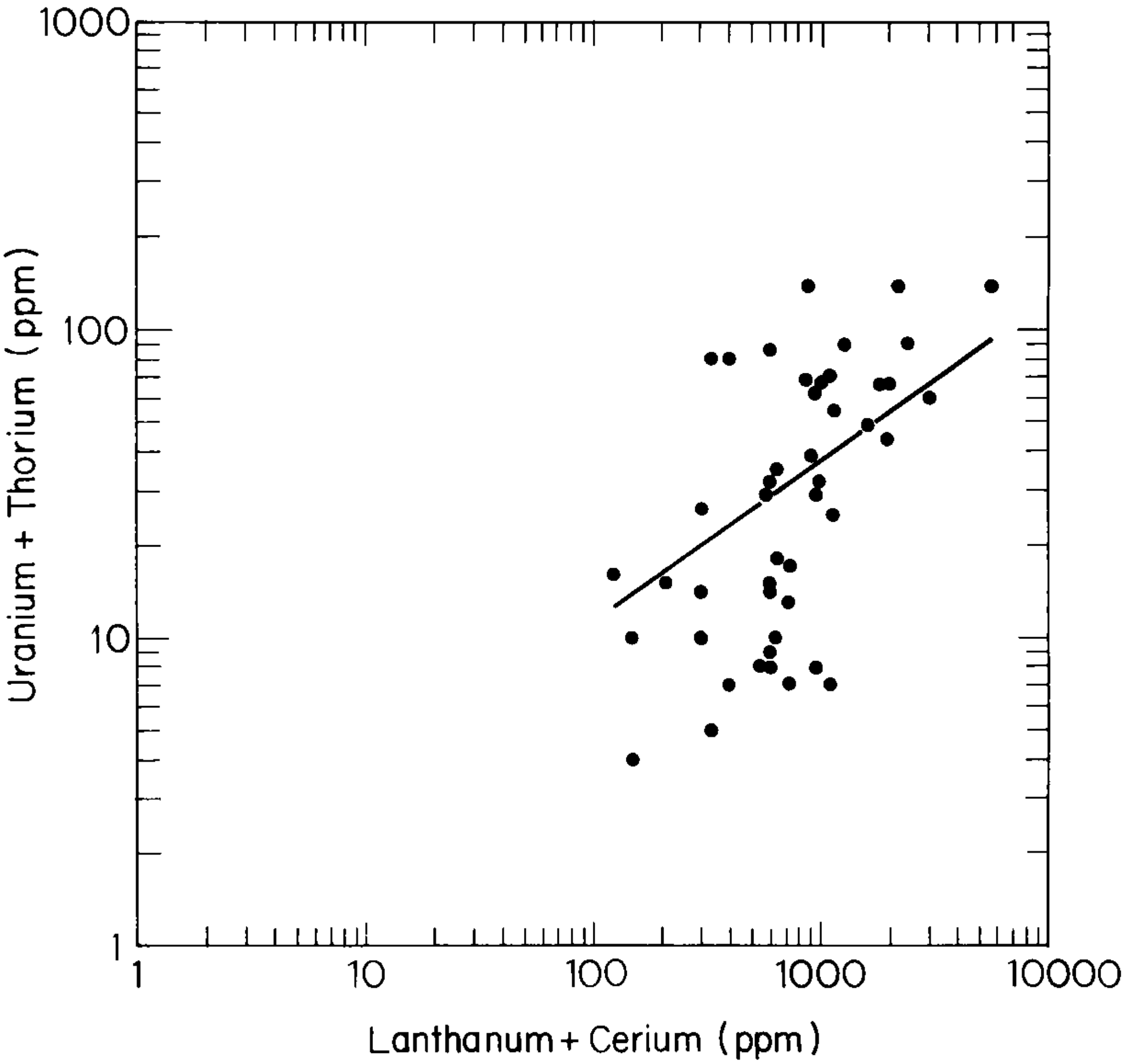

Fig. 3. Lanthanum plus cerium *versus* uranium plus thorium; data from the sources listed in Table 3. (XBL 781-123)

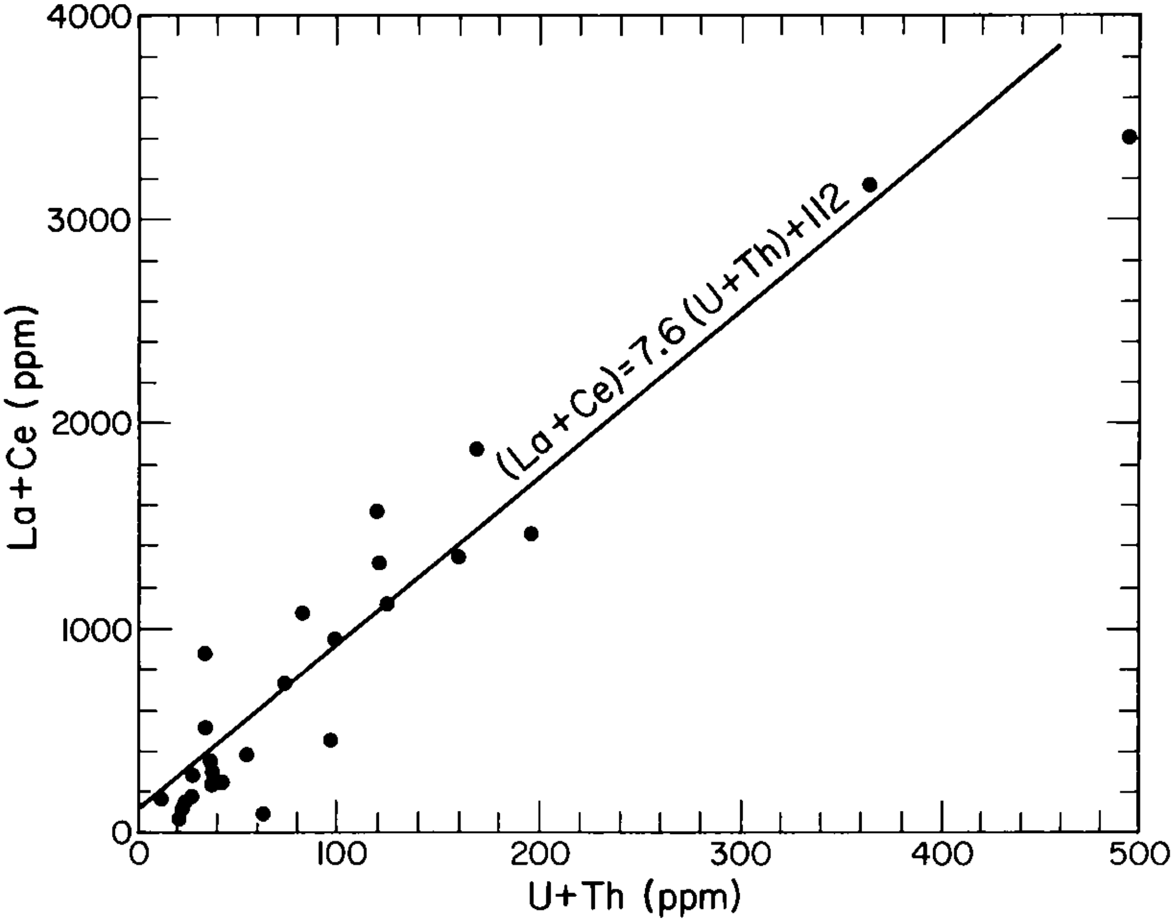

Fig. 4. Lanthanum plus cerium versus uranium plus thorium; data from LBL analyses in Appendix B. (XBL 782-2381)

II. CHARACTERIZATION

In dealing with the radioelement contents of alkaline intrusive rocks we considered three interrelated categories: feldspathoid-rich alkaline-peralkaline rocks, alkaline-peralkaline granites, and carbonatites. At a given occurrence, one category predominates, but at least one other category is usually present. For example, alkali granite occurs with the nepheline syenite-rich Ilímaussaq intrusion; nepheline syenites are often associated with carbonatite, such as at Magnet Cove , Arkansas. Late-stage differentiates of these intrusives contain minerals and elements of interest to this study: steenstrupine-bearing lujavrites containing uranium and thorium at Ilímaussaq, pyrochlore veins associated with carbonatites, pegmatitic phases of peralkaline granites, the juxtaposition of hydrothermal activity and deep weathering at Poços de Caldas.

In this section of the report we briefly describe the classification of alkaline rocks and the factors leading to the concentration of radioelements and their companion elements.

A. CLASSIFICATION OF ALKALINE ROCKS

1. General

In his introduction to "The Alkaline Rocks" Sørensen (1974) stated a definition "...that alkaline igneous rocks are characterized by the presence of feldspathoids and/or alkali-pyroxenes and -amphiboles." He expressed preference for the definition of Shand (1922) wherein the alkaline rocks were divided into two categories:

Miaskitic rocks, where $K+Na<Al$, $K+Na>1/6\ Si$;
Agpaitic rocks, where $K+Na>Al$, $K+Na\gtrless 1/6\ Si$.

Agpaitic nepheline syenites are characterized by a relatively high content of rare elements (including uranium and thorium) and the minerals eudialyte, aegirine, and arfvedsonite, while miaskitic nepheline syenites have generally low contents of rare elements but appreciable zircon, sphene, apatite, and hornblende. The terms agpaitic and peralkaline are nearly synonymous, although agpaitic can be used for rocks containing the minerals listed above; a rock can be considered peralkaline-agpaitic if its content of Al_2O_3 (in molecular proportions) is less than the sum of potassium and sodium oxides. A diagrammatic classification of the alkaline rocks undersaturated in silica was developed by Sarantsina and Shinkarev (1967) and is reproduced in Figure 5 (from Sørensen, 1974).

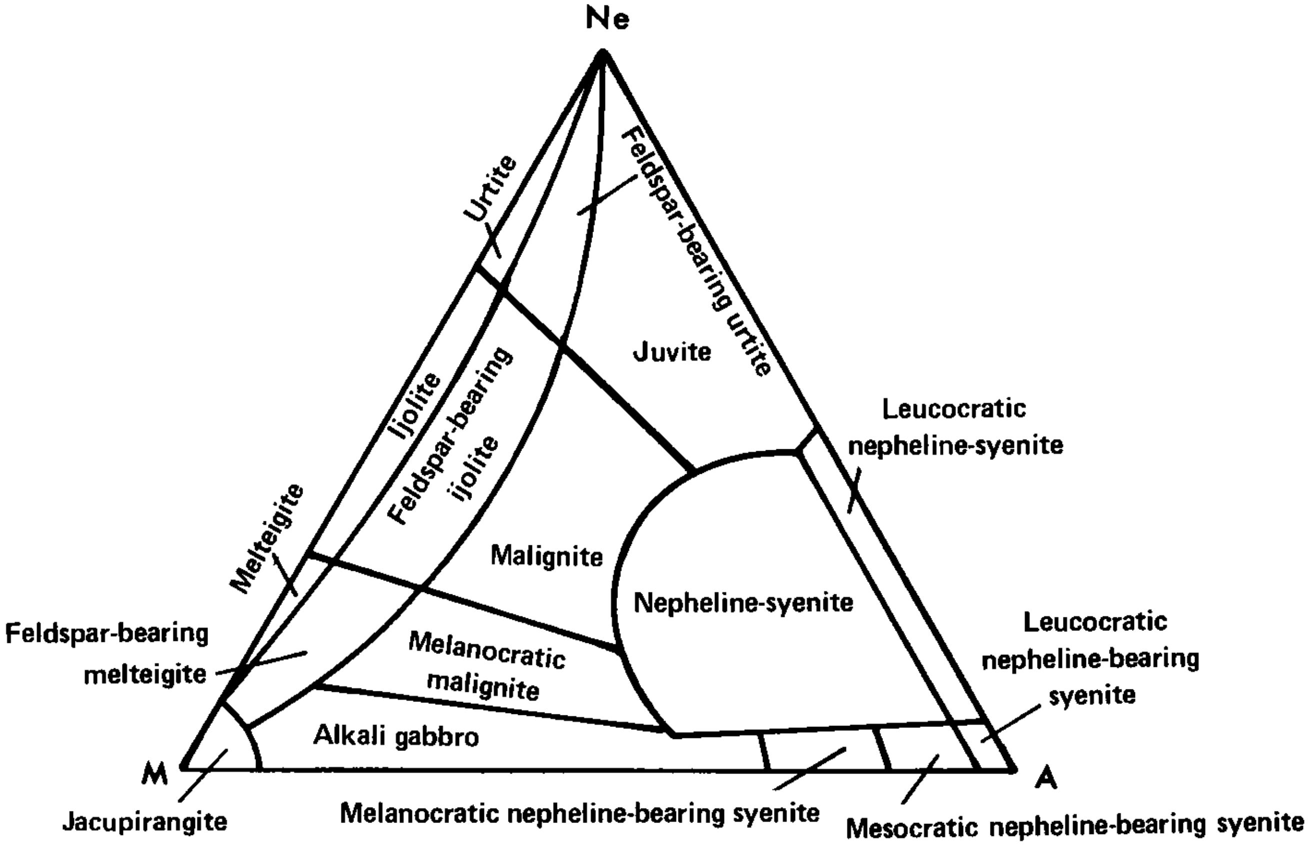

Fig. 5. Classification of alkaline rocks by G. M. Sarantsina and N. F. Shinkarev. A = alkali feldspar, N = nepheline, M = mafic minerals. (Reproduced with permission, from The Alkaline Rocks, edited by Sørensen. Copyright © 1974, by John Wiley & Sons Limited.)

XBL 782-7167 A

In this project we also include siliceous granitic rocks rich in alkalies. These so-called alkaline and peralkaline granites are quite often associated with intrusions of feldspathoidal syenites. Their composition is generalized (Bowden, 1964):

- potassium feldspar and albite: 35 - 60+%
- quartz: 25 - 40%
- mafic minerals (aegirine and arfvedsonite-riebeckite): 3 - 10+%

2. Peralkaline Granite

The peralkaline granites form a group of oversaturated alkaline rocks that has intrigued petrologists for many years. Peralkaline granites and their volcanic equivalents, pantellerites and comendites, are distinct both geologically and chemically from calc-alkaline granites and granodiorites. Peralkaline granites are usually holocrystalline and leuco- to mesocratic. Quartz makes up 25-40% of the rock, with alkali feldspar (microcline, perthite, or late-forming albite) being about 50% of the remainder. Aegirine or aegirine-augite are the common pyroxenes, along with the amphiboles, riebeckite and, in strongly peralkaline phases, arfvedsonite. Pantellerite and comendite norms generally contain sub-equal amounts of normative quartz, orthoclase and albite, and significant quantities of acmite. The latter mineral is important since the ratio of ferric to ferrous iron in the whole-rock depends primarily on the acmite content.

Theories of the origin of peralkaline granite are tied to the controversy surrounding theories of origin of all alkaline rocks. From their experiments, Tuttle and Bowen (1958) proposed that alkaline granite was derived from mantle material. Other workers (Thorpe et al., 1977) supported this concept. The formation of peralkaline magmas through anatexis of lower-crustal material was defended by Bailey (1964) and Bowden (1970). Crustal contamination of mantle material may also be a factor, as Ferguson (1964) pointed out regarding the alkaline granite of Ilímaussaq.

Perhaps a combination of genetic models, along with other factors such as tectonic setting, crustal contamination, and volatile segregation best explain the occurrence of alkaline granites. The peralkaline-granite type area reported here, Bokan Mountain, Alaska, indicates this complexity. For one thing, it occurs spatially and temporally in proximity to island-arc vulcanism in the western Pacific. Also, it is not, like most other peralkaline granites, associated with a peraluminous granite. Whether these factors have any bearing on the uranium abundance at Bokan Mountain is not known at this time.

3. Carbonatites

A carbonatite is defined by Heinrich (1966) "...as a carbonate-rich rock of apparent magmatic derivation or descent." The close association of carbonatitic rocks with alkaline intrusives is well documented by Heinrich (1966) and Tuttle and Gittins (1966). In their introduction Tuttle and Gittins (1966) state that "...in carbonatitic complexes there appears to be a succession from ijolite rocks through nephelinites...to carbonatite liquids. There can be no doubt about the carbonatite-alkaline rock association." Heinrich grouped alkalic-carbonatitic complexes into two broad categories:

- alkalic-carbonatitic ring complexes containing core carbonatites and/or dikes, ring dikes, cone sheets and breccia zones of carbonatite
- alkalic-carbonatitic sheets, tabular masses, dikes and stockworks

He also pointed out that there are sheets and swarms of carbonatite dikes and sills that are not associated with any alkalic complex, such as Mountain Pass, California.

An idealized carbonatite occurrence might contain an inner zone of carbonate-rich rock, and successive outer zones of ijolite, pyroxenite, nepheline syenite, fenitized syenite, and fenitized country rock, respectively. If there had been little erosion, the volcanic manifestation of the occurrence: nephelinite, phonolite, or trachyte, might still be intact. Carbonatitic and/or nepheline-rich ring dikes and cone sheets, emanating at depth from the core zone, would cut the country rock.

The genesis of carbonatites is still controversial. Daly's theory (Daly, 1933), that carbonatite was remobilized sedimentary limestone, has been largely rejected; however, many other early theories still remain. Most workers are satisfied that carbonatites are derived from magmatic processes, but from this point the lines diverge. Carbonatite is thought of as a primary magma (Dawson, 1964), the result of metasomatic (Borodin, 1960) or hydrothermal (Garrels and Richter, 1955) alteration, or even a gas phase (Pecora,1956). Strongest support favors the concept of magmatic emplacement.

Carbonatites are characterized by high contents of phosphate and rare elements, predominantly rare earths, niobium, zirconium, uranium, and thorium. Nearly all of the world's niobium is derived from carbonatite, a good portion from Brazil (at the Araxá occurrence U and Th-rich slag from the Nb beneficiation is stockpiled for future use--see Brazil trip report in Appendix A.2). A principal source of rare-earth elements is the carbonatite of Mountain Pass, California. Olson et al. (1954) describe the association of thorium and rare earths at that location.

B. TYPE LOCALITIES

To choose criteria to judge the uranium resource potential of alkaline rocks of the United States, four type localities were identified from the literature search, and characterized. The areas were selected primarily because they are well documented and contain economic uranium concentrations, and because they are significantly different in character.

Criteria are summarized at the conclusion of each type-locality description, and form the basis for the site-comparison tables in Section III.

1. The Ilímaussaq Type Locality

The Gardar province in Southwest Greenland contains one of the most spectacular and unique alkaline intrusions in the world, the Ilímaussaq. It is only rivaled by similar intrusions on the Kola Peninsula and in eastern Brazil for degree of alkalinity, variety of minerals, and volume of rocks. One of the several peralkaline complexes in the Gardar province, the Ilímaussaq on the Narssaq peninsula (see location map, Figure 6), is an area of economic uranium potential and as such is one of the type-localities used in this report.

The geology of the Ilímaussaq was described in detail by Ferguson (1964). The major rock types, radioactive minerals, and other minerals of economic potential are tabulated in Appendix A.1. The intrusion and many of the contemporaneous rocks of the region were emplaced during the Gardar event, a time of widespread rifting in what is now southwest Greenland, 1000 to 1400 million years ago. Ilímaussaq is 1020±24 m.y. old (Bridgewater, 1965) and therefore is one of the youngest intrusions of the Gardar event. It intrudes Gardar lavas, intraflow sandstones, and the pre-Gardar Julianehaab granite. The main body of the intrusion is a layered complex that formed through closed-system differentiation and crystal settling. Within an envelope of augite syenite, density-separation of early formed crystals created an upper zone of lighter foyaite and naujaite and a lower zone of denser kakortokite (see Figure 7). Sandwiched between these two layers was a residuum of lujavrite.

The last stage of differentiation involved crystallization of this lujavrite at rather high pressure but relatively low temperature. Sørensen (1962) estimated that depths of crystallization of the lujavrite were 6 - 7 km. At these depths the load pressure is ~ 2 kbar, upon which was superimposed appreciable vapor pressure from the magma. Feldspars of the lujavrite indicate that it crystallized at temperatures of 400° C or less. As the residual liquid from the lujavrite penetrated overlying rocks, decreasing pressure caused it to separate into two phases, with the vapor phase containing appreciable NaCl. Albite and analcime, together with associated rare minerals such as steenstrupine, were precipitated from the liquid phase. Where the analcitizing

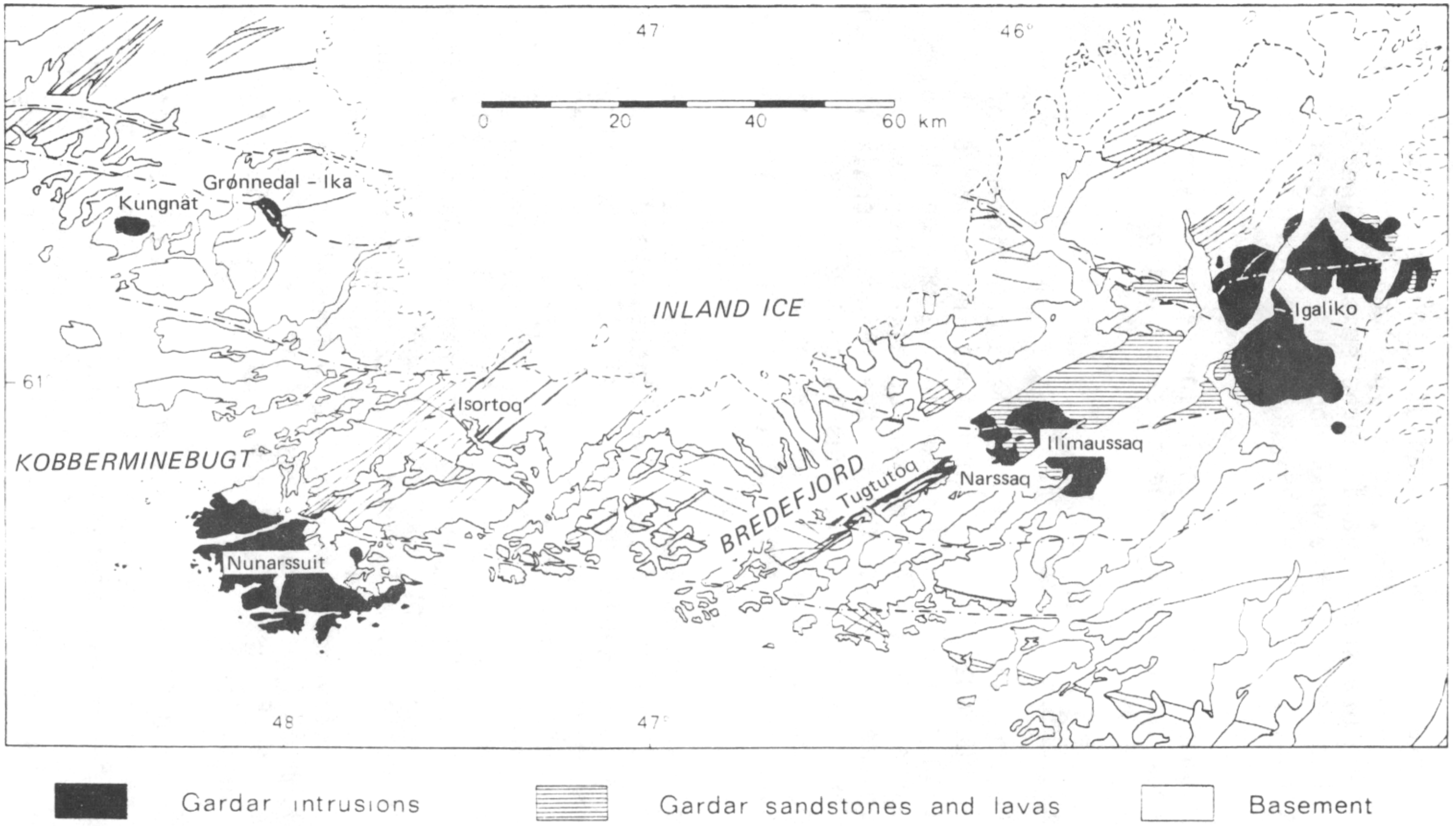

Fig. 6. Generalized geologic map of the Gardar Province, Southwest Greenland (from Sørenson, et al., 1974). (XBL 782-7170) (permission to reproduce granted by the Geological Survey of Greenland)

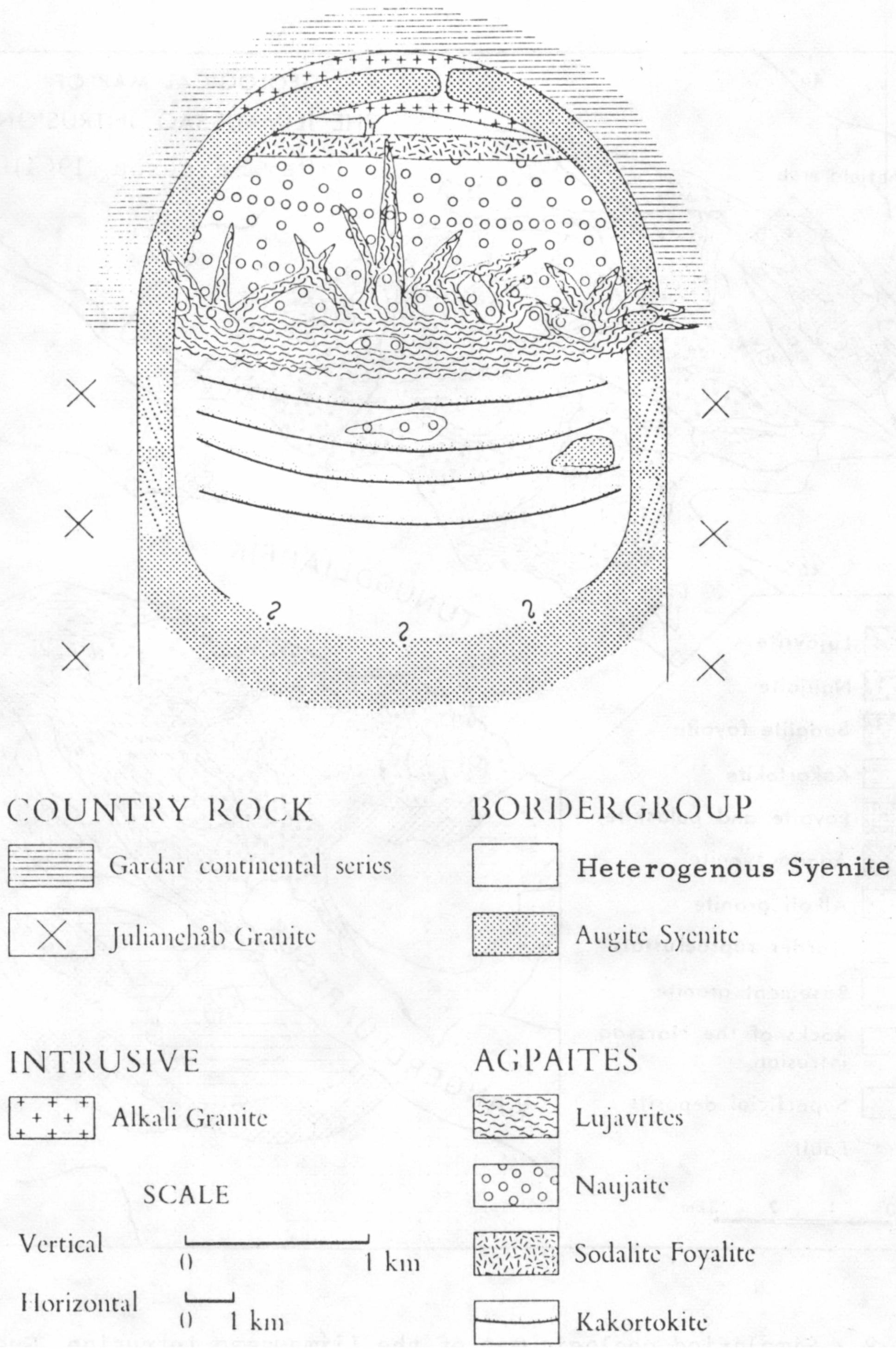

Fig. 7. Schematic diagram of the Ilímaussaq layered intrusion (after Ferguson, 1964). (XBL 782-7169) (permission to reproduce granted by the Geological Survey of Greenland)

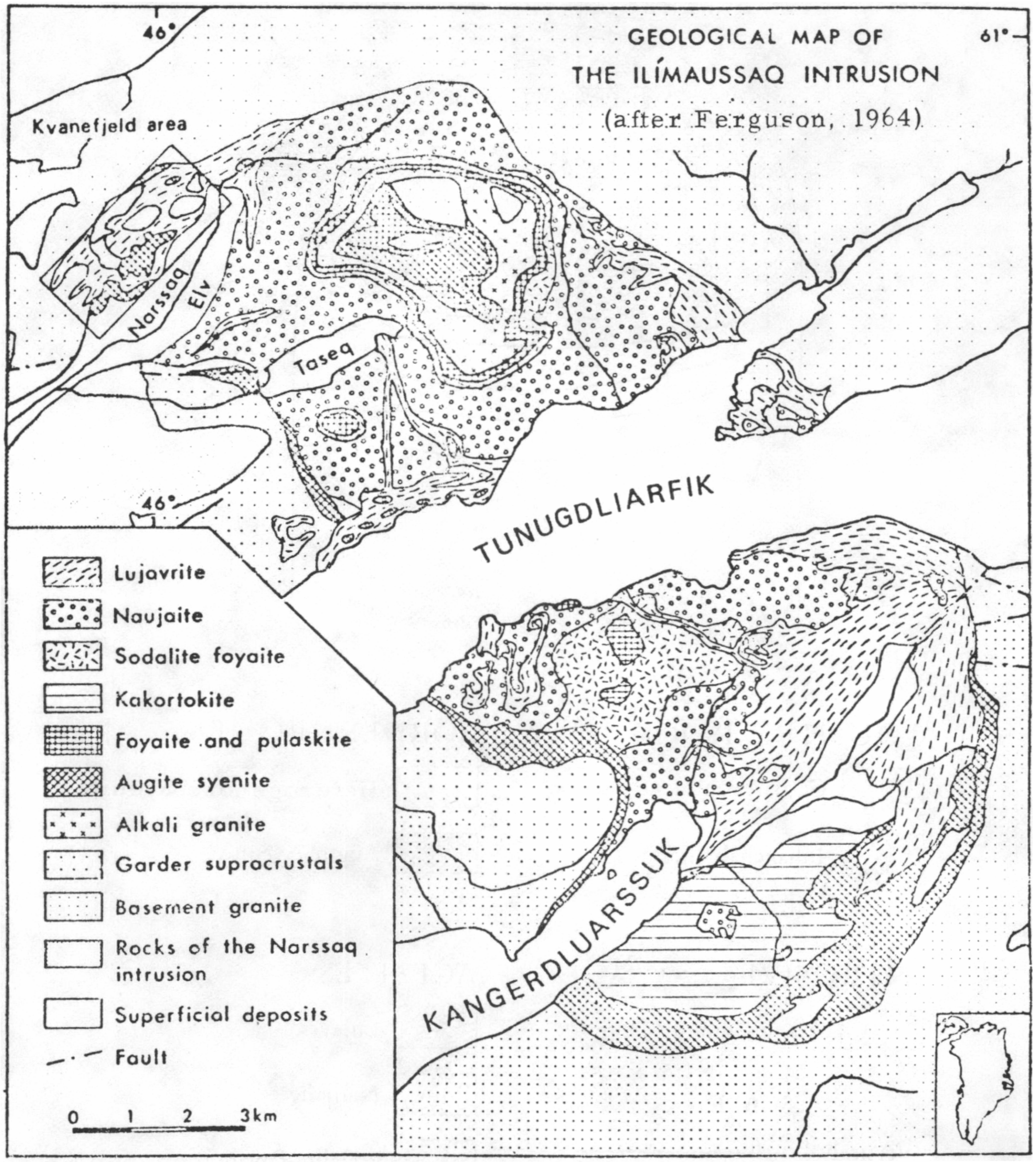

Fig. 8. Simplified geologic map of the Ilímaussaq intrusion, Greenland (after Ferguson, 1964). (XBL 782-7168) (permission to reproduce granted by the Geological Survey of Greenland)

fluids penetrated earlier-formed aegirine lujavrite and naujaite, eudialyte was broken down and eventually replaced by steenstrupine.

Oxidation-reduction conditions have affected the distribution of uranium. Rim zones of steenstrupine crystals are deficient in U compared to the crystals' centers, suggesting to Sørensen (1962) that oxidation of the rims formed UO_2^{2+}. Some of the uranium in the rim zones was then removed by leaching. A reducing environment, afforded by arfvedsonite, may have helped to localize uranium in pigmentary material, perhaps pseudomorphic after eudialyte (Sørensen et al., 1974; Wollenberg, 1971) in the medium-to-coarse arfvedsonite-rich lujavrite of the Kvanefjeld.

The late-stage lujavrite and its residual liquid intruded the naujaite and foyaite along sheared and brecciated zones. Large blocks of naujaite were detached and engulfed in the magma. Intense shearing in the Kvanefjeld area permitted the lujavrite to penetrate the Gardar sandstones and lavas.

The exposed portion of the intrusion, shown on the geologic map, Figure 8, covers about 100 square kilometers northwest and southeast of Tunugdliarfik Fjord. A major fault of normal movement transects the southern portion of the intrusion, exposing the strongly layered kakortokites. Lujavrites and naujaites are well exposed north of the fault. The lujavrites are mineralogically complex. Their feldspars are predominantly microcline and albite, not perthite as in many of the other rocks in the complex. Albite is frequently converted to analcime. Aegirine and arfvedsonite make up the largest mafic group. Aegirine often approaches acmite in both crystal form and chemical norm. Segregation of these minerals leads to a strong banding and the differentiation of the 'green' (aegirine-rich) and 'black' (arfvedsonite-aegirine-rich), lujavrites. Nepheline, often altered to analcime, is abundant, especially so in the arfvedsonitic lujavrites. Sodalite is rare. Eudialyte is the most common radioactive mineral. It is primary and often altered to katapleite. Steenstrupine is both a primary and secondary mineral in these rocks. Other secondary and minor minerals include monazite, mesodialyte, eucolite, biotite, garnet, muscovite, fluorite, and villiaumite. The rare beryllium mineral, tugtupite, is present in analcime veins.

The most intense uranium mineralization occurs in medium- to coarse-grained lujavrite in the northwest portion of the intrusive on the Kvanefjeld plateau (Sørensen et al., 1974). This coarse-grained lujavrite is the latest formed rock and intrudes both the earlier-formed lujavrite, and the Gardar-roof lavas along shear planes and within fold axes. The area is further enriched by hydrothermal analcime/albite veins, some of which contain pyrochlore. The major ore mineral of the lujavrite is primary and secondary steenstrupine; monazite, thorite, and pigmentary material follow in importance. The ore minerals and their U and Th contents are listed on Table 4. The uranium content of the lujavrite ranges from 50 to 3000 ppm, thorium from 60 to 1500 ppm (Sørensen et al., 1974).

TABLE 4

PRINCIPAL URANIUM-BEARING MINERALS OF THE KVANEFJELD.

Mineral	Percent	
	U	Th
Steenstrupine	0.2-0.3	2+
Pigmentary Material	1-3	
Thorite	2-3	28-55
Monazite	0.1-1+	0.5-5+
Eudialyte	0.005-0.1	0.003-0.1
Pyrochlore	0.2+	0.7+

To 1974, surveys and drilling resulted in calculations of "reasonably assured" reserves of ~19 million metric tons of ore averaging 310 ppm U. Estimated additional reserves were 33 million tons of 300-350 ppm U. Results of drilling in the northeast portion of the Kvanefjeld in 1977 have considerably enlarged these estimates (B. Leth Nielsen, private communication). On the basis of 1977 estimates, Leth Nielsen (1977) categorized the Kvanefjeld deposits as a "low-grade occurrence with large tonnage." Beneficiation studies have included pilot operations of a sulphate-roasting process where 55 to 65% of the uranium is recovered (Sørensen et al., 1974), and a pressurized carbonate leaching system that recovers about 80% of the uranium from the most resistant ore (B. Leth Nielsen, personal communication, 1978). More detailed description of the work at Kvanefjeld and the sulphate-roasting process are contained in the trip report in Appendix A.1.

Besides uranium, the Ilímaussaq intrusion contains an unusually high enrichment of Th, Nb, Zr, Be, Li, F, Zn, and rare-earth elements. Many unique minerals are found containing these elements. Both Nb from pyrochlore and murmanite, and Be from analcime veins, are possible targets for production. The potential of zirconium from the kakortikites of the southern portion of the intrusion has also been investigated (Bohse et al., 1971).

In summary, the sequence of events leading to uranium mineralization at Ilímaussaq was:

(1) intrusion at depths of 5-7 km of a strongly peralkaline magma containing a high proportion of volatile and incompatible elements;

(2) closed differentiation of this magma to further concentrate rare- and radio-elements in late-stage lujavrite;

(3) crystallization of lujavrite at high pressure (~2 kbar) and relatively low temperature (~400^0 C) with separation of a residual liquid;

(4) fracturing of the early-formed intrusive rocks and surrounding country rocks and injection of the residual liquid along these passageways; and

(5) albitization and analcitization of host rocks, and deposition of associated minerals such as steenstrupine, monazite, thorite, and pyrochlore. Deposition occurred in structurally favorable areas: northwest-southeast-trending fracture zones and in zones of arching in the volcanic roof rocks above the lujavritic intrusions.

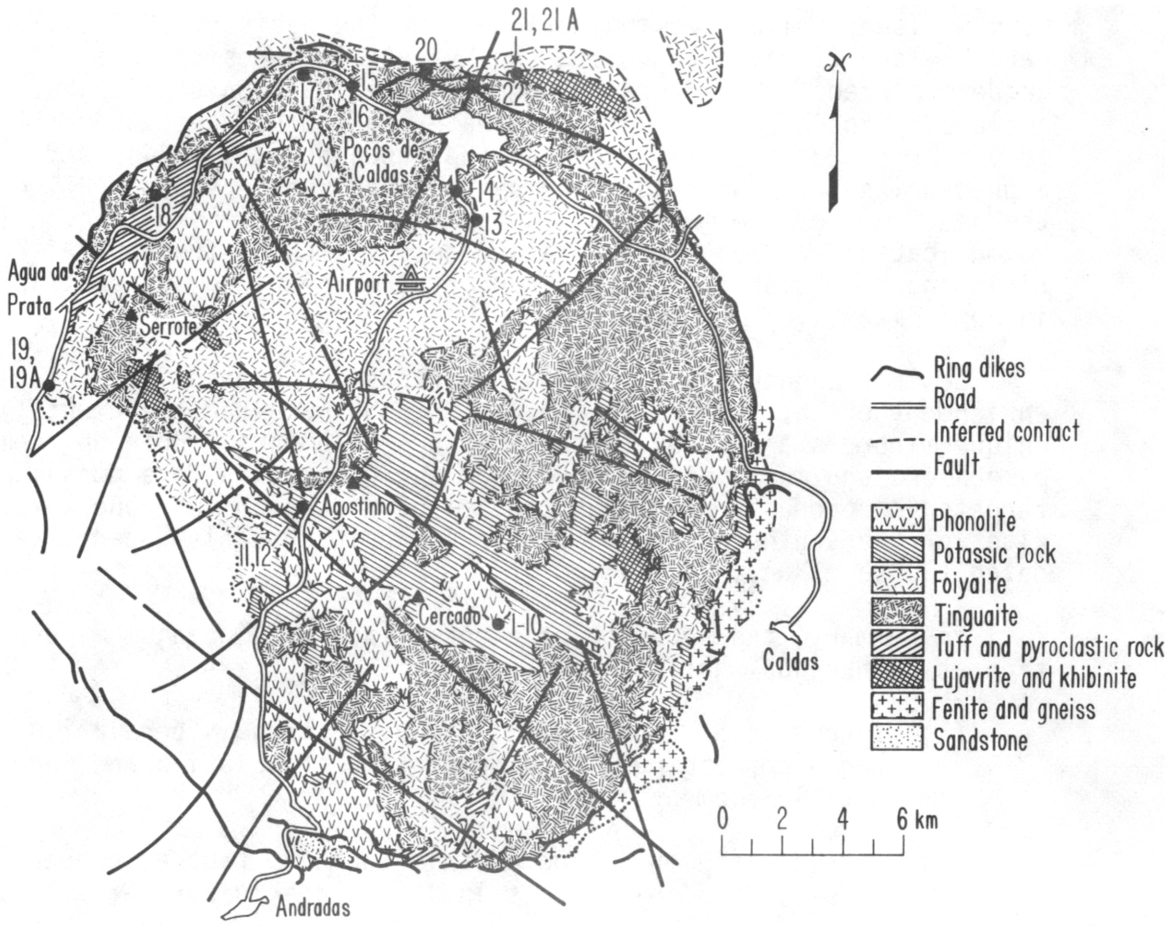

Fig. 9. Simplified geologic map of the Poços de Caldas intrusion, Brazil, based on a map by Asturio Garcia de Oliveira. (XBL 7710-2147)

2. The Poços de Caldas Type Locality, Brazil

The Poços de Caldas intrusion, covering ~800 square kilometers, is situated on the border between the states of Minas Gerais and São Paulo. It is the largest intrusive in a belt of alkaline-carbonatitic centers, extending nearly 1000 km north-northwestward across Brazil from Minas Gerais to Goiás. Southeast of Poços de Caldas, a northeast-trending belt of alkaline intrusives parallels the Atlantic coast. The ages of the intrusions in the Minas-Goiás belt range from 53 to 93 million years (Ulbrich and Gomes, in press). The successive intrusions at Poços de Caldas covered almost the entire span, from the early pyroclastic rocks at 87 m.y. to 53 million-year-old phonolitic dikes.

A location-geologic map of the Poços de Caldas plateau is shown as Figure 9. The geologic setting of the Brazilian alkalic rocks and those of Poços de Caldas have recently been summarized by McNeil (1977). Age dating of rocks from the intrusive was done by Bushee (1968). The alkaline rocks intrude Precambrian gneisses and granites and the Jurassic Botucatu sandstone. Many different alkaline rocks were emplaced. The first event was the extrusion of lavas, tuffs, and tuff-breccias. Subsidence followed and was succeeded by intrusion of the bulk of the tinguaites. Phonolite was also erupted at that time and is in gradational contact with the tinguaite. Small stocks of lujavrite, khibinite, and foyaite were injected after the tinguaite/ phonolite. The last major event was the emplacement of late tinguaite and phonolite ring dikes. Fenitization of the country rocks probably accompanied the entire sequence. Ore deposition was related to at least two episodes of hydrothermal alteration and brecciation, mainly affecting the tinguaites in the center of the intrusion. In the northern portion, eudialyte-bearing lujavrite and khibinite, rocks similar to those at Ilímaussaq and Lovozero, crop out (Ulbrich et al.; in press). However, no apparent mineralization has been found to be associated with these rocks. Unlike Ilímaussaq and Lovozero, Poços de Caldas was primarily a volcanic/subvolcanic center, not a deep-seated layered intrusion.

There are two general types of uranium mineralization in the intrusion: caldesite (zircon-baddeleyite) veins, and hydrothermal mineralization (Zr, F, Mo, U) associated with brecciated zones. Caldesite veins (up to 25 cm in width) occur in shallow zones (less than 40 m beneath the surface) near the contact between foyaite and tinguaite. These veins are presently of less interest economically than the brecciated mineralization; they offer the possibilities of selected mining, but not large, open-pit operations. The presently-active open-pit mining area is in brecciated ore at Cercado in the south-central portion of the intrusion (see location map, Figure 9).

Along with uranium, the Poços de Caldas intrusion has been recognized as a center for thorium mineralization. This is the most evident at Morro do Ferro (Hill of Iron), described by Wedow (1967). Here, near the center of the intrusion, a stockwork of limonitized magnetite contains an average of 1% ThO_2 and 5% total rare earths.

In and around the mine area (Cercado), two stages of foyaite have been recognized: an older stage, gradational with tinguaite; and a younger stage of foyaite in sharp contact with tinguaite. This younger stage has a close relationship with the uranium mineralization. Together with hydrothermally altered "potassic rock," the brecciated contact zones of foyaite/tinguaite appear to have localized mineralization at Cercado. Circular structures in the south-central part of the Poços de Caldas plateau, visible on satellite imagery, appear to be related to the mineralized, hydrothermally altered zone of younger foyaites/tinguaites.

Deeper weathering (as deep as 100-150m) has had a profound effect on mineralization at Poços. An oxidation-reduction (redox) zone, progressing downard as laterization proceeded, tended to convert "primary" Zr-Mo-F-U-pyrite ore to a pitchblende "secondary" ore. In the near-surface oxidized zone above the redox front, a "tertiary" ore occurs as uranium associated with limonite and clay minerals.

NUCLEBRAS geologists have hypothesized the evolution of the Poços de Caldas deposit as:

(1) doming accompanying early intrusion,

(2) contraction-faulting of the roof rocks,

(3) injection of syenitic ring dikes,

(4) erosion,

(5) a second intrusion of foyaite with accompanying volcanic episodes (tuffs), primary mineralization, hydrothermal alteration, and

(6) formation of "secondary" ore from redox effects of deep weathering.

At Cercado 60 to 80 km of drilling has identified three principal mineralized bodies. (They are described in more detail in Appendix A.2-1). The first is characterized by vein-type mineralization associated with brecciated fault zones, incorporating "primary" (Zr, F, Mo, U) ore; a redox zone of "secondary" pitchblende ore; and some "tertiary" near-surface mineralization. Another body is a lens-shaped mass of primary-type ore below the redox zone. Mineralization is most intense in the vicinity of faults. A third body contains essentially only "secondary" pitchblende ore. The first body is most similar to mineralization at Agostinho, an area near the center of the Poços intrusive, earlier considered of high uranium potential. In all three bodies it appears that the richest mineralization was achieved through a combination of intensive faulting and brecciation, hydrothermal alteration, and deep weathering. The intense alteration has enhanced the propensity for deep weathering in this area.

Speculations on the origin of mineralization included the lujavrites as a possible source of the fluids. Though lujavrites have not been encountered in the surface or subsurface in the Cercado area, they are the latest differentiates of the intrusive, and a late lujavritic phase may have furnished the fluids for hydrothermal alteration and mineralization.

In two of the bodies there appears to be a zonation of thorium, uranium, and iron in the primary ore. The thorium/uranium ratio is higher in the ore at greater depths. There is not as much molybdenum at Cercado as at Agostinho. The ore mineral most important at Ilímaussaq, steenstrupine, is absent at Poços and has not been noted at any other place in Brazil. Eudialyte, however, is common to both localities.

Mining operations at Cercado, started in 1977, will involve a single open pit, encompassing the three ore bodies. The pit will ultimately be ~800m in diameter and ~300m deep. Approximately 10^8 cubic meters of material will eventually be removed over a 10- to 12-year period. In the beneficiation of the ore by sulphate leaching and solvent extraction, it is expected to achieve 65% to 90% recovery of U_3O_8.

Based on observation at Poços de Caldas, the principal criterion for uranium mineralization at this type of occurrence is the concordance of peralkaline rocks, hydrothermal alteration, and deep lateritic weathering. The effects of deep weathering are also very important at carbonatite-type deposits, such as Araxá, where niobium mineralization was upgraded in the weathered zone in comparison to the fresh rock.

Other definitive criteria are:

- the location in a belt of peralkaline rocks and carbonatites, intruding a Precambrian shield
- localization of strongest mineralization in a zone of intersection of regional faults
- the strong association of uranium with zirconium, molybdenum, thorium, and fluorine in hydrothermally altered, brecciated tinguaite

3. The Ottawa Graben Type Locality, Canada

The Ottawa Graben is a tectonic feature of eastern Canada, oriented roughly east-west and extending from southern Ontario to southern Quebec. It more or less controls the course of the Ottawa River from Lake Nippissing to its junction with the St. Lawrence River at Montreal (a generalized location map is shown on Figure 10). It is a zone of crustal rifting bounded on the north and south by high-angle, down-

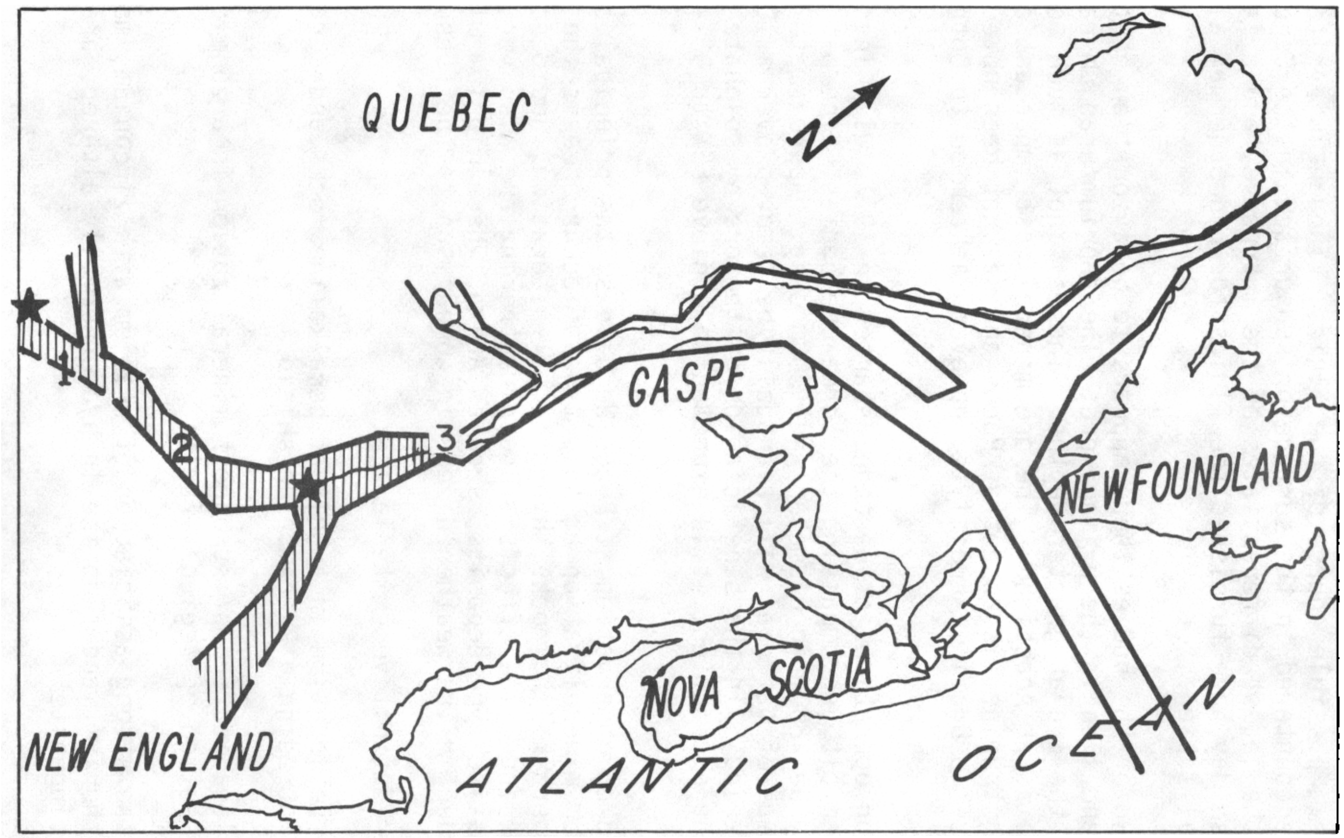

Fig. 10. Location map of the Ottawa Graben region, Canada. The star at the western edge locates Lake Nippissing, the other star locates the Oka complex. Numbers: 1) Nippissing Graben, 2) Ottawa Graben, 3) St. Lawrence Graben. (XBL 781-2372) (permission to reproduce granted by the Geological Survey of Canada)

drop faulting. The graben is about 400 km long and from 50 to 75 km wide. It runs from the NE/SW trending St. Lawrence graben on the east across terrain of the Grenville province, to the west. Here it merges with the Nippissing Valley and dies out (Kumarapeli, 1976).

The entire length of the graben is marked by alkaline to peralkaline rocks of various ages. In general, the youngest rocks occur in the east. Most of the rocks are sub-volcanic with very few strictly plutonic or volcanic manifestations. Tectonic and igneous events along the graben began in the early Paleozoic and lasted until the late Mesozoic. Current seismicity is minor. A number of workers (Kumarapeli, 1976; Kumarapeli and Saull, 1966; Bailey, 1964.) have noted the similarity between the St. Lawrence-Ottawa Graben system and the East African Rift Zone.

Carbonatite is wide spread within the graben. Niobium-rich uraniferous carbonatite crops out in two locations, the Oka and Newman occurrences. These intrusions are widely separated in time and are at opposite ends of the graben. The Oka carbonatite is a member of the Monteregian Hills alkaline series near Montreal. The Newman deposits of Manitou Island in Lake Nippissing are located at the extreme west. Uranium mineralization in both cases is very similar.

Both complexes are composed primarily of carbonatite, silicocarbonatite, biotite-calcite-nepheline rock, fenites, and lamprophyric dikes. Oka, in addition to these rocks, contains ijolite, urtite, and melteigite. Sodic pyroxene and biotite are the predominant mafic minerals in these rocks. The carbonatites comprise a variety of different mineralogical types. About nine distinguishable types occur containing varying proportions of aegirine-augite, pyrochlore, biotite, magnetite, pyrite, pyrrhotite, perovskite, melilite, and apatite. Another suite of rocks range from okaite to jacupiranguite. All are magnetite-rich and contain varying abundances of melilite and titanaugite. Hydrothermal alteration has produced bands of sulfide minerals along fractures and shear zones (Rowe 1956).

The Oka complex has been described by Gold (1969) as a "figure-eight" intrusion (see Figure 11). It intrudes a Precambrian inlier of gneiss and has a K-Ar date of 126 m.y. Two central masses of carbonatite occur at opposite ends of the complex and were emplaced as cone sheets. The mafic rocks are dikes and arcuate intrusions. Lamprophyres and late carbonatites form dikes and plugs throughout the area. The genesis of the Oka complex is unusual in that the oldest rocks are on the outside. In most carbonatite complexes, fenites and metasomatic rocks are formed after intrusion of the carbonatite. At Oka it is believed that a carbonatite magma was emplaced at depth. This magma fenitized its roof, creating the nepheline syenites of the border group and the ijolite series. The ultramafic series was emplaced next as a magma, followed by the main body of the carbonatite. Hydrothermal soaking of the previously formed rocks gave rise to the sulfate mineralization. The latest episode was the injection of the lamprophyric and late carbonatitic dikes (Gold, 1967).

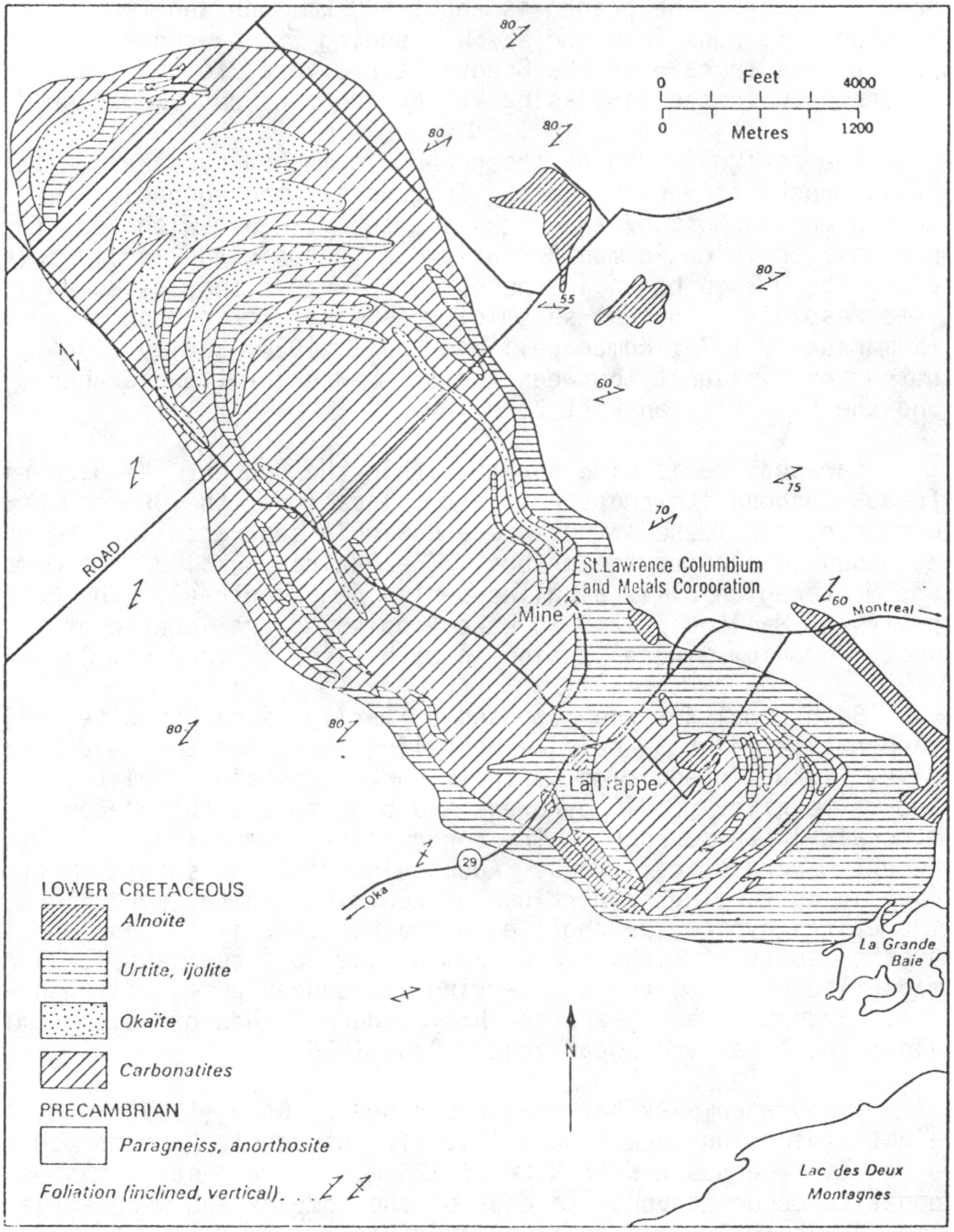

Fig. 11. Geologic map of the Oka carbonatite complex, Canada (from Currie, 1976). (XBL 782-7166) (permission to reproduce granted by the Geological Survey of Canada)

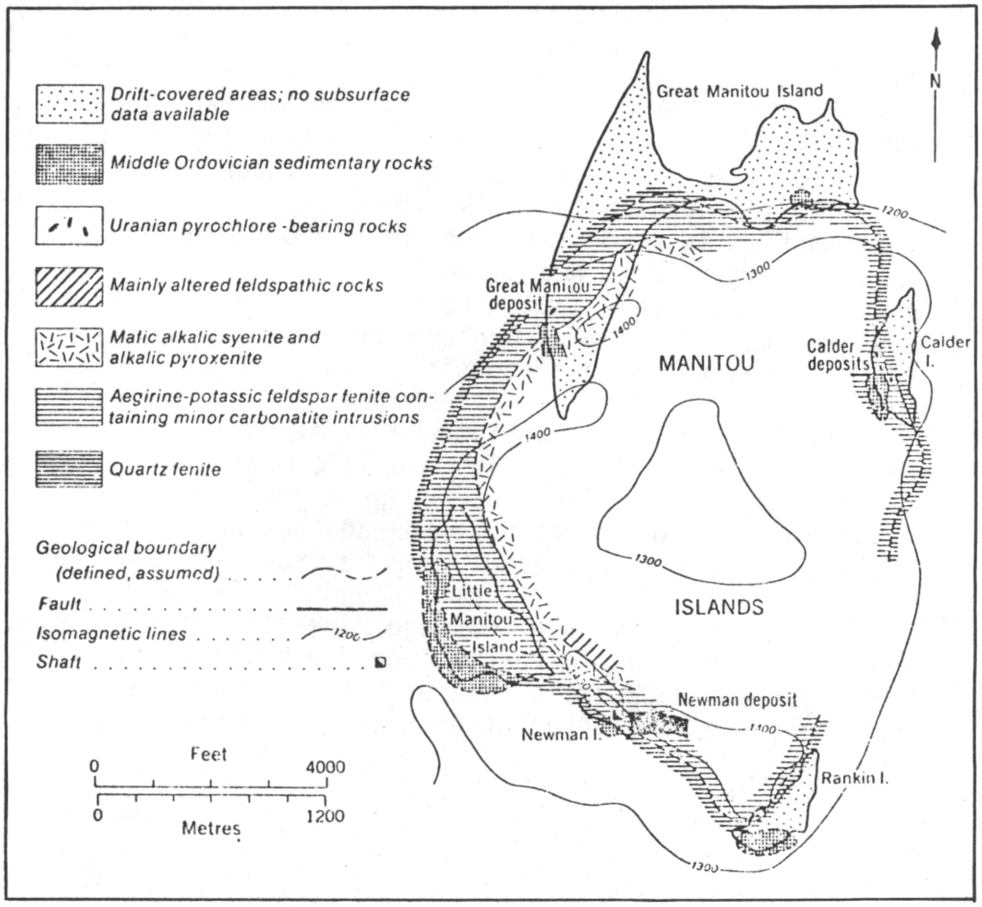

Fig. 12. Geologic map of the Manitou Island complex, Lake Nippissing, Canada (from Currie, 1976). (XBL 782-7165) (permission to reproduce granted by the Geological Survey of Canada)

The petrogenesis of the Newman prospects is somewhat less clear (Currie, 1976). Drilling in Lake Nippissing has shown that no central alkaline magma exists, that each of the islands in the lake complex is a separate intrusion. Manitou Island, which contains the Newman deposit, is an arcuate spit of land in the eastern part of the lake (Figure 12). The country rocks are sedimentary in origin and Ordovician in age. Alkaline rocks have a K-Ar age of 568 m.y. Carbonatite occurs as ring dikes and sheets. Interspersed among these are the alkaline pyroxenites, also thought to be primary. Widespread metasomatism is evident throughout the occurrence. On Manitou Island this is displayed as nepheline syenite, fenites, and biotite-K feldspar-pyroxene rock. This latter rock contains minor pyrite, magnetite, and calcite. Uranium pyrochlore and betafite also occur here and are mined at the Newman deposit (Rowe, 1956).

At Oka a similar niobium ore is mined at the St. Lawrence Columbian pit near La Trappe. The ore is composed of pyrochlore and uraniun pryochlore; uranium is recovered as a by-product of niobium. The pryochlore is concentrated at the contact between ijolite and carbonatite in a metasomatic zone. The La Trappe deposit was first mined in 1961 by St. Lawrence Columbian and Metals Corp. The Newman prospect was first opened by Nova Beaucage Mines, Ltd. They have estimated reserves at Manitou Island to exceed 2.9 million tons of ore containing 0.041 percent U_3O_8. The recovery of uranium as a by-product of niobium is also being considered at Araxá, Brazil (see trip report in Appendix A.2).

The primary criteria for an Ottawa Graben-type occurrence are:

(1) a multiple carbonatite-nephelinite-pyroxenite magma containing an abundance of volatiles,

(2) intrusion of this magma, followed by widespread fenitization and biotization,

(3) distribution of Nb, Zr, REE, and Fe throughout the metasomatic zone,

(4) possible late-stage reintroduction of carbonatite as dikes and veins,

(5) possible hydrothermal reworking of older rocks, and

(6) the presence of economic minerals whose beneficiation would provide uranium as a by-product.

4. Bokan Mountain Type Locality, Alaska

Bokan Mountain is unique in this study because it is the only type-locality in the United States. While there are several other potentially uraniferous peralkaline granites throughout the world, none has been as productive or apparently contains as profitable an

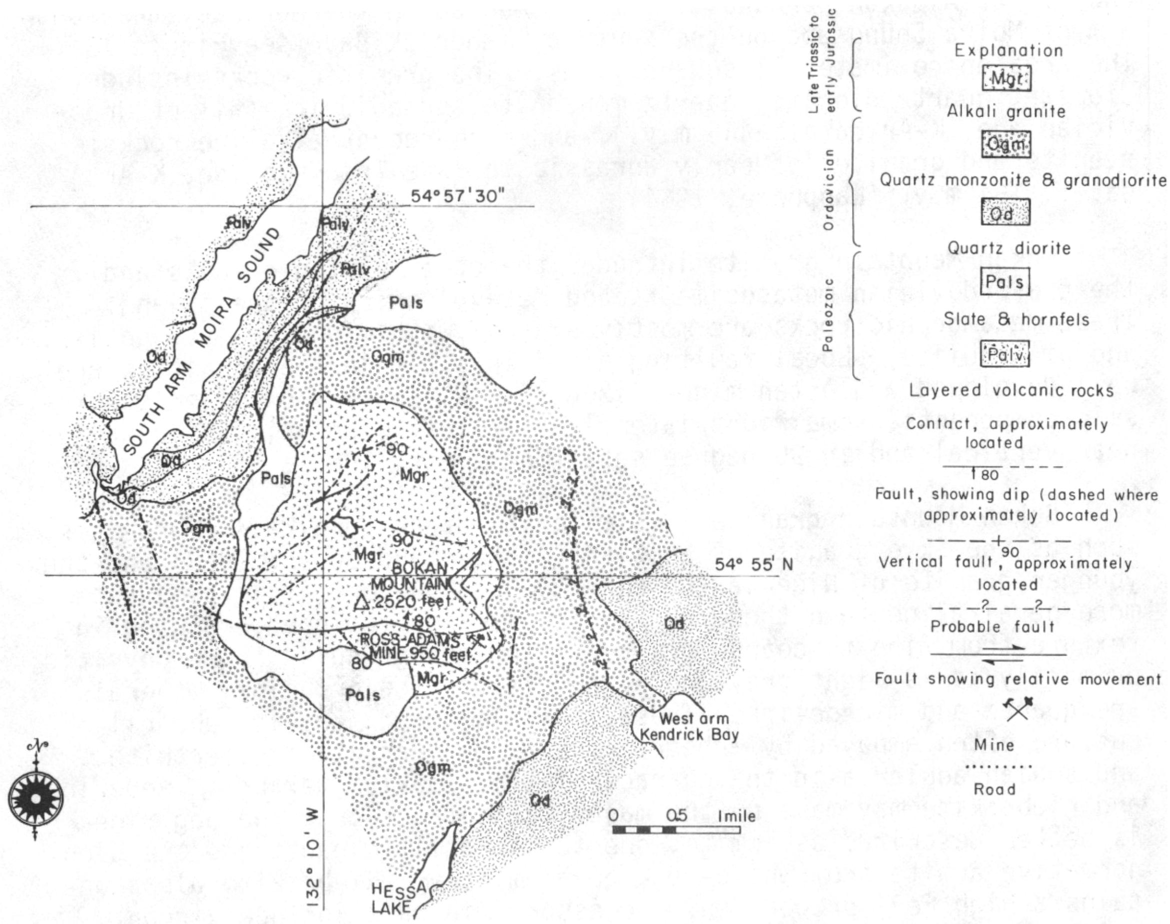

Fig. 13. Geologic map of the Bokan Mountain area, Alaska (after MacKevett, 1963). (XBL 782-200)

ore body as the Bokan Mountain area. The granite occurrence is located at the southern tip of Prince of Wales Island at the southern end of the Alaskan panhandle. It is bounded on the north by the south arm of Moira Sound and on the south by Kendrick Bay (see Figure 13). The area approximates 71 square miles. The granitic rocks include diorite, quartz diorite, quartz monzonite, grandiorite (all of Ordovician age, K-Ar date: 446 m.y.), and more-recent alkaline rocks; syenite and granite (of early Jurassic to late Triassic age, K-Ar date: 184 m.y. (Lanphere, 1964).

Bokan Mountain granite intrudes the other plutonic rocks and the pre-Ordovician metasediments and metavolcanics of the island. These metamorphic rocks are mostly slates, with minor schist, gneiss, and amphibolite. Local faulting and joints within the granitics are well developed and often mineralized. Most faults show major strike-slip components, some right lateral, some left. Jointing is usually near vertical and in 90 degree sets (MacKevett, 1963).

Bokan Mountain granite is similar to other peralkaline granites, such as the Skye granite of Scotland (Tuttle and Bowen, 1958) and the younger granite of Nigeria (Bowden, 1970); however, it is somewhat more peralkaline than these rocks. It is light colored, ranging in texture from fine to coarse grained, from equigranular to porphyritic; primarily it is light grey and porphyritic. The principal minerals are quartz and microcline. These minerals are generally euhedral but are often embayed by anhedral masses of quartz, microperthite, and sodian adularia in the characteristic rapakivi texture. Aegerine and riebeckite may make up the major mafic fraction. The aegirine is better described as acmite, due to its acmitic habit and the high normative acmite from whole-rock geochemistry. Riebeckite also contains a high Fe^{3+} proportion. Accessory minerals include zircon, xenotime, fluorite and uranothorite; some cordierite occurs in marginal zones of the granite. The pegmatitic phase of Bokan Mountain granite is similar in mineralogy to the granitic rocks, but contains more perthite, zircon, and a varied suite of radioactive minerals (Mackevett, 1963).

Four types of uranium ore occur within the Bokan Mountain granite: syngenetic deuteric or autometasomatic concentrations within the magma body, syngenetic emplacement in the pegmatitic phase, epigenetic hydrothermal replacement veins, and a deposit in the country rocks of probable epigenetic emplacement. The most valuable deposit is the Ross-Adams. It was discovered by local prospectors in 1955 and was sold to Climax Molybdenum in that year. Development began in 1957, and 15,000 tons of ore with a grade of 0.80% U_3O_8 were mined. In 1958 Climax sold its rights to the property which eventually were transferred to Standard Metals (Mackevett, 1958; W. Short, personal communication).

Two of the four ore-forming mechanisms created the Ross-Adams deposit. Uranium minerals were syngenetically concentrated in a magmatic or possibly deuteric stage, and further enrichment was provided in a hydrothermal vein stage. Uranothorite and uranian thorianite, surrounded by iron-stained fractures, are the primary ore minerals. Coffinite and pigmentary material are also present. The ore is similar to the host rock, but has hematite and a generally higher content of sodian adularia. Calcite, fluorite, pyrite, galena, quartz, and clay minerals are particularly abundant in the veins. The ore occurs in a zone 2 to 20 feet wide, containing pods alternating with barren rock. The ore contains appreciably greater amounts of iron, lead, and aluminum (and, in some cases, niobium) than did the host rock, and significantly less potassium. The association of hydrothermal ore with faults indicates that solutions used them as passageways. The localization of the primary ore is not well understood but is probably related to late-stage, volatile-rich fluids.

The Atom Marietta and Carol Ann prospects are located in the albitized sheared, and fractured Paleozoic granitics surrounding the Bokan Mountain deposit. The mineralization consists of uraninite, hematite, and fluorite, and is probably the result of the late-stage fluid associated with the peralkaline intrusion. The pegmatites are mined at the I and L deposit. Their mineralogy is similar to that of the veined deposits (Mackevett, 1963).

The most important criteria for the Bokan Mountain occurrence are:

(1) the strongly peralkaline nature of the host granite, representing extreme chemical differentiation;

(2) the concentration of incompatible elements in the volatile stage from the parent magma;

(3) high oxygen fugacity as evidenced by the high Fe^{3+}/Fe^{2+} ratio and normative acmite;

(4) the reinjection of the late-stage fluids either as a deuteric or metasomatic event;

(5) the additional enrichment of the volatile phase in the form of pegmatites; and

(6) hydrothermal reinjection of fluids into the host rock along faults.

III. EVALUATION OF ALKALINE OCCURRENCES IN THE UNITED STATES

A. INTRODUCTION

This part of the project consisted essentially of two tasks. The first was to construct a current list of known alkaline occurrences within the United States. Description of these sites was assembled from the literature, from personal communication with workers in the field, and, in two cases, from on-site visits. The second task was to select from this list the U.S. alkaline sites most interesting for future uranium exploration. The criteria used to select these sites were based upon characteristics of type localities (described in the preceding section).

Because the U.S. list was compiled with this comparison in mind, certain parameters were necessary in selecting U.S. sites. Several well-known U.S. alkaline provinces were not included, i.e., the alkaline basalts of the Balcones Fault Zone and the Leucite Hills of Wyoming. This exclusion was justified on the basis that no economic uranium deposits are known to occur in these types of rocks. Further exploration may, however, change this condition.

B. THE U.S. TABULATION

Table 5 is the master list of U.S. occurrences; they are located on Figure 14. The list is restricted to alkaline and peralkaline syenites and granites, carbonatites, phonolites, and tinguaites. Definitions for these rock types were based upon the sources cited in Section II.A and the glossary, Appendix C.

The identification of sites came through careful examination of many sources, but Barker's (1974) compilation of North American alkaline rocks provided an excellent starting point. The literature on each site was reviewed. Table 5 lists sites by state, site name, and county. The second and third columns of Figure 14 locate the sites using approximate latitude and longitude and the appropriate quadrangles in the USGS 1:250,000 scale topographic map series. The fourth column is a brief description of the applicable rock type, and the fifth column is the most recent or most complete reference in the literature on the site. References in this list range from 1899 to December of 1977.

It is hoped that this table will be interpreted as part of an on-going process, and not the last word on U.S. alkaline rocks. New sites should be identified or reinterpreted and added to the next list by future workers. It is also hoped that this list will encourage others to further work on the lesser known sites.

TABLE 5
MASTER LIST OF U.S. ALKALINE OCCURRENCES.

ALASKA	LAT/LONG.	1° x 2° QUADRANGLE	ROCK TYPE	REFERENCE
SELAWIK HILLS (1)	66°30'N 160°45'W	SELAWIK	NEPH. SY.	PATTON & MILLER 1968
GRANITE MOUNTAIN (2)	65°00'N 161°30'W	CANDLE	NEPH. SY.	MILLER 1972
DRY CANYON CREEK (3)	64°45'N 162°30'W	SOLOMAN	NEPH. SY.	MILLER 1972
EKIEK CREEK (4)	66°30'N 158°30'W	SHUNGNAK/ SELAWIK	NEPH. SY.	WALLACE 1977
CHICHAGOF ISLAND (5)	57°45'N 135°00'W	SITKA	NEPH. SY.	LANPHERE 1965
BOKAN MOUNTAIN (6)	55°00'N 135°00'W	DIXON ENTRANCE	PERK. GRN.	MacKEVETT 1963
ST.LAWRENCE ISLAND (67)	63°15'N 170°00'W	ST.LAWRENCE	NEPH. SY.	CSEJTEY 1974
SALMON BAY (68)	56°15'N 133°30'W	PETERSBURG	CARB.	EAKINS 1969
WASHINGTON				
SHASKET CREEK, FERRY CO. (7)	49°00'N 118°30'W	OKANOGAN	NEPH. SY.	PARKER 1964
OREGON				
NEWPORT, LINCOLN CO. (8)	44°30'N 123°45'W	SALEM	NEPH. SY.	SNAVELY 1961
CALIFORNIA				
NEW IDRIA, SAN BENITO CO. (9)	36°15'N 120°30'W	SANTA CRUZ	NEPH. SY.	ECKELS 1946
COYOTE PEAK HUMBOLT CO. (10)	41°30'N 124°00'W	EUREKA/WEED	ALK. MAF.	BLAKE 1977
TIN MOUNTAIN, INYO CO. (11)	37°00'N 117°30'W	DEATH VALLEY/ GOLDFIELD	NEPH. SY.	McALLISTER 1952
MOUNTAIN PASS, SAN BERNADINO CO.(12)	35°30'N 115°30'W	KINGMAN	CARB.	OLSEN 1954

IDAHO	LAT/LONG.	1° x 2° QUADRANGLE	ROCK TYPE	REFERENCE
CARIBOU MOUNTAIN, BONNEVILLE, CO. (13)	43°15'N 111°15'W	DRIGGS	ALK. SY.	ANDERSON 1931
LEMHI PASS LEMHI CO. (14)	45°00'N 113°30'W	DUBOISE/DILLON	CARB.(?)	SHARP 1963
HALL MOUNTAIN BOUNDARY CO. (15)	49°00'N 116°30'W	SANDPOINT	NEPH. SY.	STAATZ 1974
MONTANA				
LIBBY (Rainy Creek) LINCOLN CO. (16)	48°30'N 115°30'W	KALISPELL	NEPH. SY.	BOETTCHER 1967
ROCKY BOY (Bearpaws) HILL CO. (17)	48°15'N 109°45'W	HAVRE	NEPH. SY. CARB.	PECORA 1962
CRAZY MOUNTAINS PARK CO. (18)	46°00'N 110°15'W	BOZEMAN	NEPH. SY.	SIMS 1968
HIGHWOOD MOUNTAINS CHOUTEAU CO. (19)	47°30'N 110°30'W	GREAT FALLS	NEPH. SY. PHONO.	LARSON 1941
LITTLE BELT MOUNTAINS MEAGHER CO. (20)	47°00'N 110°45'W	WHITE SULPHER SPRINGS	NEPH. SY.	WEED 1899
JUDITH MOUNTAINS FERGUS CO. (21)	47°15'N 109°15'W	LEWISTOWN	ANAL. SY. PHONO.	McDOWELL 1966
UTAH				
LA SAL MOUNTAINS SAN JUAN CO. (22)	38°30'N 109°15'W	MOAB	NEPH. SY.	HUNT 1958
COLORADO				
POWDERHORN (Iron Hill) GUNNISON CO. (23)	38°30'N 107°15'W	MONTROSE	CARB.	TEMPLE 1965
JAMESTOWN BOULDER CO. (24)	40°15'N 105°30'W	GREELEY	PERK. GRN.	NASH 1973
CRIPPLE CREEK TELLER CO. (25)	38°45'N 105°15'W	PUEBLO	PHONO. ANAL. SY.	LOVERING 1950
MT. ROSA TELLER/EL PASO CO.(26)	38°45'N 104°45'W	PUEBLO	PERK. GRN.	GROSS 1966

COLORADO (cont.)	LAT/LONG.	1° x 2° QUADRANGLE	ROCK TYPE	REFERENCE
SOUTH PARK PARK CO. (27)	39°00'N 105°45'W	PUEBLO/DENVER	ANAL. SY.	JAHNS 1938
McCLURE MT./GEM PARK (Wet Mts.) FREMONT CO. (28)	38°15'N 105°30'W	PUEBLO	NEPH. SY.	PARKER 1963
ARKANSAS RIVER (Wet Mts.) FREMONT CO. (29)	38°15'N 105°30'W	PUEBLO	CARB.	HEINRICH 1966
NEW MEXICO				
PAJARITO MOUNTAIN OTERO CO. (30)	33°15'N 105°30'W	ROSWELL	NEPH. SY.	KELLY 1968
TEXAS				
DIABLO PLATEAU HUDSPETH CO. (31)	32°00'N 105°30'W	VAN HORN	NEPH. SY.	BARKER 1977
BARRILLA MOUNTAINS JEFF DAVIS CO. (32)	31°00'N 104°15'W	VAN HORN	PERK RHY.	EIFLER 1951
CHRISTMAS MOUNTAINS BREWSTER CO. (33)	29°30'N 103°30'W	EMORY PEAK	NEPH. SY. PERK. RHY.	JOESTEN 1977
SOLITARIO PRESIDIO/BREWSTER CO. (34)	29°30'N 103°45'W	EMORY PEAK	ANAL. SY.	LONSDALE 1940
OKLAHOMA				
WICHITA MOUNTAINS COMANCHE CO. (35)	34°30'N 98°30'W	LAWTON	PERK. GRN.	AL-SHAIEB 1977b
MISSISSIPPI				
JACKSON DOME† HINDS CO. (36)	32°15'N 90°00'W	JACKSON	NEPH. SY. PHONO.	MONROE 1938
C.B. BOX ESTATE† HUMPHREYS CO. (37)	33°00'N 91°00'W	JACKSON/ GREENWOOD	PHONO.	MOODY 1949

† from drill core

LOUISIANA	LAT/LONG.	1° x 2° QUADRANGLE	ROCK TYPE	REFERENCE
MONROE FIELD† OUACHITA CO. (38)	32°30'N 92°00'W	JACKSON/ SCHREVEPORT	PHONO.	MOODY 1949
TENNESSEE				
McGREGOR† TIPTON CO. (39)	35°30'N 89°45'W	BLYTHEVILLE	NEPH. SY.	MOODY 1949
BATEMAN† SHELBY CO. (40)	35°15'N 90°00'W	BLYTHEVILLE	NEPH. SY.	KIDWELL 1951
ARKANSAS				
MAGNET COVE HOT SPRINGS CO. (41)	34°15'N 92°45'W	LITTLE ROCK	NEPH. SY. CARB.	NESBITT 1977
WILSON SPRINGS (Potash Sulphur Sps.) GARLAND CO (42)	34°30'N 93°00'W	LITTLE ROCK	NEPH. SY. CARB.	STONE 1964
FOURCHE MOUNTAIN (Little Rock) PULASKI CO. (43)	34°45'N 92°15'W	LITTLE ROCK	NEPH. SY.	HAYES 1900
BENTON SALINE CO. (44)	34°30'N 92°30'W	LITTLE ROCK	NEPH. SY.	HAYES 1900
NEBRASKA				
ELK CREEK† JOHNSON CO. (45)	40°15'N 96°15'W	LINCOLN	CARB.	BROOKINS 1975
WYOMING				
DEVILS TOWER CROOK CO. (46)	44°30'N 104°45'W	GILLETTE	PHONO.	BASSETT 1961
WISCONSIN				
WAUSAU MARATHON CO. (47)	44°45'N 89°45'W	EAU CLAIRE/ GREEN BAY	NEPH. SY.	EMMONS 1953

† from drill core

MINNESOTA	LAT/LONG.	1° x 2° QUADRANGLE	ROCK TYPE	REFERENCE
SNOWBANK LAKE LAKE CO. (48)	48°00'N 91°30'W	TWO HARBORS	NEPH. SY.	OJAKANGAS 1974
KEKEKABIC LAKE LAKE CO. (49)	48°00'N 91°15'W	TWO HARBORS	NEPH. SY.	OJAKANGAS 1974
MICHIGAN				
MARQUETTE MARQUETTE CO. (50)	46°30'N 87°30'W	MARQUETTE	ALK. SY.	KALLIOKOSKI 1976
MAINE				
LITCHFIELD KENNEBEC CO. (51)	44°15'N 69°50'W	BANGOR	NEPH. SY.	BARKER 1965
PLEASENT MOUNTAIN CUMBERLAND/ OXFORD CO. (52)	44°00'N 71°00'W	LEWISTON	ANAL. SY.	SANDERS 1971
CASHES LEDGE ATLANTIC OCEAN (53)	43°00'N 69°00'W	BATH?	PERK. GRN.	TOULMIN 1957
AGAMENTICUS YORK CO. (54)	43°15'N 70°45'W	PORTLAND	PERK. GRN.	FOLAND 1977
NEW HAMPSHIRE				
RED HILL CARROLL CO. (55)	43°45'N 71°30'W	PORTLAND	NEPH. SY.	QUINN 1937
WHITE MOUNTAINS CARROLL/COOS/ GRAFTON CO. (56)	44°30'N 71°30'W	LEWISTON	PERK. GRN.	BOUDETTE 1971
VERMONT				
CUTTINGSVILLE RUTLAND CO. (57)	43°30'N 72°50'W	GLENS FALLS	NEPH. SY.	EGGLESTON 1918
BARBER HILL CHITTENDEN CO. (58)	44°15'N 73°15'W	LAKE CHAMPLAIN	ALK. SY.	FOLAND 1977
MT. ASCUTNEY WINDSOR CO. (59)	43°30'N 72°30'W	GLENS FALLS	ALK. SY.	FOLAND 1977

MASSACHUSETTS	LAT/LONG.	1° x 2° QUADRANGLE	ROCK TYPE	REFERENCE
PEABODY/CAPE ANN ESSEX CO. (60)	42°30'N 70°45'N	BOSTON	PERK. GRN. ALK. SY.	TOULMIN 1964
BLUE HILLS/QUINCY NORFOLK CO. (61)	42°15'N 71°00'W	BOSTON	PERK.GRN.	CHUTE 1966
RATTLESNAKE HILL NORFOLK CO. (62)	42°15'N 71°15W	BOSTON	PERK. GRN.	LYONS 1976
RHODE ISLAND				
CUMBERLAND PROVIDENCE CO. (63)	42°00'N 71°30'W	PROVIDENCE	PERK. GRN.	ZARTMANN 1977
NEW JERSEY				
BEEMERVILLE SUSSEX CO (64)	41°15'N 74°45'W	SCRANTON	NEPH. SY. ANAL. SY.	AUROUSSEAU 1922
BROOKVILLE HUNTERDON CO. (65)	40°30'N 75°00'W	NEWARK	NEPH. SY.	BARKER 1969
VIRGINIA				
STAUNTON AUGUSTA CO. (66)	38°15'N 79°00'W	CHARLOTTESVILLE	NEPH. SY.	JOHNSON 1971
NORTH CAROLINA				
MOUNT ROGERS ASHE CO. (69)	36°30'N 81°30'W	WINSTON-SALEM	PERK. GRN. PERK. RHY.	RANKIN 1974

KEY

ANAL. SY.	ANALCIME SYENITE
NEPH. SY.	NEPHELINE SYENITE
ALK. SY.	ALKALINE SYENITE
PERK. GRN.	PERALKALINE GRANITE
PERK. RHY.	PERALKALINE RHYOLITE
ALK. MAF.	ALKALINE MAFICS
CARB.	CARBONATITE
PHONO.	PHONOLITE

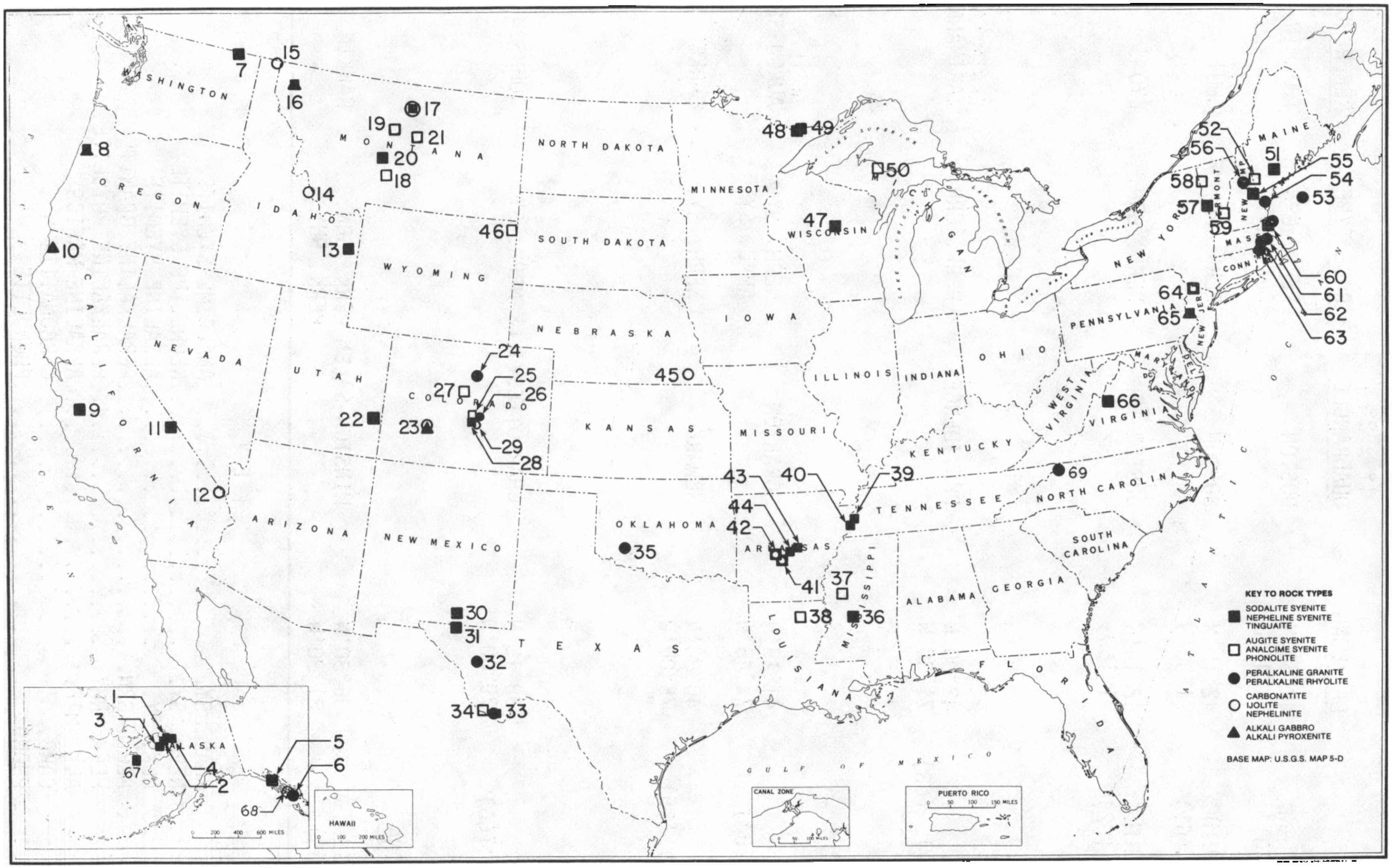

Fig. 14. Alkaline rock occurrences of the United States; site numbers keyed to Table 5. (XBL 782-7418)

C. THE RANKING SYSTEM

As each of the 69 U.S. sites was added to the list, an attempt was made to match the appropriate characteristics of the site to one of the type localities. Key criteria were extracted from the published data and compared to the models described in the previous section. On this basis we were able to compare 40 of the U.S. sites to the world-wide models. The remainder either did not fit at all or were too poorly defined in the literature.

Tables 6 through 9 present the ranking of the 40 sites. The criteria were described in the previous section. These criteria are listed in brief along the top of the charts in eleven standardized headings. Each criterion is given a numerical weight that reflects the relative importance of that factor to the presence of uranium ore. This, too, is based on the study of the specific type-locality. This weight is presented at the bottom of the appropriate column.

Listed along the left side of the charts are the various U.S. sites that fit one of the type-localities. In line with each site and beneath each criterion is a symbol and number indicating the degree of fit, on a scale of -2 to 5, of the various sites. The product of the criterion weight and degree of fit to each criterion is summed. This sum represents the goodness of fit of each site to the model.

The system of ranking is somewhat subjective. Its strongest advantage, however, is that it organizes large amounts of information into an easily understood and comparable format. In reviewing the charts several important results stand out. In each chart two or three localities become especially interesting in view of their fit to the models. These sites will be discussed further in a following section. Some sites contain aspects of more than one model, i.e., Rocky Boy and Magnet Cove. In these cases the chart indicates which aspects of a multiple alkaline intrusion best fit the type-locality models. Some sites rank low or do not even rank in this system. They will be discussed under the section entitled 'Speculations.'

D. DESCRIPTIONS OF PROMISING TARGET AREAS

1. Magnet Cove, Arkansas

Magnet Cove is a composite nepheline-syenite-carbonatite-pyroxenite intrusion, one of a series of alkalic centers in central Arkansas. It was emplaced during the Cretaceous within the Ouachita extension of the Appalachian belt. Figure 15 is a simplified geologic map. The dominant rock types of the intrusion are nepheline syenite and alkaline pyroxenite. These are accompanied by a small carbonatitic intrusion. The pyroxenite and much of the nepheline syenite is considered to be metasomatic in origin (Erikson and Blade, 1963) although there is no fenite zone bordering the intrusion. In addition, the rocks have undergone hydrothermal alteration. Hydrothermal activity continues, as evidenced by warm springs in the region. This

Table 6

ILÍMAUSSAQ
TYPE LOCALITY

	-ALKALINITY- Strongly Peralkaline	-PETROLOGY- Lujavrite, Foyaite, Kakortakite	-MINERALOGY- Nepheline, Sodalite Arfvedsonite, Acmite, Perthite	-TECTONIC SETTING- Crustal Weakness, King Fault Zone	-FORM OF EMPLACEMENT- Plutonic Deep Seated	-AGE OF EMPLACEMENT- Precambrian	-COUNTRY ROCKS- Volcanics, Sediments, Metamorphics	-LATE STAGE ACTIVITY- Analcime Veins, Albite, Brecciation	-PATHFINDER ELEMENTS- Th, REE, Zn, Nb, Be	-URANIUM MINERALIZATION- Steenstrupine, Thorite, Eudialyte	-RADIOACTIVITY- Strong	-TOTAL-
SELAWIK HILLS, ALASKA	-2	2	2	2	2	-2	5	ND	2	ND	5	64
DIABLO PLATEAU, TEXAS	2	5	5	2	-2	-2	5	5	2	2	ND	109
WAUSAU, WISCONSIN	2	2	2	5	-2	5	5	5	2	ND	2	105
PLEASANT MT., MAINE	-2	-2	-2	5	5	-2	-2	5	2	ND	5	50
BEEMERVILLE, NEW JERSEY	2	5	2	2	-2	-2	-2	5	5	2	5	113
CRAZY MTS., MONTANA	2	2	2	2	2	-2	-2	2	ND	ND	ND	40
GRANITE MT., ALASKA	-2	2	2	2	2	-2	5	ND	ND	ND	5	56
RED HILL, NEW HAMPSHIRE	2	2	2	5	5	-2	-2	2	ND	ND	5	83
MARQUETTE, MICHIGAN	ND	-2	2	5	-2	-2	5	ND	2	ND	5	56
LINDON, MINNESOTA	2	-2	2	2	2	5	5	ND	ND	ND	ND	45
SNOW BANK/KEKEBEC, MINNESOTA	-2	-2	2	2	2	5	5	ND	ND	ND	ND	25
Criterion Weight	5	5	4	3	3	2	3	5	4	5	5	

Table 7

POÇOS DE CALDAS
TYPE LOCALITY

	-ALKALINITY- Peralkaline	-PETROLOGY- Tinguaite, Foyaite, Phonolite	-MINERALOGY- Nepheline, Orthoclase, Aegirine, Sodalite	-TECTONIC SETTING- X Fault Zones, Crustal Weakness	-AGE OF EMPLACEMENT- Cretaceous	-FORM OF EMPLACEMENT- Sub-Volcanic	-COUNTRY ROCKS- Precambrian Shield	-LATE STAGE ACTIVITY- Hydrothermal Veins, Lateritization	-PATHFINDER ELEMENTS- Zr, Mo, F, Th	-URANIUM MINERALIZATION- Coffinite, Uranothorite, Mo & F Minerals, Pitchblende	-RADIOACTIVITY- High	-TOTAL-
MAGNET COVE, ARKANSAS	5	5	5	2	5	5	-2	5	5	2	5	187
WILSON SPRINGS, ARKANSAS	ND	2	5	2	5	5	-2	5	2	ND	5	125
JACKSON DOME, MISSISSIPPI	ND	2	2	2	5	5	-2	2	ND	ND	ND	60
McCLURE MT., COLORADO	ND	2	5	-2	-2	5	-2	2	5	ND	5	95
LIBBY, MONTANA	2	2	5	-2	-2	5	2	2	ND	ND	ND	67
CRIPPLE CREEK, COLORADO	ND	2	2	-2	-2	5	2	2	2	2	ND	62
SOLATARIO, TEXAS	2	2	5	2	2	5	-2	ND	ND	ND	ND	69
LA SAL MTS., UTAH	2	2	5	-2	-2	5	2	2	ND	ND	2	77
BEARPAW MTS., MONTANA	5	2	5	-2	-2	5	-2	2	2	2	5	115
CUTTINGSVILLE, VERMONT	2	2	5	-2	2	5	2	ND	2	2	ND	85
Criterion Weight	5	4	5	4	2	4	3	5	5	5	5	

Table 8

OTTAWA GRABEN
TYPE LOCALITY

	-ALKALINITY- Alkaline	-PETROLOGY- Carbonatites, Ijolites, Fenites, Pyroxenites	-MINERALOGY- Calcite, Siderite, Biotite, Nepheline	-TECTONIC SETTING- Rifted Continent, Crustal Weakness	-AGE OF EMPLACEMENT- pЄ to Mesozoic	-FORM OF EMPLACEMENT- Ring Dikes, Plugs	-COUNTRY ROCKS- pЄ Metamorphics	-LATE STAGE ACTIVITY- Metasomatic, Autometasomatic	-PATHFINDER ELEMENTS- Nb, REE, Th, Fe, P, Zr	-URANIUM MINERALIZATION- Betafite, Pyrochlore	-RADIOACTIVITY- Moderate	-TOTAL-
MAGNET COVE, ARKANSAS	$\boxed{5}$	$\boxed{5}$	$\boxed{5}$	△2	$\boxed{5}$	$\boxed{5}$	(-2)	(-2)	$\boxed{5}$	ND	$\boxed{5}$	131
WILSON SPRINGS, ARKANSAS	$\boxed{5}$	△2	△2	△2	$\boxed{5}$	△2	(-2)	ND	$\boxed{5}$	$\boxed{5}$	$\boxed{5}$	128
MOUNTAIN PASS, CALIFORNIA	$\boxed{5}$	△2	$\boxed{5}$	(-2)	$\boxed{5}$	(-2)	$\boxed{5}$	△2	△2	ND	$\boxed{5}$	94
POWDERHORN, COLORADO	$\boxed{5}$	$\boxed{5}$	$\boxed{5}$	(-2)	$\boxed{5}$	△2	$\boxed{5}$	△2	△2	ND	$\boxed{5}$	127
WET MOUNTAINS, COLORADO	$\boxed{5}$	△2	△2	(-2)	$\boxed{5}$	(-2)	$\boxed{5}$	△2	$\boxed{5}$	ND	$\boxed{5}$	97
ROCKY BOY, MONTANA	$\boxed{5}$	△2	$\boxed{5}$	(-2)	(-2)	△2	(-2)	△2	$\boxed{5}$	ND	$\boxed{5}$	100
ELK CREEK, NEBRASKA	$\boxed{5}$	ND	△2	△2	ND	ND	△2	ND	△2	ND	ND	50
Criterion Weight	4	5	4	4	1	3	2	4	5	5	5	

Table 9

BOKAN MOUNTAIN
TYPE LOCALITY

	-ALKALINITY- Strongly Peralkaline	-PETROLOGY- Aegirine/Riebeckite Granite	-MINERALOGY- Aegirine, Riebeckite, Perthite, Zircon	-TECTONIC SETTING- Post-Orogenic	-AGE OF EMPLACEMENT- Mesozoic	-FORM OF EMPLACEMENT- Shallow Plutonic	-COUNTRY ROCKS- Paleozoic Metamorphics, Earlier Granites	-LATE STAGE ACTIVITY- Deuteric Alteration, Autometasomatism, Pegmatization	-PATHFINDER ELEMENTS- Th, Fe, Mg, Pb, Zr, etc.	-URANIUM MINERALIZATION- Zircon, Coffinite, Uranothorite, Pigmentary Material, Uraninite	-RADIOACTIVITY- Strong	-TOTAL-
MT. ROSA, COLORADO	2	5	5	5	-2	5	2	5	2	2	2	141
PAJARITO MT., NEW MEXICO	ND	2	5	ND	-2	2	2	2	ND	ND	ND	47
WITCHITA MT., OKLAHOMA	ND	5	5	5	-2	2	2	2	2	2	2	104
JAMESTOWN, COLORADO	ND	2	2	5	-2	5	5	5	2	5	2	140
CENTRAL WHITE MTS., NEW HAMPSHIRE	-2	2	2	-2	5	2	5	2	2	2	5	90
PEABODY, MASSACHUSETTS	-2	5	5	5	-2	5	5	-2	2	*2	2	101
QUINCY, MASSACHUSETTS	-2	5	5	5	-2	5	5	2	ND	ND	5	116
RATTLESNAKE HILL, MASSACHUSETTS	-2	2	2	5	-2	5	5	5	2	ND	ND	75
Criterion Weight	5	4	3	3	2	4	5	5	5	5	5	

*Pyrochlore Reported

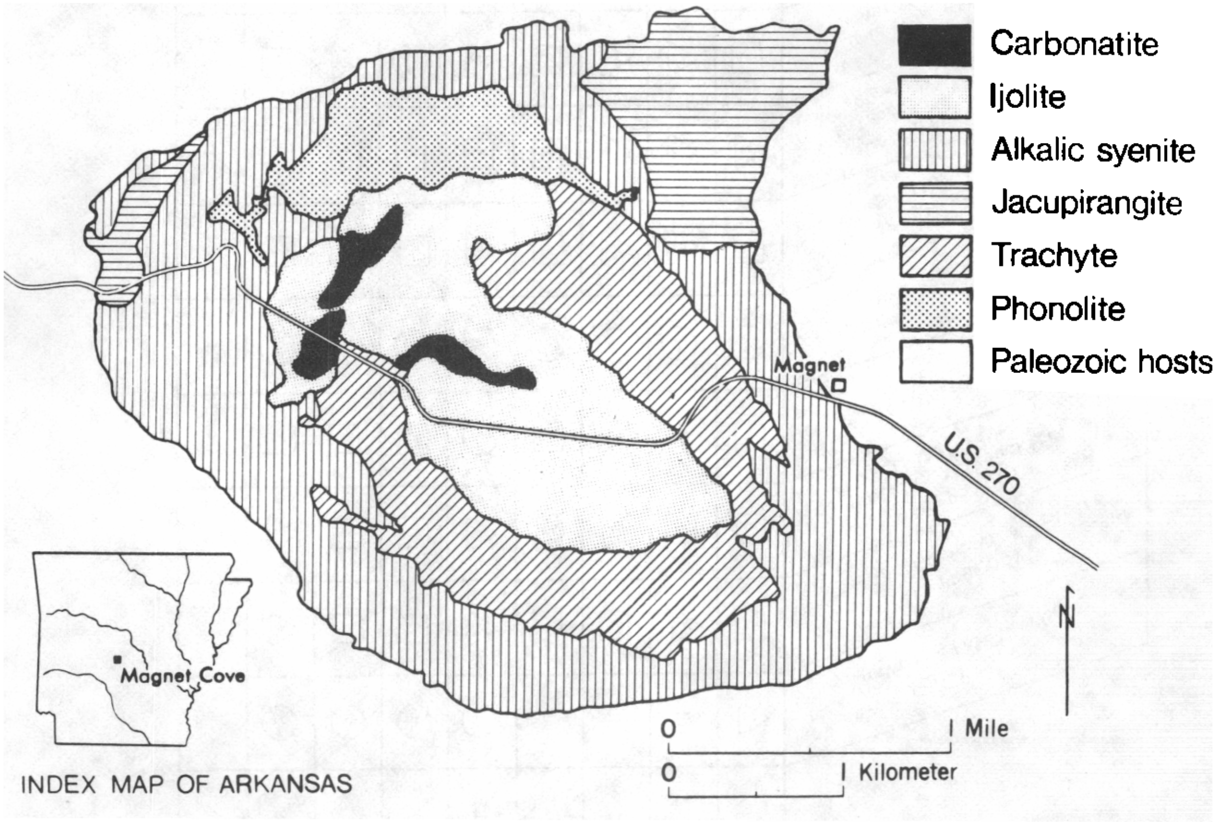

Fig. 15. Simplified geologic map of the Magnet Cove area, Arkansas (from Nesbitt and Kelley, 1977) (XBL 783-7638) (permission to reproduce granted by Springer Verlag)

activity has altered a large segment of phonolite and tinguaite (volcanic equivalents of nepheline syenite). A zone of eudialyte-bearing syenite pegmatite is also present. Throughout the Tertiary the area underwent strong lateritic weathering and development of bauxite.

The area is similar to Poços de Caldas in the combination of rock type, style of intrusion, and post-intrusive events. Primarily because of its carbonatitic character, the area is also similar in some respects to the Ottawa Graben region. The area was radiometrically surveyed in the 1950's and found to be strongly radioactive, up to 0.14% eU. An investigation for uranium was started by the Atomic Energy Commission in the winter of 1951-52, but was discontinued (R. Stroud, private communication).

Further work should be concentrated in the weathered phonolite, the border zone and metasomatized rocks, and the areas of high volatile enrichment.

2. Potash Sulphur Springs, Arkansas

Potash Sulphur Springs is within 3 km of Magnet Cove and probably shares its origin (Stone and Sterling, 1964). However, very little has been published on this occurrence. As with Magnet Cove, Potash Sulphur Springs is similar to Poços de Caldas, but with a more restricted range of rocks. Nepheline syenite is the most common rock type encountered. It is strongly hydrothermally altered, and lateritic alteration is also common. Bauxite is currently mined, and pyrochlore has been identified in the rocks. Vanadium is being mined by Union Carbide at the Wilson Springs pit (Taylor, 1969). This area was explored for uranium after high radioactivity was detected in the early 1950's but has never been fully covered (Raymond Stroud, personal communication). Carbonatite also occurs at Wilson Springs in brecciated pipes containing some pyrochlore. The best targets for future exploration are strongly weathered zones, the breccia zones, and areas of intense hydrothermal activity.

3. Diablo Plateau, Texas

This area is located within the Trans-Pecos alkaline province of West Texas, near the northern terminus of the province. Barker et al. (1977) consider the Trans-Pecos to be an area of intra-continental rifting. The Trans-Pecos, together with the alkaline rocks of the Balcones fault zone in central Texas may be a system similar to that of the Kenya rift in East Africa. The Diablo Plateau contains some of the most strongly peralkaline rocks in the United States. The eudialyte-rich, foliated nepheline syenites are quite similar in lithology to lujavrites of the Ilímaussaq intrusion (Barker et al., 1977b). Other nepheline syenites containing eudialyte, arfvedsonite, analcime, sodalite, enigmatite, bastnaesite, and normative acmite are probably similar to rocks at Ilímaussaq.

This volatile-rich rock at Diablo has been altered by late-stage fluids, producing analcimization and fluoritization. The intrusion was emplaced 34 to 36 million years ago (Hodges, 1975) as a series of stocks and sills. The best prospects for uranium mineralization may be the foliated nepheline syenitic sills and laccoliths, as well as altered zones in other eudialyte-rich nepheline syenites. To our knowledge the Diablo Plateau has not been explored for uranium.

4. Beemerville, New Jersey

A late Ordovician (430 MYBP, Rb-Sr, Zartmann, 1967) tinguaitic dike associated with a nepheline-syenite laccolith is located near Beemerville, about 30 miles north of New York City. The laccolith, described by Aurousseau and Washington (1922), intrudes Silurian and Ordovician sedimentary rocks, including the Martinsburg shale. A geologic map is shown on Figure 16. The occurrence is similar to Ilímaussaq in that the rocks are very peralkaline. Lujavrites and tinguaites make up part of the intrusion. Zirconium and rare earths are also abundant and thorium has been identified. The rocks contain high normative acmite. Analcimization is common throughout. The intrusion is composite, and may have differentiated in place, causing a concentration of volatiles. Several varieties of nepheline syenite occur at Beemerville. The porphyritic lujavrite offers the best possibilities for uranium mineralization, as that rock is most similar to the Ilímaussaq rocks.

5. Quincy, Massachusetts

The Blue Hills igneous complex is one of a number of alkaline intrusives that occur along a line between Cape Ann, Massachusetts and Cumberland, Rhode Island (Lyons, 1976). The Blue Hills pluton is located on this line about 10 miles southwest of Boston. Within the pluton, in close conjunction with the Quincy granite, is a riebeckite granite containing aegirine, perthite, and quartz; the Blue Hills granite poryphyry (Chute, 1966). The intrusion is a small, shallow cupola of a larger magma chamber which underlies a considerable area of southeastern New Entland. Its age is Pennsylvanian, (290 MYBP, K-Ar, Rb-Sr, Lyons, 1976). The concentration of volatiles, Na, Fe^{3+}, and F, and of pegmatitic veins around this pluton, is similar to the Bokan Mountain occurrence. In contrast to the White Mountain series in northern New England, the alkaline rocks of southern New England have not been explored extensively for radioelements. It is not known whether any uranium exploration has been done at Blue Hills. The pegmatitic veins, representing the largest concentration of volatiles, may be the best targets.

6. Wichita Mountains, Oklahoma

Cambrian magmatic activity in central Oklahoma resulted in a granitic series that culminates in the Quanah granite, exposed in the Wichita Mountains, approximately 10 miles northwest of the town of Lawton (Al-Shaieb, 1977b). These aegirine/riebeckite granites,

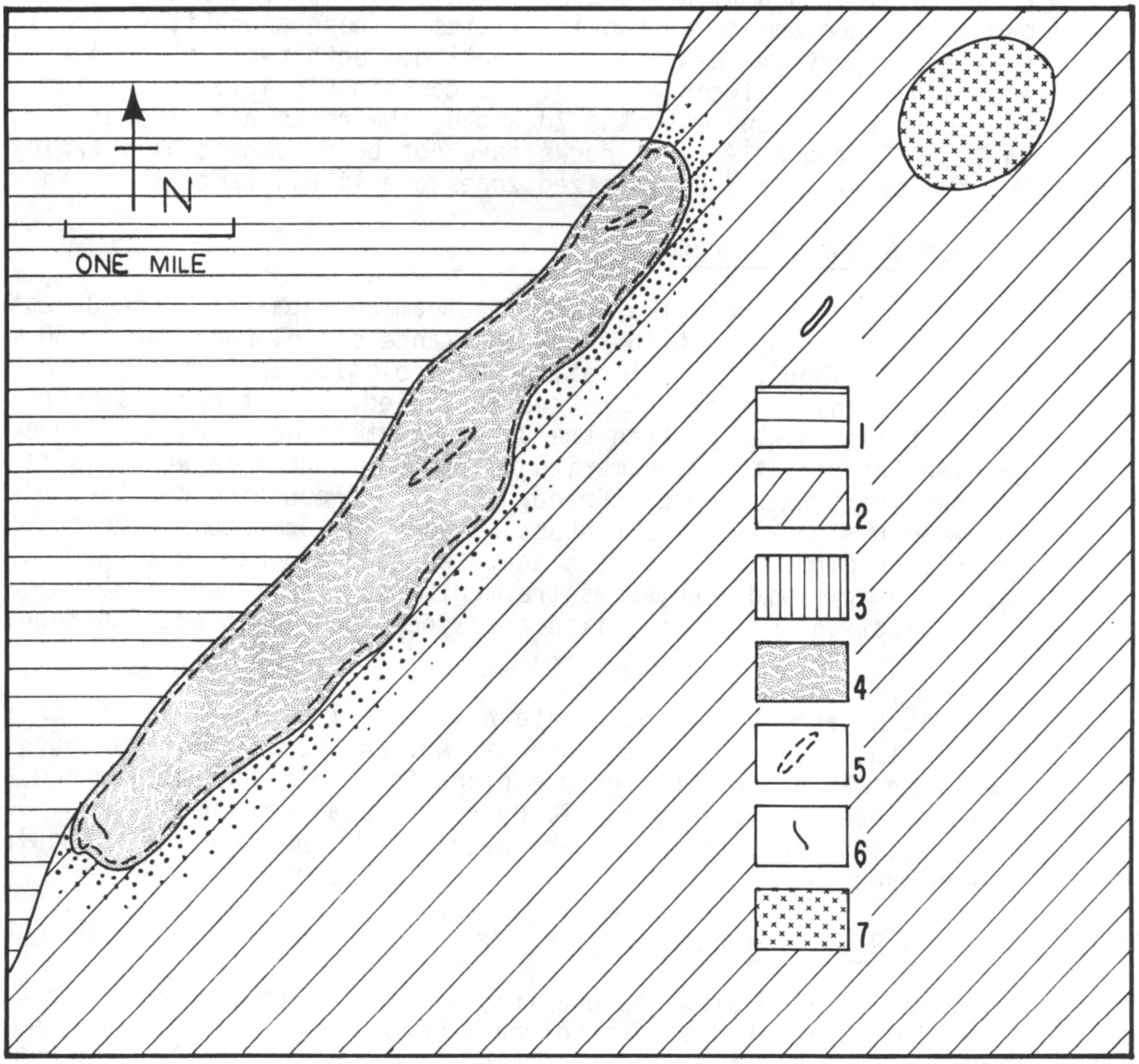

Fig. 16. Geologic map of the Beemerville area, New Jersey (after Aurousseau and Washington, 1922). (XBL 782-155)
1) Shawangunk conglomerate, 2) Martinsburg shale, 3) nepheline syenite with lujavritic facies, 4) biotite-rich nepheline syenite, 5) nepheline porphyry with tinguaite, 6) leucite tinguaite, and 7) ouachitite breccia.

the most differentiated phase of the granitic activity, contain perthite, albite, and metamict zircon. Zircon-rich and pyroxene-rich pegmatites are common in two localities. These pegmatites were localized in part by shearing and jointing. Both types of pegmatites are radioactive; zircon and aegirine contain significant uranium (up to 1500 ppm). Along with the Zr and U, the rocks are also enriched in Th, REE, and Fe^{+3}. The rocks have not been commercially exploited but the pegmatitic and albitized zones are likely targets for investigation.

7. Jamestown, Colorado

An occurrence of alkaline post-Laramide magmatism, the Jamestown soda granite, crops out in the Front Range of Colorado, about 50 miles northwest of Boulder. A location and geologic map is shown on Figure 17. The granite itself is not well studied, but it appears to be somewhat less alkaline than the Bokan Mountain occurrence. The soda granite intrudes the Precambrian Silver Plume granite which is strongly radioactive (Phair and Gottfried, 1964), and contains cerite and other rare-earth minerals. The contact between the Jamestown granite and the Silver Plume is sheared, brecciated, and mineralized. Hydrothermal and deuteric fluids served as the medium for the mineralization. Silicification and albitization are widespread (Nash and Cunningham, 1975).

Pitchblende and uranothorite have been identified in the breccia zones. The area is also enriched in Au, Pb, F, and Mo. Although Jamestown was a locus for gold exploration, no "major" uranium ore bodies have yet been discovered (J. T. Nash, personal communication). Besides the breccia zones, the silica-rich, altered, and dike rocks should be explored.

8. Mt. Rosa, Colorado

The Mt. Rosa alkaline granite, similar in some respects to Bokan Mountain, is located in the Colorado Front Range about 5 miles east of Cripple Creek. The geologic setting, shown in Figure 18, has been described by Gross and Heinrich (1965, 1966A, 1966B). (A report of a visit to the area is included as Appendix A.3). The Mt. Rosa granite is a late-differentiate of the Precambrian radioactive Pikes Peak granite series. The Mt. Rosa is a thin, sheet-like intrusion. The alkaline granite contains riebeckite, aegirine-augite, perthite, and zircon. The area has been sheared and faulted.

In the area of St. Peter's Dome, peralkaline pegmatites crop out in numerous locations. These pegmatitic phases cut Mt. Rosa granite and older rocks, and are accompanied by small occurrences of finer-grained, altered Mt. Rosa granite. The pegmatites have been explored for uranium, and small amounts of uranothorite have been described (Gross, 1966A). Future exploration should uncover more information on other areas of sheared and altered Mt. Rosa granite.

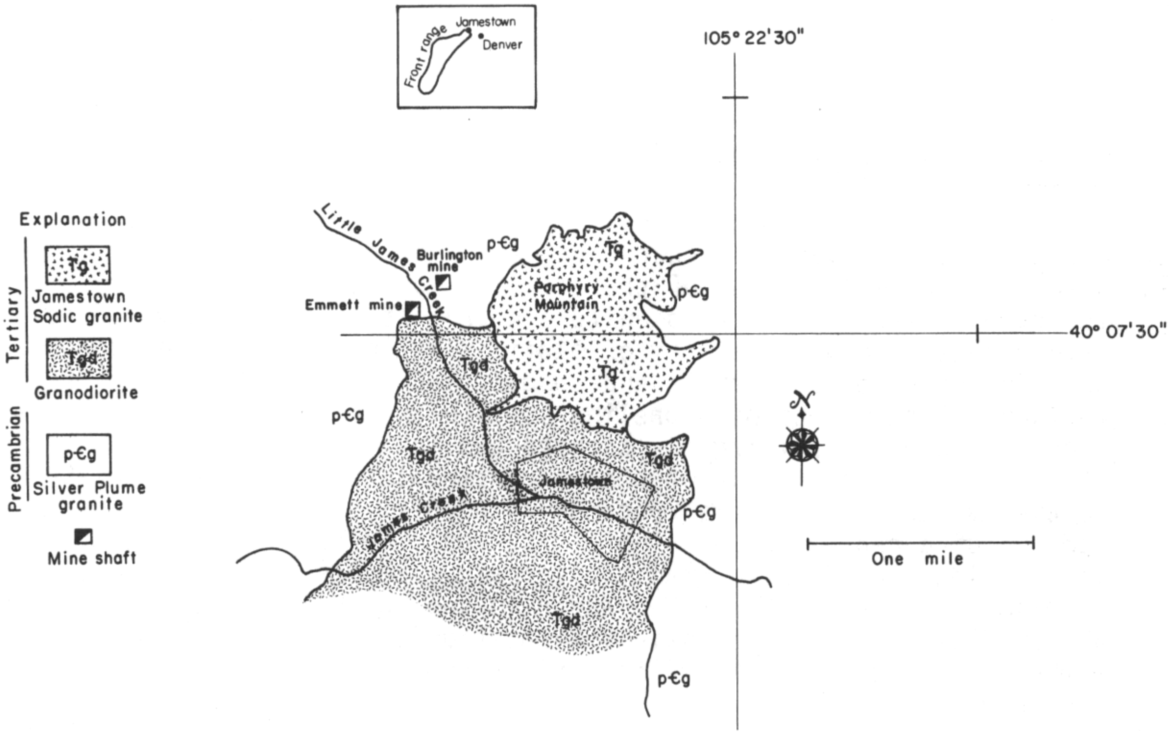

Fig. 17. Simplified geologic map of the Jamestown area, Colorado (after Nash and Cunningham, 1973). (XBL 782-198)

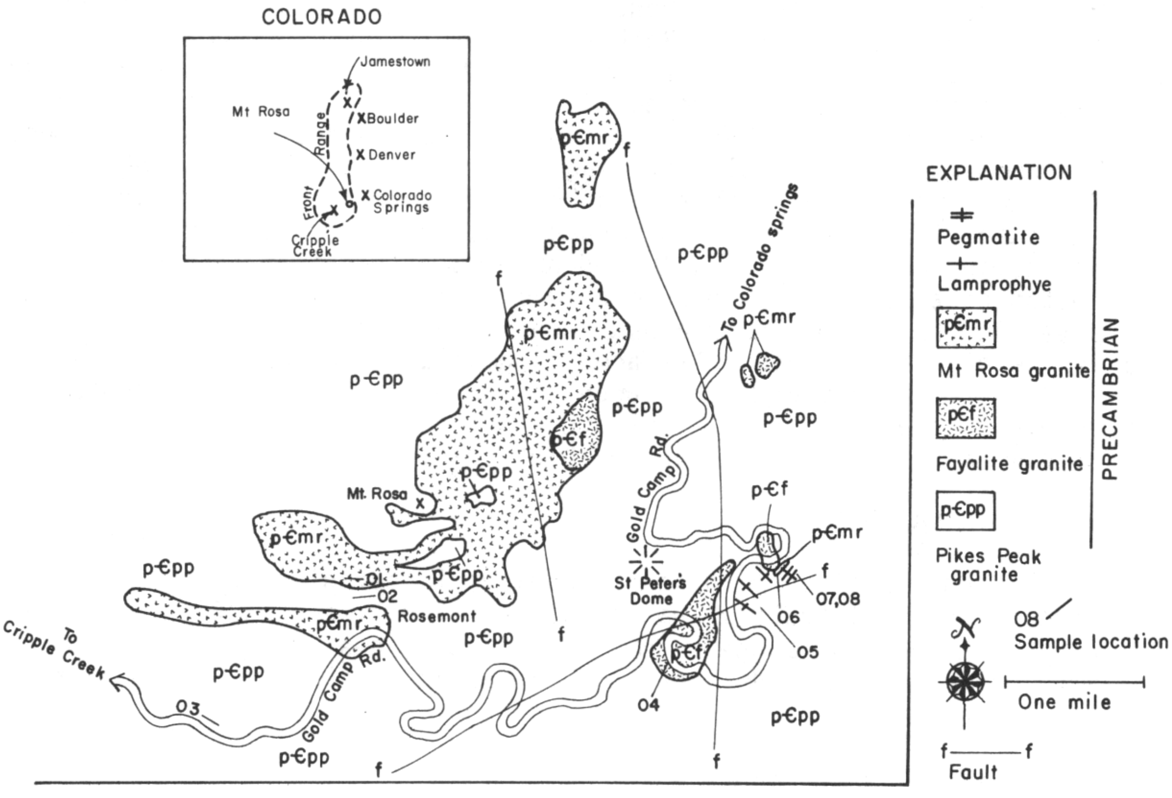

Fig. 18. Geologic map of the Mt. Rosa area, Colorado (after Gross and Heinrich, 1965). (XBL 782-199)

9. Powderhorn, Colorado

The Powderhorn, or Iron Hill intrusion is a carbonatite pyroxenite-nepheline syenite, located between Gunnison and Lake City , Colorado. A geologic map of the area is reproduced on Figure 19. The carbonatite and the pyroxenite are thought to be primary and to have created the wide variety of exotic alkaline rocks of the complex through metasomatism (Temple and Grogan, 1965). These exotic rocks include a fenite zone of nepheline syenite and a biotite-calcite-pyroxene rock. Down-drop faulting has exposed two levels of the intrusion. It is not precisely known whether extensional tectonics were related to the emplacement of this Precambrian complex. The intrusion is made up of a central plug, ring dikes, and numerous thorium veins in the older Precambrian granitic terrain. Besides Th, the complex is also enriched in REE, Fe^{+3}, and P (Olson and Wallace, 1956). Although AEC studies carefully investigated the thorium veins, it is not known whether the biotite rock or the fenite zone received the attention they now deserve.

10. Rocky Boy, Montana

Rocky Boy is the main carbonatitic occurrence in the Bearpaw Mountains of north-central Montana. The geological setting was described by Pecora (1962). Both a sericitized syenite and a non-sericitized carbonatite occur at the site. Metasomatism and autometasomatism created a biotite-rich and silicified mixture of calcite- and dolomite-rich rocks. Mineralization has occurred along fault planes. The complex is a sub-volcanic plug with numerous dikes cutting the Paleozoic to Tertiary country rocks. The age of the Rocky Boy stock is Eocene. Unlike the Ottawa Graben occurrences, the Rocky Boy stock was subjected to considerable hydrothermal alteration. Extensional tectonics also probably played a lesser role in emplacement of intrusives in the Bearpaw Mountains. Uranian pyrochlore has been found in the biotitized zone. The area is generally enriched in Nb, Fe, P, and Zr. In its uranium search in 1955-56, the AEC concentrated on pyrochlore deposits. A new study of the area should continue this work to include more of the biotite-rich and metasomatized rocks.

E. SPECULATIONS

In this section we discuss problems in defining criteria, propose some geochemical factors that might be definitive if sufficient data were obtained, and suggest some U.S. occurrences which, though information on them is not adequate for our ranking system, may deserve further investigation.

1. SPECULATIVE COMMENTS

An objective of this project was to develop, primarily from existent literature, a set of criteria to evaluate the potential of uranium in alkaline and peralkaline rocks, and to apply these criteria to comparable U.S. alkaline occurrences. The results, to date, of

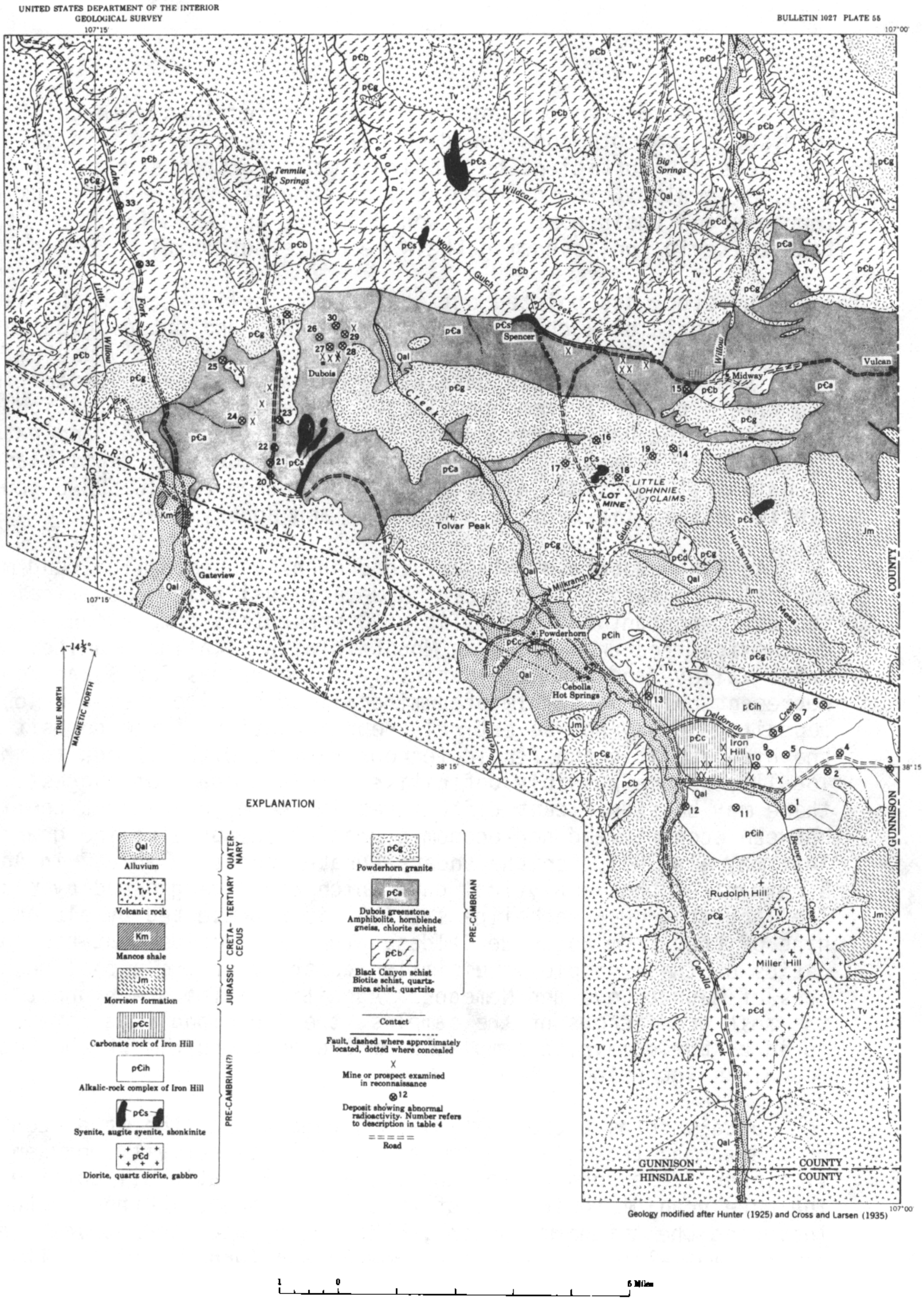

Fig. 19. Geologic map of the Powderhorn-Iron Hill area, Colorado (from Olsen, et al., 1956). (XBL 782-7172)

this study have been presented in previous sections. In this section, we discuss concepts considered speculative because data in the literature were not sufficient to confirm them. Further study of the petrology, mineralogy, and geochemistry of samples from uraniferous alkaline terranes and their host rocks would permit better definition of important criteria for assessing their resource potential.

Our study has pointed out that, principally because of insufficient data, criteria of a chemical, mineralogical, and petrological nature could not be well enough defined to be considered fully useful. Therefore, the absence of such data was a primary factor in separating legitimate criteria from speculative criteria. This situation is changing. The Danish government supports a geochemical and petrological study of Ilímaussaq (Larsen, 1975). The Cercado deposit and surroundings at Poços de Caldas are being studied by NUCLEBRAS geologists, Ulbrich et al. (in press), and Gorsky and Gorsky (1974).

At Bokan Mountain, Alaska, comprehensive geochemical and mineralogical information is scarce. However, available geochemical data suggest important factors. Table 10 presents a comparison of some geochemical features of Bokan Mountain with alkaline granites at Skye, Kaffo Valley, and the Kola Peninsula. The values for Bokan Mountain represent only one sample of unmineralized granite near the Ross-Adams deposit, and may not be entirely representative of the deposit. However, the high agpaitic and ferric-ferrous ratios, with respect to the other localities, are possibly definitive. This comparison suggests that there may be significant differences in the major-element chemistry between economic and non-economic uraniferous peralkaline granites. This may also hold for the undersaturated rocks. Table 7 in Appendix B summarizes that analytical data which could be grouped by rock type. The largest group, nepheline syenite, is represented by eleven samples, nine of them from Poços de Caldas. The major-oxide contents and agpaitic ratios of these samples are similar to those of the nepheline syenites of Magnet Cove and Nemegos. Agpaitic ratios are highest in the most uraniferous of the samples, the Greenland lujavrites, followed by the lujavrite samples from the northern rim of the Poços de Caldas intrusion.

Data such as those in Table 10 suggest that the water content of the magma, the volatile component, halogen activity, oxygen activity, ferric-ferrous ratio, and the agpaitic ratio all combine to indicate uranium enrichment of an alkaline magma. Other factors, including the titanium content, K-Rb ratio, and other trace-element ratios, may also be indicators (Bowden and Turner, 1974). It has also been demonstrated that properties of the mafic minerals, feldspars, opaques, fluid inclusions, and late-stage minerals may be quite informative. For example, the medium- to coarse-grained lujavrites of the Kvanefjeld plateau at Ilímaussaq are the only rocks of the intrusion that do not contain modal perthite. They are also the rocks richest in uranium. It is these types of concepts that only hard analytical data will be able to define.

Table 10 Comparison of Some Geochemical Factors at Peralkaline Granite Sites.

	Agpaitic Ratio	Fe^{3+}/Fe^{2+}	H_2O+	CO_2	TiO_2	U ppm
Bokan Mountain, Alaska, U.S. (MacKevitt, 1963)	1.31	2.0	.35	.26	.20	up to 25K[a]
Isle of Skye, Scotland, U.K. (Tuttle & Bowen, 1958)	1.14-.12	.98	.39	nil	.36	low
Kaffo Valley, Jos, Nigeria (Bowden & Turner, 1974)	1.22	1.19	.25	n.d.	.56	100
Kola Peninsula, U.S.S.R. (Batieva, 1968)	1.25	1.19	.22	n.d.	n.d.	2.5-12

a) from Nishimori, et al.(1977).

2. Further Occurrences of Interest

Because the essence of the project was the development of criteria, certain U.S. locales of interest were excluded from the final list. Either their dissimlarity to type localities or the lack of data in the literature was responsible. This does not mean that these areas are not important to resource assessment. Some of these areas are briefly discussed.

At Libby, Montana, the Rainy Creek intrusion is an interesting complex of alkaline felsic and mafic rocks, which possibly contains carbonatite at depth (Heinrich, 1966). Hydrothermal mineralization has created a large vermiculite deposit (Boettcher, 1967). The Seward Peninsula in west central Alaska has been considered, but scores low in the ranking (Table 6) due to insufficient data. Airborne surveys have uncovered significant radiometric anomalies associated with highly potassic nepheline syenites (Miller, 1972; Jones et al., 1977; Robert Forbes, personal communication). These rocks should receive a detailed analytical study. The Cripple Creek intrusion of the southern Front Range, Colorado is a subvolcanic, mildly alkaline region comparable to Poços de Caldas. Fluorine- and molybdenum-rich hydrothermal solutions have permeated shear zones and breccia pipes to enrich the area in base and precious metals (Lovering and Goddard, 1950; Koschmann, 1949). The Elk Creek carbonatite in eastern Nebraska is a sub-surface occurrence of interest (Brookins, 1975). It occurs along a geophysical structure known as the mid-continent gravity high. Other subsurface alkaline rocks may occur along this lineament. USGS work has outlined another alkaline belt running from Virginia to Hicks Dome in Illinois (Zartmann, 1977). Most of the rocks along this lineament are kimberlites, statistically the poorest uranium resource. However, felsic rocks or carbonatites could easily be associated with this belt.

The alkaline diatremes at Hopi Buttes, Arizona; Morro do Ferro, Brazil; and the Grand Canyon have been explored as possible uranium resources (Wedow, 1967; Shoemaker, 1962; Gabelman, 1977). Mantle-derived gases are believed to accumulate uranium in their passage through the crust and to deposit this uranium in the matrix of the diatreme. This concept implies that the sandstone deposits often associated with these structures have been mineralized by leaching of the diatreme matrix, not the opposite as has been believed in the past (Gabelman, 1977). It should be noted that controversy still surrounds the origin of uranium-rich diatremes. In general, the diatremes currently studied have not been considered appreciable uranium resources.

Another area of interest is the Colorado Front Range. Some authors consider the Front Range to be a uranium province (Phair, 1957; Phair and Jenkins, 1975; Nishimori et al., 1977). Of primary interest are the bostonite (dike syenite) dikes, described by Goddard and Lovering (1950). These dikes occur within the entire length of the Front Range mineral belt and are reported to have an average uranium concentration of 40 ppm and Th/U ratio of 3.6 (Nishimori et al., 1977). Nishimori also reports a high ferric/ferrous ratio, volatile enrichment, and degree of fluoritization in the dikes, supporting conclusions of this study. It is rare that such high uranium values occur in rocks of such low agpaicity. Further study is indicated.

The foregoing discussion points out the need for continued field and laboratory studies of uranium in alkaline rocks. A literature search is insufficient because data are so sparse, especially for U.S. alkaline occurrences. This project has pointed out regional, local, and general topics for further investigation. These studies should be made if the U.S. uranium resource potential is to be fully and systematically evaluated.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. PROMISING OCCURRENCES

We have identified, from a literature search, over 60 alkaline, peralkaline, and carbonatitic occurrences in the U.S whose attributes have been compared with type-occurrences containing potential radioelement resources. These type-occurrences are exemplified by Ilímaussaq, Greenland; Poços de Caldas, Brazil; alkaline-carbonatitic rocks in the Ottawa Graben, Canada; and alkaline-peralkaline granites of Bokan Mountain, Alaska. In comparing U.S. occurrences with these type localities, we found that sufficient information existed on 40 U.S. sites to permit them to be ranked as candidates for further investigation. From these 40, 10 have been chosen:

- the alkaline-carbonatitic occurrences at Magnet Cove and Potash Sulphur Springs, Arkansas
- the carbonatite-pyroxenite-nepheline syenitic Powderhorn intrusion near Gunnison, Colorado
- the Rocky Boy hydrothermally altered carbonatitic stock in the Bearpaw Mountains, Montana
- the lujavritic stocks and sills of the Diablo Plateau, West Texas
- the lujavritic-tinguaitic dike near Beemerville, New Jersey
- pegmatitic veins in riebeckite granite near Quincy, Massachusetts
- peralkaline pegmatites in the alkalic Quanah granite of the Wichita Mountains, Oklahoma
- hydrothermally altered shear zones at the contact between alkalic granite and Precambrian granite near Jamestown, Colorado
- sheared and altered granite and pegmatites of Mt. Rosa, Colorado

Having identified these promising alkaline rock occurrences, primarily from a literature search, it is recommended that a selected number of these sites be examined to confirm their resource potential. They would be chosen on the basis of access, availability of information, and the degree to which they typify other areas.

B. CRITERIA

In this project, several criteria have been developed to judge the uranium resource potential of the alkaline rocks. The criteria were weighted as to their considered importance, and used to rank 40 U.S. occurrences. Criteria considered of high priority in all four type localities are their petrologic and mineralogic settings, which essentially determine the degree of alkalinity (or agpaicity), exemplified by nepheline syenitic rocks at Ilímaussaq and Poços de Caldas, and aegirine-riebeckite granite at Bokan Mountain. Also important are the presence of late-stage hydrothermal, deuteric alteration, or metasomatic activity; an abundance of pathfinder elements such as Th, Zr, Nb, Mo, F, rare earths and Zn; and, of course, the presence of uranium minerals and accompanying anomalous radioactivity. Petrologic criteria: the presence of ijolite, fenite, and pyroxenite, are also considered important in the carbonatite-type localities exemplified by those in the Ottawa Graben. The tectonic settings: strong fault intersections at Poços de Caldas and intracontinental rifting in the Ottawa Graben are considered to be of somewhat greater importance to uranium deposition at those localities than are the tectonic settings of the Ilímaussaq and Bokan Mountain-type occurrences.

The comparatively shallow emplacements of the Poços de Caldas (subvolcanic) and Bokan Mountain (shallow-plutonic) type localities are considered relatively more important for uranium mineralization at those occurrences than are the deep plutonic setting of Ilímaussaq or the ring-dike carbonatitic forms of the Ottawa Graben occurrences. The age of emplacement was not considered especially definitive of the presence of uranium in any of the type localities. For example, ages of emplacement range from Precambrian to Mesozoic in the Ottawa Graben. With the exception of Bokan Mountain, the nature of the country rocks was of little importance. At Bokan Mountain, however, the peralkaline granite, Late Triassic to Early Jurassic in age, intruded a much older (Ordovician), predominantly calc-alkaline plutonic sequence whose presence might have influenced the distribution and abundance of radioelements in the peralkaline granite.

C. MODELS OF OCCURRENCES

Because of the presence of disseminated mineralization, it is considered that the Ilímaussaq and Poços de Caldas type-occurrences offer the greatest promise for significant tonnages of uranium from alkaline igneous rocks. Uranium would most likely be a byproduct of niobium production from Ottawa Graben (carbonatite) type occurrences, or produced from discrete veins associated with peralkaline granite of the Bokan Mountain types. Therefore, in this section the characteristics of the Ilímaussaq and Poços de Caldas alkaline intrusives, which are definitive of the occurrence of uranium, are briefly discussed. We emphasize characteristics that should be looked for in the evaluation of prospective U.S. occurrences of these types.

1. Ilímaussaq Types

In evaluating this type of occurrence one would look for a strongly layered intrusive, which differentiated under appreciable thickness of cover (several km), leading to development of agpaitic rock types.

Gravity separation of dense and light phases might or might not have occurred, but the development of a late-stage lujavritic phase from which residual liquids emanated is most important. The liquids would most likely be albitic-analcitic in character and have interacted strongly with previously crystallized agpaitic rocks to form albite-analcime veins containing rare- and radio-elements such as steenstrupine, monazite, thorite, and pyrochlore. This mineralization would occur in veinlets in the lujavrite and earlier-crystallized rocks, and also in more disseminated form throughout strongly sheared and altered country rock. Mineralization would be strongest in structurally favorable zones near the contact between lujavrite and pre-intrusive rocks. The resulting "low grade" (300 - 600 ppm U) ore body would be dominated by the aforementioned radioelement minerals and uranium-rich pigmentary material, as well as possibly villiaumite, murmanite, pyrochlore, and beryllium minerals. In other parts of the intrusive, not necessarily in direct contact with the uranium-rich zone, there might be lujavritic or cumulate-mineral assemblages containing abundant Zr, Nb, and rare-earth minerals such as eudialyte and rinkite.

2. Poços de Caldas Types

In evaluating an intrusive of this type one would note its shallow-intrusive, subvolcanic character, in contrast to the deep-seated origin of Ilímaussaq types. This would be indicated by the presence of phonolite and tinguaite as the prevalent rock types, with lesser amounts of intrusive rocks such as foyaite, lujavrite and khibinite. The presence or absence of carbonatite would probably not have a bearing on the presence or abundance of uranium mineralization. An episode of strong hydrothermal activity, perhaps accompanying the emplacement of lujavrite or khibinite during the latter stages of differentiation of the intrusive, would have caused deposition of primary ore (Zr, F, Mo, U) in veins in brecciated zones of the earlier volcanic rocks. This, or earlier hydrothermal activity may have formed prominent zircon-baddeleyite (caldesite) veins containing abundant uranium, most likely located at or near the contact between foyaite and tinguaite. The principal ore, however, would be concentrated in an oxidation-reduction zone which progressed downwards to depths as great as 300 m as laterization of the hydrothermally altered tinguaite proceeded. This "redox" effect would have converted the primary ore to a secondary pitchblende ore. The most intense mineralization (contents of several tenths to over 1% U_3O_8) would be located in zones of strongest faulting and brecciation. Because of the effects of deep weathering, it is likely that ore would not crop out, but drilling targets would be the locations of fault intersections and strong hydrothermal alteration of laterized peralkaline terrane.

From a study of the type-localities, it appears that the literature is deficient in data of petrologic, mineralogic, and geochemical studies. These data are needed to sharpen criteria and thereby better evaluate prospective uraniferous alkaline occurrences. Field and laboratory analytical work on ore and host rocks from localities of demonstrated uranium resource potential are needed. This work should concentrate on the distribution of uranium in both framework and accessory minerals, and the roles of such parameters as oxygen fugacity, ferric-ferrous ratios, agpaicity, and partitioning of uranium between earlier- and later-formed minerals.

APPENDIX A.1

TRIP REPORT, VISIT TO ILÍMAUSSAQ ALKALINE INTRUSION, SOUTH GREENLAND, AUGUST 1977

H. Wollenberg
8 September 1977

INTRODUCTION

Arranged by discussions and correspondence with Bjarne Leth-Nielsen of the Geological Survey of Greenland (GGU), an agency of the Danish government, Harold Wollenberg of LBL and William Short of B.F.E.C., Grand Junction, visited the Ilímaussaq alkaline intrusion, 19-29 August, 1977.

In the Western nations two alkaline-peralkaline intrusive areas contain identifiable uranium resources: the Ilímaussaq of South Greenland and the Poços de Caldas in Brazil (a visit to the latter is planned for the autumn of 1977).

Several articles over the past decade have discussed the geologic setting of Ilímaussaq. The most complete treatment of the subject is that by Ferguson (1964). Sørensen (1962) wrote a detailed description of the mineralogy, with emphasis on steenstrupine, the principal uranium-bearing mineral. The Ilímaussaq is one of several alkaline bodies which intruded the Precambrian granite, sandstone, and lavas of the Gardar province of South Greenland 1 to 1.5 billion years ago.

Initial field surveys and drilling at Ilímaussaq in the late 1960's and early '70s delineated $\sim$19 million tons of "reasonably assured" reserves of ore averaging 310 ppm U, with additional reserves estimated at 33 million tons of 300-350 ppm ore (Sørensen, et al., 1974). This ore lies on the Kvanefjeld Plateau near the northern border of the intrusion where U and Th -rich minerals (steenstrupine, monazite, thorite, and pigmentary material) have concentrated in medium to fine grained lujavrite (aegirine-arfvedsonite nepheline syenite) near the contact with older roof rocks. A regional location map is reproduced as Figure A.1-1, and a detailed geologic map of Ilímaussaq

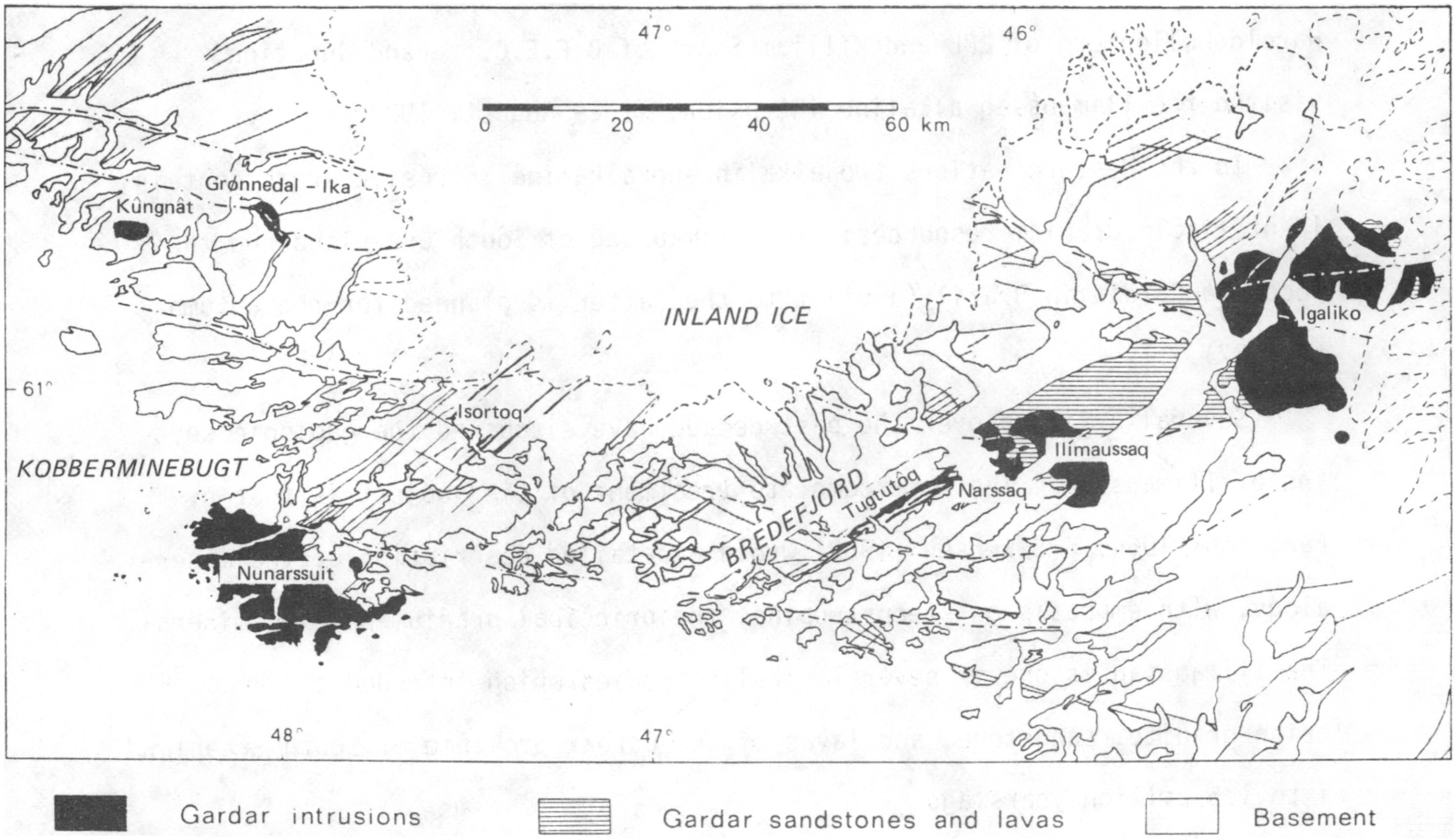

Fig. A.1-1. Simplified geologic map of the Gardar alkaline province, South Greenland (from Sørenson et al., 1974). (XBL 782-7170) (permission to reproduce granted by Geological Survey of Greenland) comprises Figure A.1-2. A list of rock types is excerpted as Table A.1-1, and minerals of interest are listed on Table A.1-2.

DRILLING AND LOGGING: CURRENT ACTIVITIES

Continued evaluation of the economic resource potential of Ilímaussaq is the responsibility of the GGU, and in this regard, with supplementary funding from the European Economic Community (EEC) they carried out an extensive additional drilling program on, and northeast of, the Kvanefjeld Plateau in the summer of 1977. The program entailed the drilling of 25 $\sim$200-meter holes, and was accomplished by three rigs and crews from the Danish Geotechnical Institute. The rigs were airlifted to the plateau by helicopter, and moved from site to site by light tractor. All holes were AX, and continuously cored. Cores were described in detail, split, and representative portions of every 2 meters crushed for subsequent gamma-ray spectral analyses at the Danish Energy Commission's Research Center, Risø.

All but two of the holes were logged by the Scintrex Company, with a gamma spectral system which included an AX-sized probe containing a 3/4-inch by 3 inch NaI(Tl) detector, electrical winch, automatic winch controls, and a Scintrex GAD-6 gamma spectrometer. Logging was done stepwise, with stops of 100 seconds every 25 cm as the probe was lowered into the hole. Therefore, for each 200 m hole, eight hundred 100-second spectra were obtained, requiring $\sim$24 hours of continuous on-site operation. Readout of the logging system (depth, total counts, Th, U, K channels) was printed on paper tape. The data will later be keypunched for computation of radioelement contents at Risø. This Scintrex system was considered to be a prototype; future models could easily have provision for magnetic tape readout.

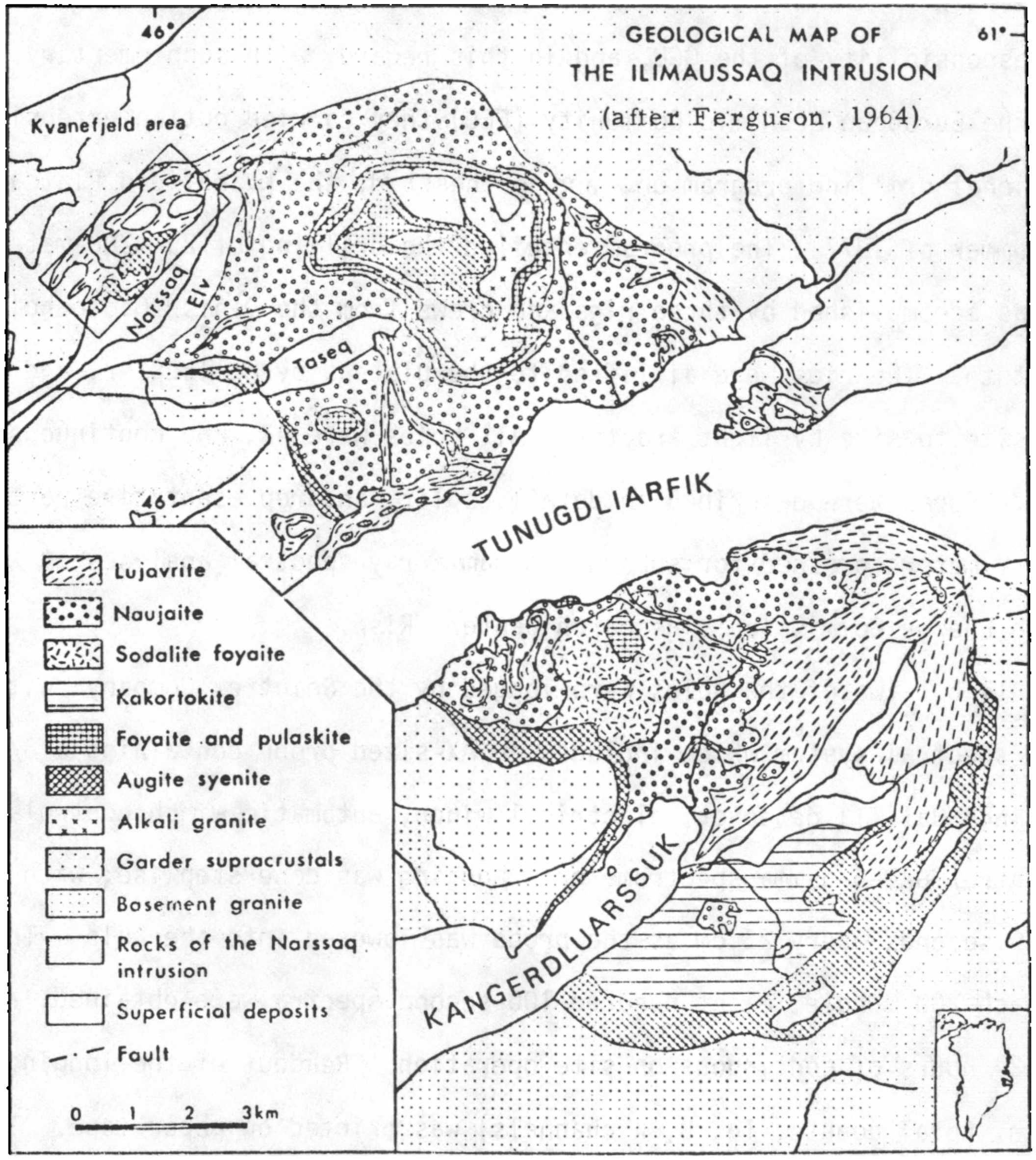

Fig. A.1-2. Simplified geologic map of the Ilímaussaq area, South Greenland, based on Ferguson (1964) and Stewart (1964) with minor corrections. (permission to reproduce granted by the Geological Survey of Greenland) (XBL 782-7168)

Table A.1-1. The major rock types of the Ilímaussaq intrusion (from Sørensen, 1974B, reproduced by permission).

rock type	texture grain size	essential minerals	minerals of interest	U ppm	Th ppm	Th/U
augite syenite	massive, layered, medium to coarse	alkali feldspar, titanaugite		3 (2–4)	8 (5–11)	2.7
sodalite foyaite	massive, coarse	alkali feldspar, nepheline, sodalite, aegirine-augite, arfvedsonite	eudialyte	16 (13–19)	48 (45–53)	3.0
naujaite	poikilitic, coarse	sodalite, alkali feldspar, aegirine, arfvedsonite	eudialyte, rinkite, villiaumite	12 (6–27)	26 (9–35)	2.5
kakortokite	laminated, layered, medium	alkali feldspar, nepheline, arfvedsonite	eudialyte, rinkite	18 (6–29)	45 (9–57)	2.5
lujavrite	laminated, fine	microcline, albite, nepheline, arfvedsonite, aegirine	eudialyte, monazite, lovozerite, steenstrupine, sphalerite, Li-mica, villiaumite	146 (117–1200)	154 (63–5500)	1
lujavrite (m-c)	massive, layered, medium to coarse	microcline, albite, nepheline, arfvedsonite, aegirine	steenstrupine, monazite	400 (50–1550)	890 (200–1100)	2.2

Based on Bondam & Sørensen (1958), H. Sørensen (1962, 1970a), Løvborg *et al.* (1968a, 1971), Gerasimovsky (1969), P. Sørensen (1971), Sass *et al.* (1972).

Table A.1-2. The radioactive minerals and other minerals of economic interest in the Ilímaussaq intrusion (from Sørensen, 1974B, reproduced by permission).

	ppm		weight percent						
	U	Th	Nb_2O_5	Ta_2O_5	ZrO_2	La_2O_3	CeO_2	BeO	Ref.
Steenstrupine (see table 3)* $Na_2Ce(Mn, Nb, Fe)H_2((Si, P)O_4)_3$	2000– 15000	2000– 74000	0.2–4.4	0.04		15–30†			1, 2, 3, 4
Monazite $(La, Ce)PO_4$	138– 12800	300– 57300				36	43		1, 4, 5, 6
Thorite $(Th, U)SiO_4$	31000	405000							2, 4
Britholite $(Na, Ce, Ca)_5 F(SiO_4, PO_4)_3$		6900							4
Eudialyte $(Na, Ca, Ce)_6 Zr(OH, Cl) (Si_3O_9)_2$	50–600	30–340	0.6–1.0	0.06	14	0.5–1.6	1–3.4		1, 4, 5, 7, 8
Epistolite $Na (Nb, Ti) (OH)SiO_4$			32–37	0.2–0.5					4, 8
Lomonosovite $Na_2Mn, Ti_3(SiO_4)_4\ 2Na_3PO_4$									
Lueshite (igdloite) $NaNbO_3$			58–63						4, 8
Murmanite $Na(Ti, Nb) (OH)SiO_4$			0.5–10	0.01–0.1					4, 8
Pyrochlore $(Ca, Na)_2 (Nb, Ta)_2 O_6 (O, OH, F)$	2000	7000	40–61	0.1–3.6					8, 9
Rinkite $(Ca, Na, Ce)_{12} (Ti, Zr)_2Si_7O_{31}H_6F_4$	3000– 12000		2.4		0–6.5	4.5	9.3		3, 4, 8
Chkalovite $Na_2\ Be\ Si_2O_6$								11–13	4, 8, 11
Sorensenite $Na_4Sn\ Be_2Si_6O_{16}\ (OH)_4$								7–8	4, 12
Tugtupite $Na_8Be_2Al_2Si_8O_{24}\ (Cl, S)_2$								5	4, 10, 11
Villiaumite NaF									4, 14

* including hydrosteenstrupine

† expressed as $(Ce, La)_2O_3$

1. Sørensen (1962)
2. Wollenberg (1971)
3. Bøggild (1953)
4. Semenov (1969)
5. Gerasimovsky (1969)
6. New data
7. Hamilton (1964)
8. Hansen (1968)
9. Semenov *et al.* (1968)
10. Sørensen (1960)
11. Engell *et al.* (1971)
12. Semenov *et al.* (1965)
13. Sørensen *et al.* (1971)
14. Bondam & Ferguson (1962)

FIELD GAMMA SURVEYS

Concurrently with the drilling, field gamma spectral surveys were conducted in the lujavrite outcrop area on and northeast of the Kvanefjeld Plateau. The surveys occupied stations spaced at 10 meters on grids encompassing areas as large as .5 by 1 km. Survey equipment comprised a 3x3 NaI(Tl) detector, mounted on a backpack frame, connected to an Exploranium DISA 410 gamma spectrometer. Counting periods were varied according to gamma radioactivity, but usually did not exceed 2 minutes. Spectral data were recorded manually, and Th, U, and K values calculated on a small programmable calculator. Based on earlier field gamma surveys with a collimated detector (Løvborg et al., 1971), it was decided to accomplish this year's survey with the detector elevated above the ground and uncollimated. This would reduce the effect of sharp dishomogeneities in the distribution of radioactive minerals in the predominantly medium-to-coarse-grained lujavrite. Experimentation with positioning of the detector unit on the pack frame showed considerable variation in count rates with detector orientation.

While at Ilímaussaq our visits to the Kvanefjeld Plateau included general orientation, observation of the various mineralizations, and sampling under the guidance of Per Nyegaard, GGU's project chief. We also traversed the northeast mineralized area, where new drill holes and surface gamma spectral measurements suggest the presence of U contents similar to those of the Kvanefjeld.

COMPANION ELEMENTS

As well as containing potentially economic uranium mineralization, the Ilímaussaq also contains significant abundances of companion elements: zirconium, niobium, beryllium, rare earths, zinc, and fluorine. (The Th/U ratio is generally greater than unity.) These elements are concentrated sufficiently in lujavrites of the Kvanefjeld Plateau to make their beneficiation along with uranium an important economic consideration. Contents and tonnages of some of these elements have been estimated by Sørensen et al. (1974):

COMPOUND	MINERALIZATION	CONTENT (%)	TONNAGE*
Nb_2O_5	pyrochlore in veins	0.8	1600
	murmanite in sheared rocks	>0.1	5000
Fluorine	villiaumite (NaF)	>0.5	10000
BeO	chkalovite, sørensite, tugtupite in analcime veins	0.01	
	small areas w/ veins	>0.1	
Zn	sphalerite in lujavrite	~0.2	
Rare Earths	eudialyte, rinkite, monazite in lujavrite	0.6-0.8	
ZrO_2	(see table for kakortokites)		

* metric tons

These elements are also concentrated at several locations away from the Kvanefjeld Plateau. Notable among these are the zirconium-rich kakortokites (eudialyte-rich nepheline syenites) of the southern part of the intrusion, and the beryllium-rich analcime veins of the Taseq Slope. The strongly layered kakortokites are considered to be a cumulate phase which preceded the differentiation and late-stage intrusion of the lujavrites. In a visit to the kakortokite area of the Kangerdluarssuk Fjord, where H. Bohse is completing a detailed study of the geology of the area, we observed and sampled the eudialyte-rich layers, as well as less mineralized agpaitic rocks.

The economic geology of the kakortokites has been described by Bohse et al. (1971), who estimated the following tonnages:

COMPOUND		CONTENT (%)	TONNAGE
ZrO_2	all kakortokites	1.2	52×10^6
	richest unit	4	52×10^3
Nb_2O_5	all kakortokites	.13	5.4×10^6
	richest unit	.42	5.5×10^3

SAMPLES

A purpose of our visit was to sample the various mineralizations and rock types. This was accomplished, and a listing of samples obtained is included below. Selected specimens will be analyzed for radio and trace-element contents.

SAMPLE NUMBER	LOCATION	DESCRIPTION
Il 1	Ilua peninsula	augite syenite
Il 2	"	" w/ MnO_2 (?)
Il 3	Narssaq Elv	Naujaite pegmatite
Il 4	"	Naujaite w/ eudialyte
Il 5	"	Black lujavrite
Il 7	"	Dark banded lujavrite
Il 8	"	Med.-Cse. lujavrite
Il 9	"	"Augen" lujavrite
Il 10	"	Anorthosite (?)
Il 11	Kvanefjeld	Anorthosite

SAMPLE NUMBER	LOCATION	DESCRIPTION
I1 12	Kvanefjeld	Analcime vein w/ pyrochlore
I1 13	"	Med.-cse. arfvedsonite lujavrite w/ steenstrupine
I1 14	"	Sheared gabbro w/ murmanite
I1 15	Kangerdluarssuk	Astrophyllite vein in naujaite
I1 16	"	Aegirine-arfvedsonite pieces
I1 17	"	Ilvaite + epidote
I1 18	"	Black kakortokite
I1 19	"	Red "
I1 20	"	White "
I1 21	"	Aegirine pegmatite
I1 22	"	Fine-grained aegirine lujavrite
I1 23	Taseq slope	Analcime vein w/ Be mineralization
I1 23B	"	Li mica + epistolite in ussingite
I1 24	Kvanefjeld	Sørensenite in lujavrite
I1 25	"	Fine-grained dark lujavrite
I1 26	"	Med.-Cse. green lujavrite
I1 27	"	Naujakasite lujavrite
I1 28	Steenstup area	St.-rich med.-cse. lujavrite

SAMPLE NUMBER	LOCATION	DESCRIPTION
Il 29	Kvanefjeld	Sørensenite w/ tugtupite
Il 30	"	Chkalovite w/ ussingite

FUTURE PLANS

A beneficiation scheme for Kvanefjeld lujavrites has been developed at Risø. A description of the process, obtained on Wollenberg's visit there in March, 1977 is appended to this report. It is possible that, since more material is needed for continued testing, some small-scale mining may take place to provide sufficient tonnage of lujavrite (several thousand tons) to operate a pilot plant in Denmark.

Additional holes may be drilled next year to assess the promising lujavrite area northeast of the Kvanefjeld Plateau.

ADDITIONAL STUDIES

Another visitor to Ilímaussaq during our stay was Ross Aitken, uranium geologist of the EEC, who are partially funding this and next year's South Greenland uranium resource assessments. The program for 1978 is still in the planning stage, but will probably include airborne and surface gamma spectral surveys, as well as geochemical studies of the region on the southwest coast from Frederikshaab on the north, southeast to Cape Farewell. As can be seen on the map, Figure A.1-1, there are several alkaline intrusives within this region besides Ilímaussaq. At least one, the Igaliko, contains nepheline syenites.

Farther north, this summer, GGU conducted field gamma spectral surveys of a carbonatite complex, the Qaqarssuk, near Sukkertoppen. This complex reportedly has a fenitized outer zone with Th contents exceeding 100 ppm. Areas within the Qaqarssuk have previously been sampled and drilled to some extent by the Danish Cryolite Company.

We shall remain in contact with our Danish colleagues to keep informed on their progress at Ilímaussaq and on their plans and conduct of the regional survey.

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STATUS OF THE ILÍMAUSSAQ PROJECT

H. Wollenberg
1 April 1977

Introduction

On my recent visit to Denmark I discussed the Danish South Greenland uranium project with scientists at the Research establishment, Risø, and with geologists at the Greenland Geological Survey (GGU). Interest has renewed in the uranium potential of the Kvanefjeld deposit in the Ilímaussaq peralkaline intrusion, because of the rapid increase in the price of uranium oxide over the past few years, and encouragement of the Danes by the European Economic Community (EEC). What was once considered an occurrence of scientifically interesting minerals is now thought of seriously as a deposit of economic potential. The key to crossing the economic threshold apparently lies in successful solution of the beneficiation of the "ore". Current estimates, based on drilling and logging in 1969 and core analyses in 1970 and '71 are approximately 40 million metric tons of ore containing 300-350 ppm U. (Sørensen et al., 1974). Depending on the success of the beneficiation scheme, as much as 10,000 tons of uranium oxide could be recovered.

Beneficiation Scheme

I had discussions with Emile Sørensen who, along with Torkild Lundgaard and others, has been working on the beneficiation of Kvanefjeld ore for nearly a decade (Asmund et al., 1971). They have recently exhausted, in laboratory and pilot plant studies, a supply of 130 tons of rock of ∿ 500 ppm U, transported to Risø from the Kvanefjeld. The general process, termed sulphating roasting involved the following steps:

1. Crushing to 80% minus 100 mesh. This corresponds to the mean diameter of the steenstrupine and monazite grains and pigmentary zones which contain most of the uranium.

2. Pelletizing for good contact with the gas in the roasting vessel. The waste liquor from the roasting process is used as a binder for the pellets. The pellets are dried at 150°C and are < 9 mm in size.
3. Roasting with hot (550°C) SO_2 gas which becomes SO_3 upon contact with the pellets. The heat of reaction raises the temperature to 700-750°C. Presently, the SO_2 gas is heated electrically; future experiments will attempt SO_2 generation by burning sulfur, with considerable saving of energy expected as well as higher initial temperatures. The pilot operations were conducted in the counter-current mode with the pellets descending against an upward flow of the gas. (It is now considered that better contact will be made if pellets and gas are traveling in the same direction). The resulting pellets contain a salt within which U is soluble. The product liquor, used as a pellet binder, is predominantly sodium sulphate.
4. Extraction is by successive solution of the salt from the pellets by water; ten stages have been used, five are now considered adequate.
5. Recovery of uranium is by solvent extraction with amine (the Oak Ridge Amix process). Zirconium is also extracted with U by the Amix process. Zinc (from sphalerite in the ore) may be recovered by electrolysis. Niobium is difficult to recover because it is in colloidal form; its recovery may be enhanced by agitation to force mixing. It may be possible to recover rare earths from the spent pellets because the RE's are present as slightly soluble sulphates. Fluorine may be recovered before pelletizing because it is primarily associated with the very soluble mineral, villiaumite.

Presently, the mineral economics of the Kvanefjeld are considered marginal. The pilot project achieved ∿ 55% recovery of U. Improvements based on this experience (e.g., parallel flow of gas and pellets, SO_2 directly from burning of sulphur) may raise recovery to 65-70%. It is presently considered that the cost of mine (open pit), plant, and extraction process is of the order of $40-50/lb uranium oxide. It has been concluded that all processing should be done within 1 km of the mine. The next step in beneficiation tests may be the construction of a larger pilot plant (probably in Denmark) treating several hundred tons of representative ore from the Kvanefjeld.

Field Projects in Southwest Greenland

Discussions with Bjarne Leth Nielsen and his colleagues at GGU indicated that a major drilling program will be conducted at the Kvanefjeld this summer. Over 5000 m of continuous-core (AX) holes will be drilled by rigs and crews from the Danish Geotechnical Institute. Gamma-spectral logs will be run in all of the holes by a contractor yet to be chosen. The northeastern portion of the Kvanefjeld plateau, an area of fine- to medium-grained lujavrites, will be drilled. Limited surface gamma-spectrometric surveys, done in the early 70's, suggest that the average grade here may be somewhat greater than the 300-350 ppm U discerned in the previously drilled area to the west. The new drilling may result in a doubling of "reserves". The drilling will be partially funded by the EEC.

Concurrently, studies will begin of the distribution and occurrence of uranium in other promising areas of Southwest Greenland. Field gamma spectrometric surveys will commence this summer in the Qarqarsuk carbonatite, east of Sukkertoppen. A full-scale airbone radiometric and surface geochemical program, covering the area from Sermilik to Cape Farewell will begin (partly under EEC sponsorship) in 1978.

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APPENDIX A.2

TRIP REPORT
Brazil, September 26 - October 9, 1977

H. Wollenberg
20 October 1977

INTRODUCTION

The purpose of the trip to Brazil was to discuss with Brazilian geologists and engineers the occurrence and potential of uranium in peralkaline rocks, and under their guidance, to visit the Poços de Caldas occurrence and other areas considered appropriate. I was joined in Brazil by Mary McNeil, geologist with Bendix Field Engineering Company, who, having lived and worked there for many years, is fluent in Portuguese and has a good understanding of the geologic setting of Brazil.

VISIT TO CNEN

On September 27, we met in Rio de Janiero with Dr. J. R. de Andrade Ramos who is an executive director of the Comissão Nacional de Energia Nuclear (CNEN). Until a few years ago, CNEN was in charge of uranium exploration and development; now a company, NUCLEBRAS has these tasks as well as production of uranium, and CNEN serves a more regulatory role. Dr. Andrade Ramos explained the Brazilian nuclear energy picture to us: a 600 MWe unit will go on-line at Angra dos Reis (on the coast between Rio and Santos) in 1978 (Angra I), followed by two 1300 MWe units over the next few years, resulting in a total of 3200 MWe nuclear at that site by the early '80s. Future plans for electrical production in Brazil envision 180,000 MWe installed, which will include ~3500 MWe nuclear; the predominant source will be hydroelectricity. The Cercado area near Poços de Caldas will be Brazil's first uranium producer, with production of 500 tons per year of yellow-cake expected by 1979, expanding soon thereafter to

∿1000 tons per year. Brazilian U_3O_8 reserves were estimated at ∿30,000 tons, one-third to one-half of which will be from Cercado. Sedimentary deposits of great promise are Figueira and Amorinapolis. (On October 6 a newspaper article announced a new uranium discovery ∿200 km from Fortaleza, in the State of Ceará, estimated at 30,000 tons of U_3O_8, not confirmed by NUCLEBRAS).

In a brief orientation of the geologic setting of Poços de Caldas, Dr. Ramos observed that Landsat imagery showed several ring structures in addition to the large well-known structure, suggesting that there may be other alkaline intrusives in the region. This was later confirmed by the NUCLEBRAS geologists who originally identified these structures.

DISCUSSIONS AT NUCLEBRAS

In the late afternoon of September 27 we met briefly with Dr. J.M.A. Forman, director of mineral production for NUCLEBRAS, and Dr. Mario Fraenkel, chief geologist. We reiterated our interest in visiting Poços de Caldas and other appropriate occurrences, and it was tentatively decided that our visits should also include carbonatite occurrences at Araxá and Catalão. We agreed to meet more extensively the next day with Dr. Fraenkel and some of his staff for orientation and planning our visits.

The orientation meeting on September 29 included Dr. Fraenkel, and Drs. Arturio Garcia and Luis Carlos Surcan. In their inventory of alkaline rocks which may have some potential for uranium production, NUCLEBRAS identified 54 areas. Those of primary interest are in southeast Brazil; their ages range from 54 to 120 million years. The age of Poços de Caldas is midrange, ∿84 million years; however, there are indications that there is a broad age range within the Poços intrusive. Pre-Cambrian alkaline rocks (syenites) have been identified in the states of Arazonas and Pará.

The occurrences of interest to us on this trip, the Poços de Caldas peralkaline intrusive and carbonatite bodies to the north, are located in a north-northwest trending belt transecting the western portion of the state of Minas Gerais into the state of Goiás. (For orientation of the reader, Figure A.2-1, copied from a report in press by Ulbrich and Gomes, shows the distribution of alkaline rocks and carbonatites in southwestern Brazil, and their ages.)

At Poços the ratio of feldspar to feldspathoids is twice that reported for rocks of the Kola Peninsula; this may be due to effects of the deep pervasive weathering at Poços. Rocks containing eudialyte at Poços are generally termed lujavrites by NUCLEBRAS geologists, though eudialyte-astrophyllite-bearing khibinites are also recognized.

Two stages of foyaite have been recognized at Poços: an older stage, gradational with tinguaite; and a younger stage of foyaite in sharp contact with tinguaite. This younger stage has a close relationship with the uranium mineralization. Together with hydrothermally altered "potassic rock" the brecciated contact zones of foyaite/tinguaite appear to have localized mineralization at Cercado. Circular structures in the south-central part of the Poços de Caldas plateau, visible on satellite imagery, appear to be related to the mineralized, hydrothermally altered zone of younger foiyaites/tinguaites.

Deep weathering (as deep as 100-150m) has had a profound effect on mineralization at Poços. A redox zone, progressing downward as laterization proceeded, tended to convert "primary" Zr-Mo-F-U-pyrite ore to a pitchblende "secondary" ore. In the near-surface oxidized zone above the redox front a "tertiary" ore occurs as uranium associated with limonite and clay minerals.

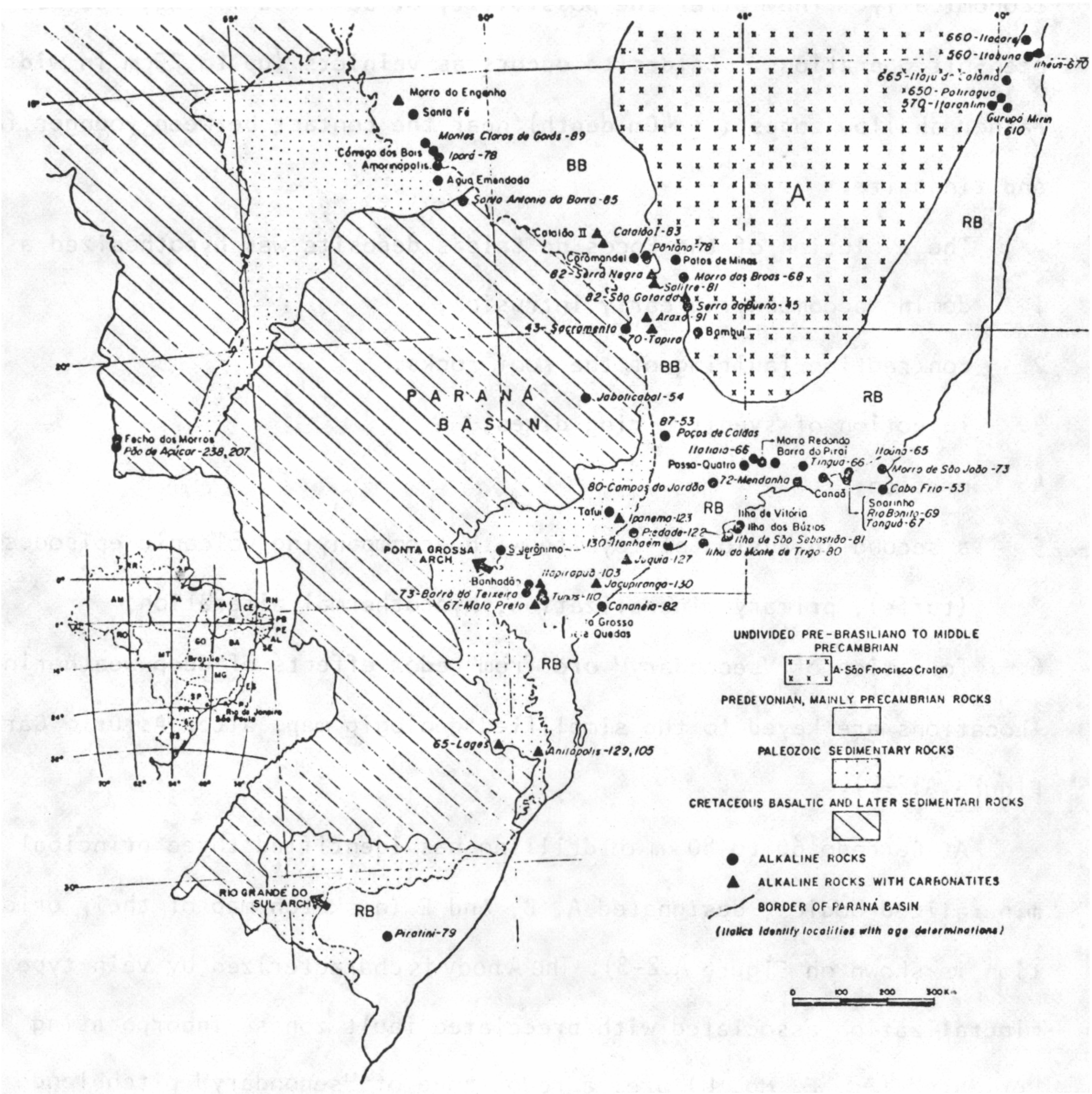


Fig. A.2-1. Location map, alkaline rock occurrences in southeastern Brazil (from Ulbrich and Gomes, in press). (XBL 782-7333)

Caldesite veins (zircon-baddelyite) are presently of less interest economically. They offer the possibility of selected mining, but not large open-pit operations. Caldesite occurs as veinlets (up to 25cm in width) in rather shallow zones (< 40m depth) near the contact between younger foyaite and tinguaite.

The evolution of the Poços de Caldas deposits was hypothesized as:

1. doming accompanying early intrusion,
2. contraction-faulting of the roof rocks,
3. injection of syenitic ring dikes,
4. erosion,
5. a second intrusion of foyaite with accompanying volcanic episodes (tuffs), primary mineralization, hydrothermal alteration,
6. formation of "secondary" ore from redox effects of deep weathering.

(Locations are keyed to the simplified geologic map, after Asturio Garcia, Figure A.2-2).

At Cercado 60 to 80 km of drilling has identified three principal mineralized bodies, designated A, B, and E (a sketch map of their orientation is shown on Figure A.2-3). The A body is characterized by vein-type mineralization associated with brecciated fault zones, incorporating "primary" (Zr, F, Mo, U) ore, a redox zone of "secondary" pitchblende ore, and some "tertiary" near-surface mineralization. B body is a lense-shaped mass of primary-type ore below the redox zone. Mineralization is most intense in the vicinity of faults which cut B body. E body contains essentially only "secondary" pitchblende ore. The A body is most similar to mineralization at Agostinho, an area near the center of the Poços intrusive, earlier considered of high uranium potential. In all three bodies it appears

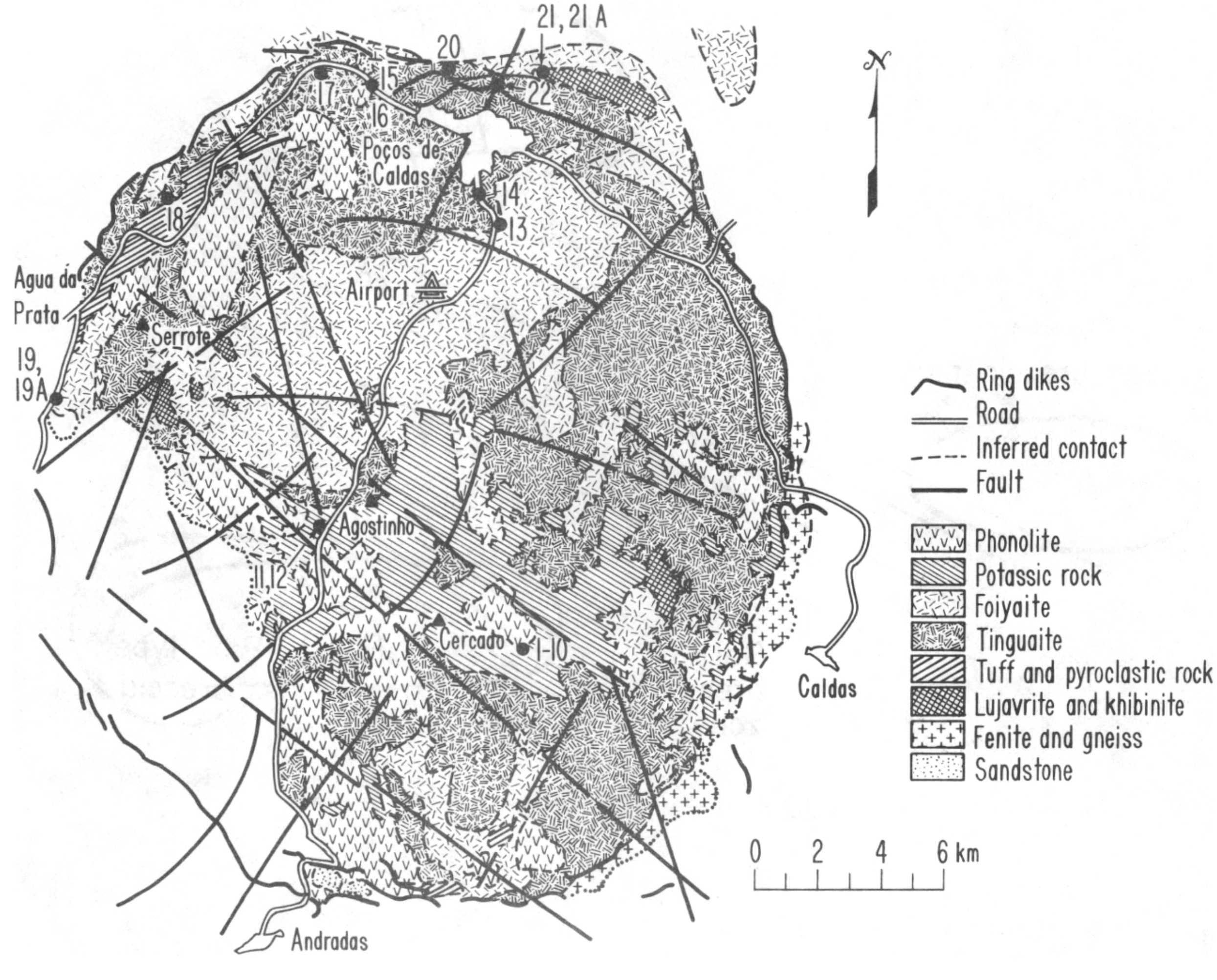


Fig. A.2-2. Geologic map, Poços de Caldas intrusion (after Asturio Garcia). (XBL 7710-2147)

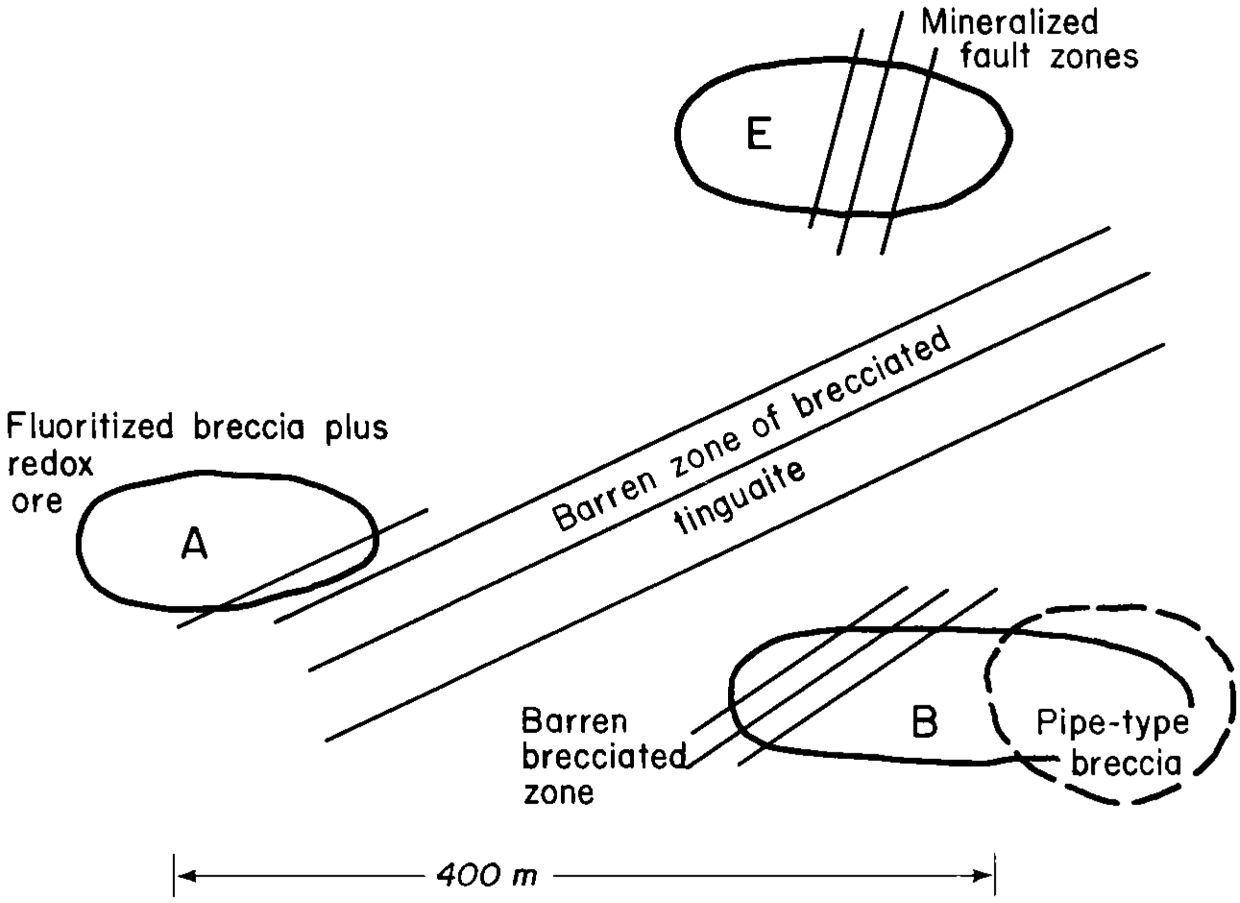


Fig. A.2-3 Schematic plan of Utsumi mine mineralized areas. (XBL 783-409).

that the richest mineralization was achieved through a combination of intensive faulting and brecciation, hydrothermal alteration and deep weathering. The intense alteration has enhanced the propensity for deep weathering in this area.

Speculations on the origin of mineralization included the lujavrites as possible sources of the fluids. Though lujavrites have not been encountered in the surface or subsurface in the Cercado area, they are the latest differentiates of the intrusive, and a late lujavritic phase may have furnished the fluids for hydrothermal alteration and mineralization.

In both the A and B bodies there appears to be a zonation of thorium, uranium and iron in the primary ore. The thorium/uranium ratio is higher in the ore at greater depths. There is not as much molybdenum at Cercado as at Agostinho. The ore mineral most important at Ilímaussaq, steenstrupine, is absent at Poços and has not been noted at any other place in Brazil. Eudialyte, however, is common to both localities.

VISIT TO POÇOS DE CALDAS

On September 30 we traveled by air from Rio de Janeiro to Poços de Caldas, and on October 1 were escorted to the Cercado area by Dr. Asturio Garcia. En route to the mine Asturio pointed out the deep weathering in roadcuts, and stated that with some practice, one can identify rocks types by their weathered surface manifestations.

The mine, where overburden stripping is presently under way, is named after Osamu Utsumi, the prominent geologist who recently lost his life in an auto accident in the Poços area. At the mine, orientation and guidance were provided by Asturio, Renato Camargo dos Santos and Armando de Conceicão, all of whom provided valuable detailed information on the mine area.

In the E block the redox front is at a depth of ~120m. Mineralization, predominantly pitchblende, is up to 20m thick. Some mineralization occurs near-surface in the oxidized zone where uranium is associated with limonite and clay minerals. Uranium ore, associated with molybdenum, occurs in lens-like bodies in both the oxidized and reduced zones in B block. The ore is restricted to hydrothermally altered zones above the foyaite. Ore also occurs with fluoritized breccia in B, the upper part of the breccia "pipe" is in tinguaite, the lower portion in foyaite. The presence of pyrite (a reducing environment) delayed progress of the oxidizing front. Mineralization in A block is a mixture of B and E block conditions.

We inspected cores of:

1. altered older foyaite,
2. fresher younger foyaite,
3. altered and fresh tinguaite,
4. mineralization associated with:
    a. brecciated tinguaite (uranium-fluorite)
    b. contact between lamprophyre and fresh tinguaite
    c. vein breccia with abundant fluorite and pyrite.

In B-block uranium mineralization associated with colloidal pyrite, and green and purple fluorite in brecciated tuff, was observed underground by Renato Camargo in a zone over 50m wide.

Molybdenum mineralization predominates in A block. Uranium is more associated with tinguaite than with the younger foyaite; foyaite fragments predominate in the breccias.

Six types of mineralization have been recognized at Cercado:

1. nodules associated with fault zones;
2. softer nodules associated with redox fronts;
3. in A block: molybdenum, fluorite, uranium mineralization in the matrix of brecciated tinguaite;
4. near-surface oxide ore associated with limonite and clays (E block);
5. uranium-fluorite in brecciated zones in B block;
6. mineralization of tuffaceous material in B block.

Rock types encountered in the mine area include:

1. tinguaitic tuff;
2. younger foyaite;
3. older foyaite;
4. khibinitic foyaite (some eudialyte);
5. dark and light breccias;
6. barren leucite tinguaite;
7. lamprophyre;
8. altered tinguaite;
9. re-worked foyaite (foyaite breccia fragments in a foyaite matrix).

Mining operations at Cercado will involve a single open-pit which will encompass the A, B, and E bodies. The pit will ultimately be ~800m in diameter and as deep as 300m. Approximately $10^8 m^3$ of material will eventually be removed, over a 10 to 12-year period.

Armando de Conceicão briefly described the planned beneficiation process for the ore:

1. acid leaching (H_2SO_4)
2. intermediate step incorporating pelletizing;

3. solvent extraction with amrine (amix process?);
4. addition of NaCl, then precipitation with ammonia;
5. stripping of precipitate with $NaCO_3$;

It is expected to achieve 90% recovery of U_3O_8 from E-body ore; 100kg of H_2SO_4 per ton of ore will be consumed. Recovery of 65 to 70% is expected for B-body ore; approximately 1.5 times the H_2SO_4 for E will be required to treat the B ore.

As to foreign cooperation, a French company, PUK, was contracted at Poços de Caldas to develop the plans for a mill based on the process developed by NUCLEBRAS. The detailed engineering is being done by Brazilian companies. Brazilian-German cooperation is only on specific areas authorized by NUCLEBRAS, so that no interference of work occurs. A company called NUCLAM has been formed with Urangesellschaft as the German partner.

Following the orientation at the mine office we visited a stock pile area where we collected several samples of mineralized material (see list of samples, Table A.2-1). We then inspected an area being stripped of overburden, and en route back to Poços collected some samples of fresh and weathered nonmineralized material from roadcuts. (Sample locations are shown on the accompanying map, Figure A.2-2.)

On October 2, Asturio conducted us on a tour of the general Poços de Caldas region, where several samples were collected of weathered and fresh material from the intrusive and the rocks which border it; locations are shown on Figure A.2-2 and brief descriptions on Table A.2-1.

Of special interest was the area northeast of the city of Poços de Caldas where lujavrite crops out on the high ridge forming the northern border of the intrusion (locations 21, 21A on Figure A.2-2). Here samples

TABLE A.2-1

SAMPLES, POCOS DE CALDAS AREA

	Sample	Description
Utsumi Mine area	PC 1	phenocrysts of pseudoleucite from tinguaite
	PC 2	molybdenum-rich, uranium-fluorite ore, typical black material from A block
	PC 3	hydrothermally altered tinguaite
	PC 4	weathered black breccia matrix from oxidized zone
	PC 5	typical hydrothermally altered potassic rock
	PC 6	enzemonite (molybdenum oxide)
	PC 7	redox front material
	PC 8	foyaite
	PC 9	black breccia with foyaite
	PC 10	near-surface material with limonite, clay, some uranium, and secondary pyrite
	PC 11	weathered water-laid alkalic tuff; roadcut
	PC 12	weathered phonolite, margin of tuff basin; roadcut
	PC 13	"old" foyaite; roadcut
	PC 14	fine-grained tinguaite, transitional from/to foyaite
	PC 15	Botucatu sandstone; quarry on São Paulo Highway
	PC 15A	reddish tuff; same quarry
	PC 16	Botucatu quartzite, fresh, in contact with "granitized" quartzite; roadcut, across creek from Campo do Osorio
	PC 17	Bluish fresh tinguaite and bauxite from C. B. A. bauxite mine; typical bauxite occurrence of "field type"
	PC 18	strongly brecciated volcanic bombs, volcanic sequence in roadcut, São Paulo Highway
	PC 19	(M. M. sample) Rio de Rasto sandstone, reddish, fine-grained, abundant concretions, underlies Botucatu ss; Aguas de Prata
	PC 19A	Botucatu ss; overhanging face in Aguas de Prata
	PC 20	bauxite, typical of mountain occurrence; white, reddish, yellow, often coating fresh tinguaite; Mina Serra
	PC 21	fresh lujavrite; eudialyte, aegirine, feldspar-analcime, strongly foliated; Pedro Balão
	PC 21A	khibinite?, coarse, lujavritic, some astrophyllite; Pedro Balão
	PC 22	brecciated foiyaite, brecciated tinguaite with inclusion of foyaite; road from Pedra Balão to Poços de Caldas.

TABLE A.1-1
(continued)

SAMPLES TO BE SENT BY ASTURIO FROM POÇOS DE CALDAS AREA	
1.	young foyaite, Agostinho
2.	tinguaite
3.	two samples of old foyaite from airport massif
4.	tinguaite from southeast part of Poços de Caldas plateau
5.	khibinite and lujavrite from southeast area
6.	foyaite from northwest contact zone
7.	tinguaite from road to C. B. A. workings above Poços de Caldas
8.	khibinite from Pedro Balão
9.	foyaite from Pedro Balão

were obtained of strongly foliated lujavrite and khibinite, the rocks most similar to those observed and sampled at Ilímaussaq.

Discussions at a later stage of this trip (October 7) with Prof. H. P. Ulbrich at the University of São Paulo, clarified the geologic setting of the lujavrite area. In detailed mapping, Ulbrich has identified a strongly layered sequence in this area, with a central zone of coarse lujavrite surrounded concentrically by the succession: fine-grained lujavrite, medium to coarse nepheline syenite, coarse nepheline syenite with < 10% mafic minerals, khibinite with coarse eudialyte. Asturio stated that three drill holes in this area penetrated through these rocks within a few hundred meters, suggesting that it is a shallow-layered sequence.

VISIT TO CATALÃO

On October 3 we traveled by bus (a 16-hour trip) from Poços de Caldas to Goiania, the capital of the state of Goiás. The next day we met briefly with the NUCLEBRAS representative in Goiania, Dr. Paulo Miranda Figueiredo, who arranged for us to meet with personnel of METAGO, the mining company of the state of Goiás which operates the phosphate workings at the Catalão carbonatite occurrence. Dr. Paulo Lobo of METAGO arranged for our immediate air transportation to Catalão where we were met by Engineer João Carlos Kasbergen, our guide.

Kasbergen explained that the principal commodity at their mine was phosphate, but that pilot plant operations were under way for recovery of titanium and vermiculite. Another company, BRASIMET, also produces phosphate from Catalão, as well as niobium concentrate from pyrochlore. NUCLEBRAS have tested the uranium content of METAGO mill products and found that ~35% of the uranium was in the slimes fraction of the process, ~15% in the phosphate concentrate (apatite). Therefore, apatite at Catalão, the principal constituent of the phosphate concentrate, does not appear to be highly enriched in uranium.

The geologic setting of Catalão was discerned with the aid of a well-colored geologic map. The carbonatite with its accompanying mineralization is of upper Cretaceous age (~83 million years). The eastern border of the roughly circular carbonatite body is predominately fenitized quartzite; fenitization decreases in the pre-Cambrian country rocks out from the border. Faults, perhaps associated with emplacement of the carbonatite and doming of the country rocks, radiate out from the central area of the carbonatite body into the country rock. This pattern is superimposed on the regional northwest-southeast grain in the pre-Cambrian rocks. An east-west fault in the eastern portion of the body is strongly mineralized with rare-earth elements; one drill hole in the area penetrated silexite with > 20% rare earths. Highest concentrations of phosphate occur in an arc through the north and east portions of the body. Vermiculite is concentrated on the east side, niobium in the east-center, titanium mineralization in an arc from east to southeast.

Within ~10km of this carbonatite is another body, Catalão II, under exploration for niobium by the mining company, CBMM, the operators at Araxá.

Weathering is intensive at Catalão; depth varies from ~10m near the borders to 250m in the center of the topographic basin formed by the carbonatite within its ring of quartzite. All mining is of essentially weathered lateritic material.

The scheme of exploration followed at Catalão included:

1. airborne and ground magnetometric surveys;
2. drilling, with geochemical analyses for special elements: niobium, thallium, lanthanum, cerium, yttrium;
3. detailed drilling on ~100m spacing.

Drilling has encompassed 20-25 km over the past eight years.

A ground radiometric survey indicated that highest values (> 1000c/sec) were associated with a titanium and magnetite-rich area (possibly thorium associated with iron and titanium as at Morro de Ferro near Poços de Caldas). Titanium mineralization includes anatase, ilmenite, goethite, and magnetite. The principal rare-earth mineral is monazite.

On October 5, we examined and sampled some of the benches in the Catalão mine; samples are listed on Table A.2-2.

In the present beneficiation scheme, 75% of the apatite is recovered. Raw material input is ~250 tons/day, producing ~55 tons/day of apatite concentrate. The deposit is estimated to encompass 250 x 10^6 tons, 175 x 10^6 tons are considered recoverable.

TABLE A.2-2

SAMPLES, CATALÃO AREA

Sample	Description
CA 1	silexite, pieces from Bench #1 in phosphate mine
CA 2	apatite, magnetite, SiO_2; Bench #2
CA 1A	silexite from Bench #2
CA 3	iron "canga" from laterite, predominately hematite
CA 4	weathered fenitized quartzite; phosphate mill area
CA 5	vermiculite and magnetite; working face
CA 6	anatase, magnetite, ilmenite, leucoshine; titanium test piles
CA 7	silexite with hydrated monazite; outcrops above old test gallery
CA 8	piece of fresh carbonatite core

VISIT TO ARAXÁ

On the afternoon of October 5, we traveled by car from Catalão via Uberlandia to Araxá. We arrived in the early evening at the Grande Hotel de Araxá, a massive spa and casino, built around warm springs near the town of Barreiro in the 1940's. Unfortunately gambling was prohibited in Brazil soon after construction, so only the health-giving aspects of Araxá remain its chief attraction.

As at Catalão, the Araxá carbonatite (predominately dolomite) is deeply weathered. The topographic configuration of the body is that of a nearly circular basin of ~6 km in diameter. The upper slopes of the basin are mined open-cut for niobium and phosphate. A zone of fenitized quartzite borders the carbonatite body.

We were met at Araxá by our guide, Dr. Mauro Marchetto, Chief geologist for Compania Brasileira de Metalurgia e Mineração (CBBM). The company is owned jointly by U. S. (International Minerals, Molycorp) and Brazilian interests. The principal niobium mineral is pandaite (barium-pyrochlore). The Wah-Chang Corp. has been working for many years on a process to recover uranium from pyrochlore, without apparent success. CBMM are not mining apatite at Araxá, another large fertilizer company operates those workings. However, CBMM investigates other carbonatites for their phosphate as well as niobium potential (as at the aforementioned carbonatite, Catalão II). The Araxá mine, producing ~700,000 tons/year, furnishes 65% of the world's niobium.

In exploring for carbonatites Marchetto relies heavily on regional aeromagnetic surveys. The magnetic maps of this region of Brazil show strong northwest-southeast lineations, paralleling the structural grain.

Carbonatite bodies are characterized by circular magnetic highs. Aeroradiometric surveys also disclose carbonatites by their high radioactivity. In this respect, uranium and thorium are considered "pathfinder" elements for niobium in carbonatites.

In the roughly circular Araxá carbonatite, the niobium mineralization is concentrated in the east-center, the phosphates in the northwest quadrant. Highest overall grade of Nb_2O_5 is in the deeply weathered zone where pandaite is rather homogeneously distributed. Pyrochlore occurs in veins and stringers in the fresh carbonatite rock (50-90% $CaCO_3$) and this material is not considered of ore grade. The relatively high grade in the lateritic material is attributed to removal of the carbonate by leaching, effectively concentrating resistate minerals.

Marchetto explained that factors for a successful niobium deposit are then:

1. prolonged deep weathering;
2. a border zone of quartzite which retains the circular mass of weathered material, inhibiting transport of resistates from the basin;
3. mineralogy of the primary rock: the 10-20% pyrite content produces acid fluids which attack the carbonate but not the niobium minerals.

The uranium mineralization is associated with the structure of the pyrochlore-pandaite; therefore uranium is retained in the acid environment. Uranium associated with apatite is more mobile, but is retained to some extent in secondary minerals, including monazite in the weathered phosphate zone. The uranium content varies roughly with niobium at Araxá, but the overall concentration in the weathered deposit is of the order of 100 ppm. An apatite concentrate (Nb_2O_5 0.4%, P_2O_5 36%, Fe_2O_3 3.5%) assayed at ~ 420 ppm uranium.

The niobium ore consists of 50% magnetite, 20% barite, and 5% pyrochlore; the thorium content of the pyrochlore is ~ 2%. Two products are presently produced by CBMM at Araxá: niobium concentrate and ferro-niobium metal. Approximately 80% of the concentrate is used to produce the metal, 20% is shipped as concentrate. The slag from the metal production contains concentrated thorium and uranium (several hundred ppm uranium); it is presently stockpiled for future beneficiation.

We visited the working benches as well as the surrounding area where samples of various materials were obtained (including stockpiled uranium-thorium-rich slag). Samples are listed and briefly described on Table A.2-3 The depth to fresh carbonatite is ~120m below the present benches, but reaches ~300m elsewhere. The ore grade is maintained throughout the entire thickness of the weathered zone.

TABLE A.2-3

SAMPLES, ARAXÁ AREA

Sample	Description
AX 1	carbonatite (dolomite); outcrop Andrade Jr. Fountain
AX 2	quartzite with bluish riebeckite on surfaces
AX 3	weathered dike in Araxá schist
AX 4	uranium-thorium rich slag from mill
AX 5	pandaite (barium-pyrochlore), with monazite (green), magnetite-hematite (black); working bench
AX 5A	barite
AX 6	silexite with barite and goethite; from mine area
AX 7	possible primary pyrochlore; float, Baritina Creek
AX 8	sample of ferroniobium product
AX 9	sample of pyrochlore concentrate

In visiting the working benches we saw the principal subsurface exploration method used by CBMM: test shafts, hand dug to a depth of 45m. They are rectangular in cross section, 80 x 90cm. A channel sample is obtained from each meter along one wall of the shaft. We viewed a shaft digging crew at work, one man in the hole, one operating the winch and bucket, and three resting between turns at digging. Marchetto explained that this method of exploration in lateritic terrain is cheaper than conventional drilling. The homogeneous nature of the laterite provides excellent sidewall support, and exploration shaft digging has been essentially accident-free over the years for the company.

On the afternoon of October 6, I traveled via car to Uberaba, then commercial plane to São Paulo. On October 7 I visited Prof. Ulbrich at the University of São Paulo where we discussed his detailed study of the geology of the Poços de Caldas area (mentioned earlier in that section of this report). Ulbrich also kindly gave me a preprint of a paper by him and C. B. Gomes: "Alkaline Rocks from Continental Brazil: A Review" submitted to Earth-Science Reviews.

On October 8 I departed São Paulo for the United States, arriving in San Francisco at ~1 a.m. on October 9.

CONCLUSIONS AND SPECULATIONS

1. There is strong regionalization of peralkaline-carbonatite occurrences in Brazil. Prominently mineralized bodies are aligned on the NW-SE Minas Gerais-Goiás belt. Occurrences may be localized at intersections of this trend with NE-SW structures.

2. The effects of deep weathering have enhanced the mineralizations at the sites visited. At Araxá, niobium was "upgraded" in the weathered zone over concentrations in fresh carbonatite. At Poços de Caldas the preferential deep weathering in hydrothermally altered rock helped to enhance the concentration of uranium at the intersection of the redox front and areas of primary mineralization.

3. Two of the important mineralized bodies contain warm spring activity, suggesting that present-day hydrothermal systems are in operation. At Poços de Caldas the thermal springs (45°C) are several kilometers north of the uranium mineralized area; however, strong alteration of the peralkaline rocks at Cercado indicates the presence of hydrothermal activity concurrent with or following emplacement of the "primary" ore. Thermal spring activity (34°C) at Araxá is located near the northern border of the carbonatite, a few kilometers north of the zone of intense niobium mineralization. Assuming that the present-day thermal spring activity indicates deep circulation of meteoric water, one can speculate that rare elements are being dissolved, remobilized and concentrated at depth in "new" hydrothermal deposits. It is significant that the thermal waters at Poços de Caldas and Araxá are noted for their higher than normal radioactivity, due to the presence of the uranium daughters radium and radon, indicating the presence at depth of their parent ^{230}U.

APPENDIX A.3

TRIP REPORT—COLORADO ROCKY MOUNTAINS

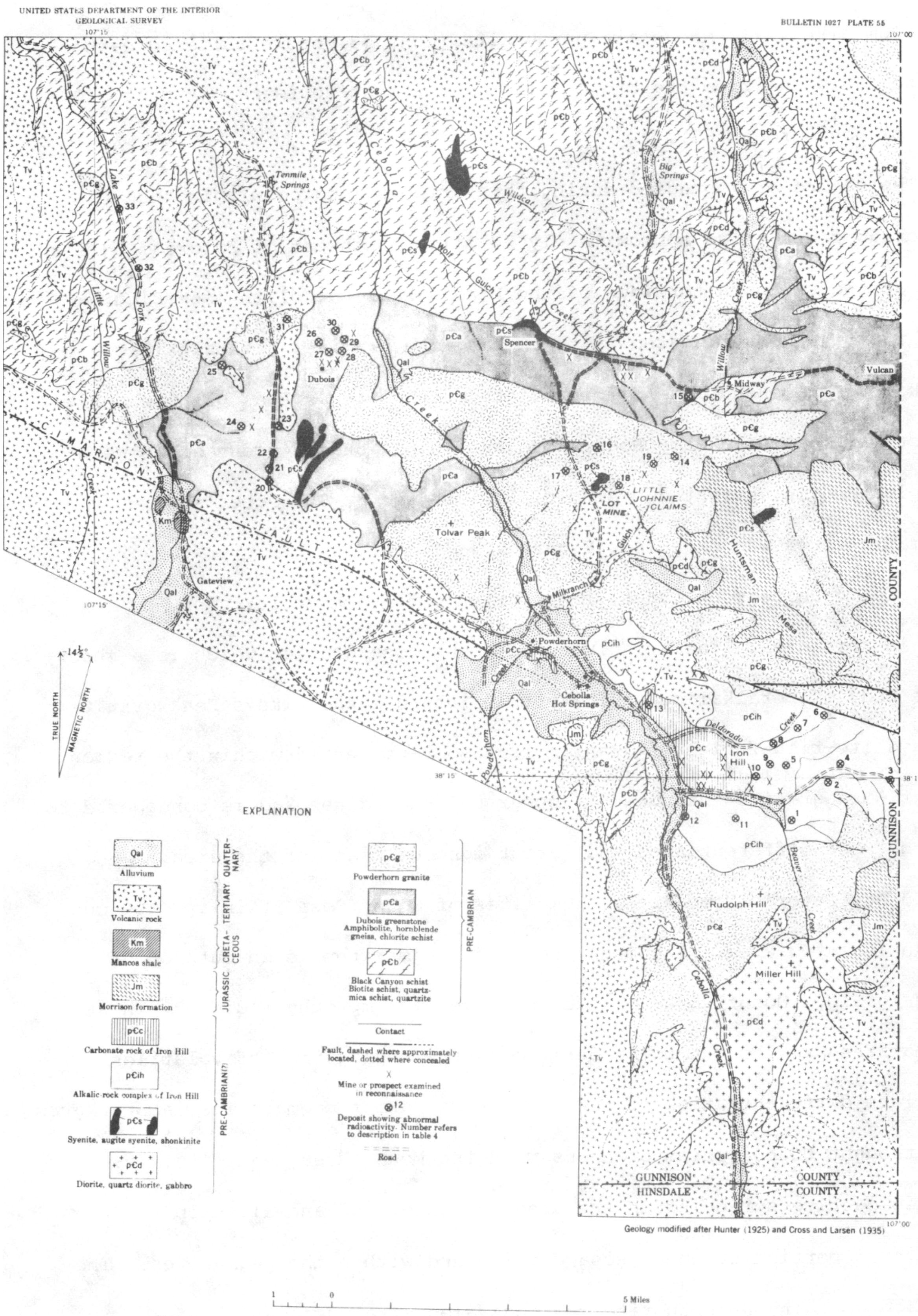
(M. T. Murphy)
(13 October, 1977)

This report details the activities of LBL staff member Mark Murphy during a five-day field orientation to two Colorado alkaline rock complexes. While field samples were collected, and a brief summary of the samples is included, the purpose of the visit was primarily to acquaint the participant to various common features of U.S. alkaline occurrences.

Two areas of vastly different peralkaline character were visited. The Powderhorn carbonatite complex is a pear shaped multi-alkaline rock occurrence located in Gunnison County, west-central Colorado (see Fig.A.3-1). It is Precambrian. The complex is made up primarily of alkaline pyroxenite in a ring structure which surrounds a bisected carbonatite plug. Other exotic alkaline rock types dot the area in isolated pods and patches. These rocks include biotite pyroxenite, magnetite-perovskite rock, ijolite (nepheline pyroxene rock), uncompahgrite (melilite-pyroxene rock), and nepheline syenite. The complex intrudes the Precambrian Powderhorn granite and is mantled by a fenite zone (the soda syenite in Figure A.3-1).

The complex is cut by a NW-SE trending normal fault, an extension of the Cimmeron fault which exposes two levels of vertical structure. Carbonatite and thorium rock dikes and veins cut both the complex itself and the surrounding area.

The primary uranium bearing members of the complex are: (1) external



Geology modified after Hunter (1925) and Cross and Larsen (1935)

Fig. A.3-1. Geologic map of the Powderhorn-Iron Hill area, Colorado (from Olsen, et al., 1956). (XBL 782-7172) thorium dikes, (2) magnetite-perovskite rock, (3) brown foliated carbonitite. Uranium from the brown foliated carbonatite is reported at 0.02% U. (Temple and Grogan 65).

The second area studied during this trip is located within the Colorado front range approximately 20 miles southwest of Colorado Springs and at the southern terminus of the Pike's Peak batholith (see Figure A.3-2). The rock type investigated is the Mount Rosa granite, a peralkaline riebeckite granite and late differentiate of the Pike's Peak granite series. Outcrops along Gold Camp Road, Rosemont Road, and adjacent areas were sampled and investigated. A special visit to the St. Peter's Dome pegmatite area was made (see Figure A.3-2).

Three granite rock types, Precambrian and co-magmatic, crop out in this area. These include the Mount Rosa granite which is a sheet-like body of peralkaline affinity that intrudes the Pike's Peak granite. A fayalite-rich facies of granite is also represented within the region. Mount Rosa granite intrudes all other units as dikes and is considered to be the most differentiated and latest igneous phase of the area.

In St. Peter's Dome area, pegmatites of Mount Rosa affinity crop out in an isolated area. Accompanying these pegmatites is an outcrop of finer grained Mount Rosa granite and several lamprophyre dikes. These pegmatites are thought to be derived by the segregation of volatiles and late differentiation of the Mount Rosa parent magma. The lamprophyres are thought to be contemporaneous with the Mount Rosa pegmatite.

Radioactive surveying in the area has uncovered anomalies in a weathered portion of Mount Rosa granite and within the pegmatites. The granite contains uranothorite coatings along fractures and grain

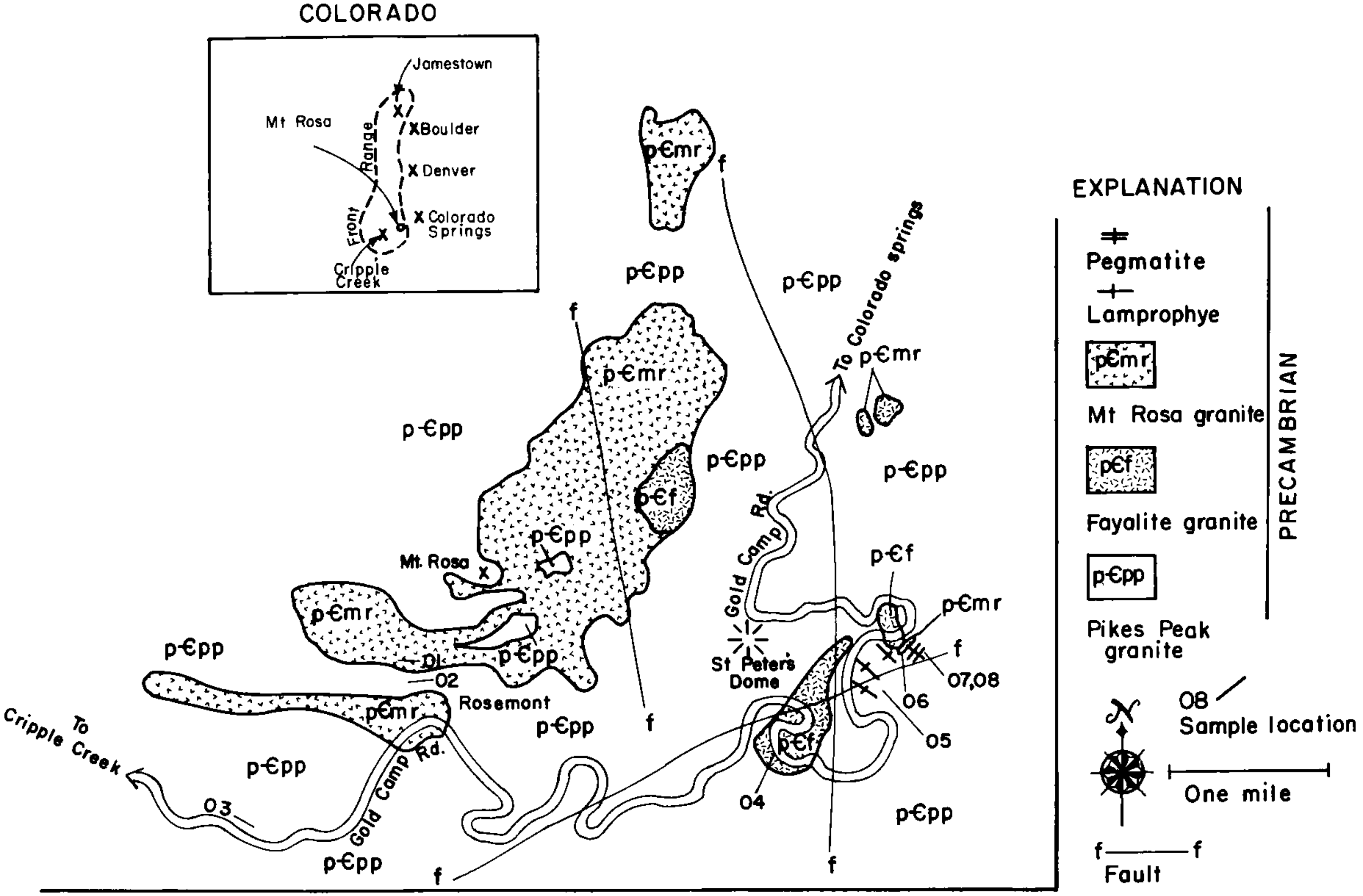


Fig. A.3-2. Geologic map of the Mt. Rosa area, Colorado (after Gross and Heinrich, 1965). (XBL 782-199)

XBL782-199

boundaries. Thorogummite, uranium opal and uranophane has also been found. In the pegmatites the radioactive minerals thorite and fluorite are found. Rutile, zircon, pyrochlore, and microlite have also been identified. No chemical results are available but thorium/uranium ratios are greater than one throughout the area. (Gross & Heinrich 1965, 1966A, 1966B).

Attempts were made to visit all appropriate sites in both localities during the Colorado trip. On September 27, Murphy was taken by William Short and William Bird of Bendix Field Engineering Corporation to the Powderhorn complex and oriented to the general type and distribution of alkaline rocks. Murphy returned to the complex and further sampled and observed the rocks. Samples were collected from the brown foliated carbonatite and the magnetite-perovskite rock.

Another day was spent at the Mount Rosa area. The contact between the Mount Rosa granite and the Pike's Peak granite on Rosemont Road was observed. Representative samples were taken. The fayalite facies was also visited. At the St. Peter's Dome area sampling and field observation was made of the three rock types above plus the Mt. Rosa pegmatite and the lamprophyre dikes. Large riebeckite crystals within a microcline/ quartz matrix served to distinguish these unusual pegmatites. The investigation was somewhat hampered by poor exposure and the lateness of the hour.

The samples and photographs were brought to Berkeley and await laboratory investigations as deemed appropriate. A sample description follows.

SAMPLE DESCRIPTIONS

(See Figures A.3-1,2)

POWDERHORN COMPLEX		
POW 7701	Uncompahgrite	graphic intergrowth of aegerine-augite and melilite; minor biotite, hematite, perovskite
POW 7702	Ijolite	coarse-grained crystals of pyroxene and nepheline clots; zeolites, magnetite, biotite
POW 7703	Brown biotite-rich foliated carbonatite	foliation vertical and weathers out; x-cut by calcite veins; biotite, garnet; gneissic foliation
POW 7704	Brown foliated carbonatite	white calcite veins perpendicular to foliation; like 03 but less biotite, more homogenous
POW 7705	White massive carbonatite	coarsely crystalline dolomite rhombs; clots of magnetite, siderite and goethite; apparently a dike
POW 7706	pyroxenite fault breccia-green	green pyroxene, garnet, f'spar, pyrite, veins of nepheline and CO_2 mineral
POW 7707	pyroxenite fault breccia-black	black pyroxene, magnetite, biotite, nepheline; nepheline syenite dikes
POW 7708	nepheline syenite, coarse grained	highly weathered, pinkish red; f'spar laths, greasy-looking nepheline, px, mag
POW 7709	nepheline syenite, fine grained	same as 09 70% f'spar
POW 7710	magnetite-perovskite rock (?)	very dense; mostly mag w/brownish perovskite; pod-like occurrence
POW 7712	aptite, Powderhorn granite	fine grained, sugary-white

MT. ROSA COMPLEX

MRA 7701	Mt. Rosa granite	light grey, med. grained, equigran.; riebeckite,fspar, qtz, bio, astrophyllite sample 1-2 from Pike's Peak granite contact
MRA 7702	Pike's Peak granite bleached zone	pinkish, fine-grained equigranular, bleached zone shows loss of mafics
MRA 7703	Pike's Peak granite coarse grained	equigranular perthite, biotite, qtz albite; taken from interior of intrusion
MRA 7704	Fayalite-rich facies of Pike's Peak granite	greenish-grey coarse grained f'sprs biotite, greenish qtz
MRA 7705	Lamprophyre dike	dark grey, very fine-grained, scattered f'spar laths; dike approx. 2m. wide
MRA 7706	Mt. Rosa granite	highly leucocratic but similar to previous Mt. Rosa granite; qtz veins
MRA 7708	Mt. Rosa pegmatite	huge crystals of riebeckite, qtz,and microcline; qtz zones at core

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APPENDIX B

Analytical Data

The rock samples analyzed came from specimens collected by H. Wollenberg on field trips to Poços de Caldas, Brazil, and Ilímaussaq, Greenland, as well as from the University of California collections of J. Bushee (Poços de Caldas), R.W. Hodder (Nemegos, Ontario), Collection #201, (Arkansas intrusives), and A. Lawson (Montreal, Quebec).

Analytic methods used were neutron activation analysis for more than 24 trace elements and X-ray fluorescence for the major elements as well as for Nb, Zr, and Sr.

Overall Accuracies

There are three independent categories of errors pertinent to these results:

(1) errors in field sampling,
(2) sample preparation,
(3) analytical errors.

Most of the samples are hand-specimens; the field sampling errors, therefore, cannot, in general, be evaluated.

Sample preparation errors may be introduced as the result of large grain size and non-uniform grain distribution in the specimen.

The analytical errors depend on the analytical procedure and are as follows:

(1) Neutron Activation Analysis

This method is capable of determining over 2 dozen elements with precisions of less than 5%, in unaltered extrusive or sedimentary rocks. The rather high concentration of heavy elements in the present samples increases these uncertainties considerably. Each element is effected differently, but we estimate that the errors could be as high as 10% in many of the samples.

(2) Major Element Analysis

The low-energy X-ray fluorescence analytical data are also affected by the higher concentration of heavy elements, but not as much as are the neutron activation data. We estimate that this effect is less than 2% on the average for the present samples.

(3) X-ray Fluorescence Analysis for NB, Zr and Sr

These analyses were made in two separate runs. For samples 41 through 56, we estimate the accuracies in these elements to be about 10%; accuracies are of the order of 20% for the remainder of the samples.

Results

Tables B.1-6 list the concentrations of major oxides in percent, elemental concentrations in ppm. Each table is arranged with samples in order of decreasing concentration of uranium. Where there is no data for a specific element, a dash indicates that an analysis is yet to be made.

A brief description of each sample is on the facing page to the appropriate table which lists the analytical results for that sample.

Table B-7 summarizes the mean concentration and range for 11 nepheline syenite samples from Poços de Caldas, Brazil; Nemegos, Ontario; and Magnet Cove, Arkansas. For rock specimens collected from three different alkaline intrusives in widely separated geographic areas, the ranges are remarkably small. The major-oxide contents and agpaitic ratios of the nine Poços de Caldas nepheline syenites are similar to those of Magnet Cove and Nemegos.

Mean values of lujavrites from Greenland (2 samples) are listed separately from those from Poços de Caldas (3 samples). The Greenland lujavrites were collected from the mineralized zone on the Kvanefjeld plateau and have considerably higher uranium, thorium and rare earth concentrations than do those from Poços de Caldas. The Kvanefjeld lujavrites have the highest agpaitic ratios of all the samples, followed by the lujavrites from Poços de Caldas.

Means and ranges are given for 4 tinguaites from Poços de Caldas, Brazil, and from Magnet Cove and Potash Sulphur Springs, Arkansas and two ijolite samples from Nemegos, Ontario.

ANALYSES AND DESCRIPTIONS OF SAMPLES

Specimens from Ph.D. dissertation of
J. Bushee, U.C. Berkeley (collection # 667)

From northern rim of Poços de Caldas massif, Brazil

PERK - 46: *_Nepheline Syenite._ Medium-grained[1] but poorly homogeneous[2] due to uneven segregations into mineral aggregates. With alkali-feldspar, nepheline, aegerine, natrolite, cancrinite, sodalite; and lesser eudialyte, sphene or rutile, and catapleite (?).

PERK - 49: *_Nepheline Syenite._ Medium-grained, moderately homogeneous. Contains alkali-feldspar, nepheline, sodalite, natrolite, and lesser aegerine, cancrinite, albite, catapleite intergrown with eudialyte, astrophyllite, lamprophyllite, and muscovite (?).

PERK - 48: *_Nepheline Syenite._ Fine-grained but only moderately homogeneous due to segregation into mineral aggregates. Contains abundant eudialyte, likely of secondary origin, as well as exsolved alkali-feldspar, nepheline altered to natrolite, aegerine in two generations of growth, and late-stage rutile (?).

PERK - 78: *_Nepheline Syenite._ Medium-grained, homogeneous to moderately homogeneous, resembles PERK-49 in hand-specimen. Contains nepheline, alkali-feldspar (?), abundant sodalite and eudialyte, and lesser albite and giannettite (?).

PERK - 45: *_Nepheline Syenite._ Coarse-to-medium-grained, moderately to poorly homogeneous. Eudialyte occurs in aggregates, and is isotropic and colorless although pink in hand specimen. Also with alkali-feldspar, nepheline, aegerine, natrolite, sodalite, and catapleite (?).

PERK - 41: *_Lujavrite._ Medium-grained, moderately homogeneous, with a foliation defined by orientation of aegerine needles. Also with alkali-feldspar, sodalite, nepheline altered in part to cancrinite, lamprophyllite or giannettite, and possibly eudialyte.

Table B-1

BUSHEE POÇOS DE CALDAS COLLECTION

PERCENT	PERK 46	PERK 49	PERK 48	PERK 78	PERK 45	PERK 41
SiO_2	54.2	54.0	50.8	54.0	54.3	54.0
Al_2O_3	19.8	19.7	16.3	20.7	17.8	17.1
FeO	2.9	4.1	7.9	3.0	4.3	6.7
MgO	<0.1	0.1	<0.1	<0.1	<0.1	0.1
CaO	1.3	1.3	3.0	1.6	1.9	2.5
Na_2O	7.0	8.0	10.0	8.3	8.3	8.0
K_2O	8.4	8.7	3.2	8.8	6.7	6.9
TiO_2	0.3	0.5	1.0	0.2	0.4	0.4
MnO	0.4	0.3	0.9	0.3	0.5	0.3
TOTAL	94.3	96.7	93.1	96.9	94.2	96.0
PPM						
U	26	25	23	21	18	18
Th	170	135	145	100	106	82
Zr	4400	900	3100	5700	7100	3800
Ta	11	5.4	12	12	18	8.3
Nb	469	246	542	456	761	314
Hf	84	16	58	100	131	72
La	700	630	870	550	510	410
Ce	760	713	1010	780	625	546
Nd	140	130	180	140	120	100
Sm	17	15	21	15	14	12
Eu	3.8	3.6	4.8	3.5	4.1	3.0
Tb	2.2	1.9	2.4	1.8	1.8	1.5
Yb	9.8	7.4	10.7	10.7	15.5	9.8
Lu	1.7	1.9	2.0	1.1	1.6	1.8
Rb	280	290	78	300	215	225
Sr	1500	1040	1960	2400	2200	1570
Cs	12	2.2	1.0	1.8	4.3	1.5
Ba	400	500	300	250	350	300
Cr	-	-	12	10	-	26
Co	1.6	-	2.4	<1	-	1.8
Ni	<20	-	-	<20	-	<10
Mo	20	15	<5	30	<10	<10
Sc	0.2	0.6	0.6	0.3	0.4	1.3
Zn	140	110	560	90	400	150

BUSHEE POÇOS DE CALDAS COLLECTION
(continued)

PERK - 47: *_Nepheline Syenite._ Medium-grained, homogeneous to moderately homogeneous, highly altered. Contains abundant eudialyte of both primary and secondary origin, as well as exsolved alkali-feldspar, nepheline altered to natrolite and cancrinite (?), and aegerine in several generations of growth.

PERK - 79: _Nepheline Syenite._ Medium-grained, homogeneous.

PERK - 43: *_Lujavrite._ Medium-grained, homogeneous to moderately homogeneous. Contains abundant euhedral, pink, pleochroic, eudialyte, as well as alkali-feldspar altering to cancrinite, nepheline, and aegerine.

PERK - 80: *_Nepheline Syenite._ Medium-grained, moderately homogeneous. Sample shows considerable alteration of its major constituents, and otherwise includes alkali-amphibole, astrophyllite, carbonate, and lesser eudialyte.

PERK - 44: *_Tinguaite._ Fine-grained, homogeneous, Phenocrysts (about 10%) consist of aegerine, giannettite, and lamprophyllite, generally in sub-parallel alignment. Groundmass consists of sanidine, nepheline, sodalite, sphene or zircon, and opaques.

PERK - 42: *_Nepheline Syenite._ Coarse-grained, moderately to poor homogeneous. Consists mainly of alkali-feldspar and nepheline, both largely altered to natrolite and lesser cancrinite. Also with aegerine, astrophyllite, sphene, and melanite.

Table B-1 (continued)

BUSHEE POÇOS DE CALDAS COLLECTION

PERCENT	PERK 47	PERK 79	PERK 43	PERK 80	PERK 44	PERK 42
SiO_2	52.0	55.3	52.6	53.9	54.6	55.3
Al_2O_3	15.2	20.0	14.8	21.8	20.7	21.3
FeO	8.3	2.3	8.2	3.0	3.9	2.7
MgO	0.4	<0.1	<0.1	0.1	<0.1	<0.1
CaO	3.8	1.9	2.5	1.2	1.9	0.7
Na_2O	8.3	6.6	7.9	6.4	7.8	5.2
K_2O	5.1	8.9	5.5	11.2	8.2	11.7
TiO_2	0.8	0.8	0.6	0.5	0.5	0.5
MnO	0.9	1.4	0.5	0.3	0.3	0.3
TOTAL	94.8	97.2	92.6	98.4	97.9	97.7
PPM						
U	14	13	11	11	5	5
Th	68	44	63	28	28	18
Zr	3500	1300	9200	750	1030	810
Ta	10	3.6	17	4.7	5.4	4
Nb	612	193	616	203	159	168
Hf	63	20	190	15	20	15
La	500	190	370	94	210	60
Ce	590	200	375	130	310	59
Nd	105	30	55	30	77	13
Sm	12	2.3	5.8	3.7	10	1.1
Eu	2.6	0.5	1.3	0.8	2.5	0.3
Tb	1.2	0.3	0.7	0.3	0.9	0.2
Yb	6.8	2.5	6.0	1.1	3.3	0.9
Lu	1.3	0.8	0.9	0.4	0.4	0.2
Rb	105	380	210	500	180	630
Sr	2300	4500	3700	700	2400	850
Cs	0.5	4.8	25	7.5	1.9	8.5
Ba	-	250	-	100	500	500
Cr	-	<5	-	<5	-	-
Co	3.0	<1	1.3	1	1	-
Ni	-	<20	-	<20	-	-
Mo	5	15	<10	20	<10	5
Sc	0.8	0.2	0.8	<1	0.6	0.2
Zn	350	180	170	2000	160	350

Specimens collected by H. Wollenberg from Poços de Caldas, Brazil

PERK - 69: *Caldesite*, Poços de Caldas. Fine-grained, homogeneous.

PERK - 68: *Tinguaitic Uranium Ore*, Poços de Caldas. Fine-grained, homogeneous.

PERK - 70: *Lujavrite*, Poços de Caldas. Coarse-grained, moderately to poorly homogeneous. Strongly foliated, with arfvedsonite, sodic plagioclase, aegerine, alkali-feldspar, and abundant eudialyte.

PERK - 67: *Magnetite*, Poços de Caldas. Dense, homogeneous.

Table B-2

WOLLENBERG POÇOS DE CALDAS, BRAZIL COLLECTION

PERCENT	PERK 69	PERK 68	PERK 70	PERK 67
SiO_2	-	54.9	54.2	0.1
Al_2O_3	-	22.1	13.0	0.4
FeO	-	3.0	9.9	80
MgO	-	0.1	0.4	-
CaO	-	0.2	2.4	-
Na_2O	-	0.5	7.9	-
K_2O	-	11.8	5.8	-
TiO_2	-	0.9	0.5	3.1
MnO	-	-	0.8	>3
TOTAL	-	93.5	94.9	≥86.6
PPM				
U	≥4000	110	11	10
Th	800	420	17	53
Zr	-	-	7300	40
Ta	16	9	11	0.5
Nb	-	-	445	31
Hf	≥4000	12	150	11
La	500	280	160	32
Ce	500	490	125	67
Nd	150	180	20	32
Sm	35	100	2	4.5
Eu	15	31	0.5	0.9
Tb	8	5.7	0.2	0.3
Yb	90	5.6	4.5	1.0
Lu	-	0.7	0.9	0.6
Rb	<10	270	215	<20
Sr	-	-	1960	<36
Cs	<1	<1	5	<2
Ba	500	2100	200	500
Cr	-	<10	<10	<5
Co	-	3	1.2	6
Ni	-	50	<20	<20
Mo	1800	150	<10	5
Sc	4	1	1	6
Zn	140	130	220	4000

Specimens from Ph.D. dissertation collection of R.W. Hodder,
U.C. Berkeley (Collection #455), from ring intrusion near
Nemegos, Ontario

PERK - 54: *Magnetite rock with Nepheline Stringers.* Magnetite rock is fine-grained, cut with irregular orange-pink stringers containing pyrochlore. Sampling error indeterminate, as it involves constituents -- stringers and host -- in uncertain proportions.

PERK - 55: **Carbonate Rock.* Medium-grained, moderately to poorly homogeneous due to segregations into aggregates of darker minerals. Mainly calcite; also containing apatite, magnetite, highly altered aegerine-augite, biotite, melanite, and/or pyrochlore.

PERK - 56: *Zone of contact between *Nepheline Syenite,* and *Magnetite-Apatite Rock.* Fine-grained magnetite-apatite rock, medium-grained nepheline syenite. Sampling error indeterminate for reasons cited under PERK-53. Contains alkali-feldspar altered to sericite, nepheline with cancrinite and calcite alteration, albite of both primary and exsolution origin, magnetite, aegerine-augite, biotite, apatite, and minor pyrochlore.

PERK - 52: **Malignite.* Fine-grained, but only moderately homogeneous as it is cut by a 1cm. thick feldspar-rich vein. Contains alkali-feldspar, nepheline, aegerine-augite, magnetite, apatite, and pyrochlore growing on borders of pyroxene grains and in cracks within nepheline.

PERK - 51: **Ijolite.* Very fine-grained, but only moderately homogeneous due to segregation into mineral aggregates. Contains unaltered nepheline, aegerine-augite bordered locally by pyrochlore, and minor biotite. Little or no feldspar.

Specimens from Ph.D. dissertation collection of R.W. Hodder,
U.C. Berkeley (Collection #455), from ring intrusion near
Nemegos, Ontario
(continued)

PERK - 50: **Nepheline Syenite.* Fine-grained, homogeneous. Contains clear alkali-feldspar, nepheline altered locally to cancrinite; and lesser calcite, aegerine-augite, biotite, and primary calcite.

PERK - 53: **Ijolite.* Border zone between nepheline syenite similar to PERK-50 and fine-grained magnetite vein. Sampling error indeterminate, as it involves constituents from either side of the border zone in uncertain proportions. Contains nepheline with some alteration to cancrinite, and calcite, aegerine-augite, magnetite, biotite, and pyrochlore (?).

Table B-3

NEMEGOS, ONTARIO

HODDER COLLECTION

PER CENT	PERK 54	PERK 55	PERK 56	PERK 52	PERK 51	PERK 50	PERK 53
SiO_2	43.6	15.5	30.4	52.3	47.1	55.0	38.8
Al_2O_3	17.4	0.6	11.4	18.8	15.5	20.6	14.2
FeO	9.9	16.6	24.2	8.9	9.4	2.2	6.1
MgO	2.7	0.5	0.2	0.7	3.4	0.5	1.2
CaO	9.3	24.6	10.8	3.3	10.5	2.7	4.3
Na_2O	8.3	3.1	3.3	7.0	7.2	5.7	5.3
K_2O	3.0	0.2	4.1	6.6	3.5	10.3	5.1
TiO_2	0.4	1.4	1.2	0.3	0.1	0.2	0.1
MnO	0.6	0.4	0.4	0.3	0.7	0.2	0.3
TOTAL	95.2	62.9	86.0	98.2	97.3	97.4	75.8
PPM							
U	200	44	22	7.7	7.3	6	4.1
Th	1000	320	472	4.2	31	35	20
Zr	2200	670	570	460	610	240	620
Ta	250	14	16	15	5	12	8
Nb	6200	1070	400	183	107	198	147
Hf	23	5	3.6	7.2	7	3.3	7
La	85	973	1000	65	95	90	50
Ce	220	2200	2400	120	200	135	80
Nd	130	900	1000	50	100	50	30
Sm	19	130	140	8	19	8	7
Eu	5.4	44	46	2	5	2.3	1.9
Tb	3.0	12.6	13.5	0.5	1.4	0.7	0.6
Yb	8.2	13.3	10.1	1.9	6.2	2.1	4.2
Lu	-	1.7	-	0.4	1.1	0.5	1.0
Rb	60	<20	40	190	100	380	250
Sr	700	6200	3700	1200	720	1520	1030
Cs	0.8	<1	<2	1	0.7	3.1	2
Ba	-	4000	4000	-	600	3000	1500
Cr	-	31	30	15	-	-	-
Co	15	24	20	6	11	2.8	6.9
Ni	-	-	-	-	-	-	-
Mo	<10	<10	<10	<10	<10	<10	<10
Sc	-	7.7	0.5	1.5	0.8	0.2	0.5
Zn	600	600	400	150	250	70	150

Specimens from U.C. Berkeley Collection "Arkansas Intrusives" (collection #201)

PERK - 76: **Nepheline Syenite,* Magnet cove. Medium-grained, moderately homogeneous. Contains nepheline, aegerine, alkali-feldspar (?), and eudialyte, in a highly poikilitic texture.

PERK - 77: *Aegerine Tinguaite Dike,* Magnet Cove. Very fine-grained, with scattered medium-grained feldspar phenocrysts; homogeneous.

PERK - 75: **Leucite Tinguaite,* (phonolite dike), Magnet Cove. Green aphanitic groundmass, phenocrysts (20%) medium-grained, sample is homogeneous to moderately homogeneous. Contains sanidine phenocrysts altered to sericite; with groundmass leucite and nepheline (?), highly altered, and late growth of euhedral magnetite.

PERK - 74: **Nepheline Tinguaite,* Potash Sulphur Springs. Aphanitic ground mass, phonocrysts (15-25%) medium-grained, sample is moderately homogeneous. Contains sanidine and smaller aegerine phenocrysts, both highly altered.

Table B-4

ARKANSAS INTRUSIVES

PER CENT	PERK #76	PERK #77	PERK #75	PERK #74
SiO_2	49.9	52.0	52.5	54.5
Al_2O_3	16.5	19.6	20.1	22.2
FeO	6.2	3.7	3.1	3.3
MgO	0.9	<0.1	0.1	0.3
CaO	5.8	4.0	2.7	2.7
Na_2O	8.9	8.9	8.4	6.5
K_2O	3.6	7.6	7.3	7.3
TiO_2	1.2	0.3	0.5	0.6
MnO	0.6	0.4	0.2	0.2
TOTAL	93.6	96.5	94.9	97.6
PPM				
U	19	9	8	7
Th	80	12	29	22
Zr	430	950	520	390
Ta	4	1.8	1.5	1.8
Nb	135	189	104	63
Hf	8	12	6	5.7
La	180	30	125	80
Ce	270	40	168	100
Nd	70	13	30	25
Sm	10	1.6	4.1	4
Eu	2.2	0.4	0.8	0.8
Tb	1.0	0.2	0.3	0.3
Yb	4.4	0.8	1.0	1.7
Lu	1.1	0.3	0.4	0.4
Rb	70	185	200	240
Sr	960	950	2200	1460
Cs	3	4.4	3.7	6.8
Ba	2000	1300	3300	1400
Cr	15	<2	<5	5
Co	12	1	2	4
Ni	<20	<20	<20	<20
Mo	20	15	40	10
Sc	3	0.2	0.6	0.7
Zn	400	200	160	130

Specimens collected by H. Wollenberg; from Ilímaussaq, Greenland

PERK - 71: **Green (Aegerine) Lujavrite,* Kvanefjeld, Ilímaussaq. Fine-grained, homogeneous. Finely-laminated, containing aegerine, albite, abundant steenstrupine, and minor neptunite.

PERK - 72: **Arfvedsonite-Aegerine Lujavrite,* Kvanefjeld, Ilímaussaq. Fine-grained homogeneous. Contains arfvedsonite, aegerine, albite, alkali-feldspar, abundant steenstrupine, and minor neptunite and sodalite (?).

PERK - 66: *White Kakortokite,* Ilímaussaq. Medium-to coarse-grained, poorly homogeneous due to uneven segregations into mineral aggregates (mainly poikilitic eudialyte). Contains nepheline, eudialyte, albite, alkali-feldspar, arfvedsonite, aegerine, astrophyllite, and rinkite (?).

Table B-5

Wollenberg Greenland Collection

PERCENT	PERK 71	PERK 72	PERK 66
SiO_2	57.7	58.5	54.3
Al_2O_3	10.5	12.3	16.4
FeO	12.0	10.3	6.1
MgO	<0.1	<0.1	0.1
CaO	0.4	0.3	2.3
Na_2O	10.4	8.1	8.2
K_2O	1.8	3.5	7.3
TiO_2	0.5	0.3	0.4
MnO	0.4	0.7	0.6
TOTAL	93.7	94.0	95.7
PPM			
U	440	420	23
Th	1670	1350	97
Zr	-	-	8600
Ta	4.5	6	19
Nb	-	-	817
Hf	10	13	155
La	6300	5400	730
Ce	8600	7300	840
Nd	2300	1900	140
Sm	250	240	18
Eu	15	14	4.3
Tb	27	26	2.0
Yb	51	50	16
Lu	20	19	1.9
Rb	340	630	200
Sr	-	-	2700
Cs	1.5	3.4	3.5
Ba	6000	1000	300
Cr	50	50	20
Co	<2	<1	1.2
Ni	-	-	<50
Mo	<20	400	<10
Sc	3	<1	0.6
Zn	2900	1900	480

Specimen from collection of A. Lawson, C. 1890, U.C. Berkeley
(Collection #269) from Montreal, Quebec

PERK - 73: **Dike in Nepheline Syenite.* Dense, aphanitic, groundmass, with medium-grained phenocrysts (under 10%); homogeneous. Contains feldspar, nepheline, aegerine with pale cores, carbonate, and a thin orange-brown stringer of an undetermined material.

Table B-6

LAWSON QUEBEC SAMPLE

PERCENT	PERK 73
SiO_2	45.5
Al_2O_3	18.6
FeO	7.4
MgO	1.8
CaO	7.3
Na_2O	7.8
K_2O	4.0
TiO_2	2.6
MnO	0.4
TOTAL	95.4
PPM	
U	7
Th	27
Zr	710
Ta	21
Nb	274
Hf	13
La	330
Ce	550
Nd	170
Sm	28
Eu	6.4
Tb	2.1
Yb	4.8
Lu	0.6
Rb	135
Sr	3000
Cs	1.7
Ba	2000
Cr	12
Co	10
Ni	<20
Mo	<10
Sc	2.4
Zn	250

Footnotes:

*Samples for which thin sections were available for study.

[1] Grain-size designations follow this usage:

Fine-grained:	average grain diameter less than 1mm.
Medium-grained:	average grain diameter 1-5mm.
Coarse-grained:	average grain diameter greater than 5mm.

[2] "Homogeneity" is here meant to refer to the error inherent in the sampling process. It is intended as a qualitative guide to the uniformity of distribution of grains or grain aggregates, relative to the size scale in which sampling was done. Thus, given two specimens of similar grain size and texture, the homogeneity would be greater for the one of which a larger sample could be taken for analysis. Three categories are used to designate this sampling error: "homogeneous", "moderately homogeneous", and "poorly homogeneous".

Table B-7

MEAN VALUES AND RANGES OF MAJOR AND TRACE ELEMENTS IN ROCK TYPES

	NEPHELINE SYENITES		TINGUAITES		LUJAVRITES-GREENLAND	
PERCENT	$\bar{X}$	Range	$\bar{X}$	Range	$\bar{X}$	Range
SiO_2	53.5	49.9-54.3	53.4	52.0-54.6	58.1	57.7-58.5
Al_2O_3	19.1	15.2-21.8	20.7	19.6-22.2	11.4	10.5-12.3
FeO	4.3	2.2-8.3	3.4	3.1-3.9	11.2	10.3-12.0
MgO	0.2	<0.1-0.9	0.1	<0.1-0.3	<0.1	<0.1
CaO	2.3	1.2-5.8	2.8	1.9-4.0	0.4	0.3-0.4
Na_2O	7.5	5.2-10.0	7.9	6.5-8.9	9.3	8.1-10.4
K_2O	7.9	3.6-11.7	7.6	7.3-8.2	2.7	1.8-3.5
TiO_2	0.6	0.2-1.2	0.5	0.3-0.6	0.7	0.3-0.5
MnO	0.6	0.2-1.4	0.3	0.2-0.4	0.6	0.4-0.7
TOTAL	95.8		96.1		93.9	
Agpaitic Ratio*	1.07	0.97-1.23	1.00	0.81-1.13	1.56	1.35-1.77
PPM						
U	16.5	5-26	7.3	5-9	430	420-440
Th	84.5	18-170	22.8	12-29	1510	1350-1670
Zr	2566.4	240-7100	722.5	390-1030	-	-
Ta	8.8	4-18	2.6	1.5-5.4	5.3	4.5-6
Nb	362.1	135-761	128.8	63-189	-	-
Hf	46.7	8-131	10.9	5.7-20	11.5	10-13
La	397.6	60-870	111.3	30-210	5850	5400-6300
Ce	479.3	59-1010	154.5	40-310	7950	7300-8600
Nd	91.6	13-180	36.3	13-77	2100	1900-2300
Sm	10.8	1.1-21	4.9	1.6-10	245	240-250
Eu	2.6	0.3-4.8	1.1	0.4-2.5	14.5	14-15
Tb	1.3	0.2-2.4	0.4	0.2-0.9	26.5	26-27
Yb	6.5	0.9-15.5	1.7	0.8-3.3	50.5	50-51
Lu	1.1	0.2-2.0	0.4	0.3-0.4	19.5	19-20
Rb	293.5	70-630	201.3	180-240	485	340-630
Sr	1811.8	700-4500	1752.5	950-2400	-	-
Cs	4.4	1.0-8.5	4.2	1.9-6.8	2.5	1.5-3.4
Ba	765.0	100-3000	1625.0	500-3300	3500	1000-6000
Cr	8.6	<5-15	-	-	50	50
Co	3.1	<1-12	2.0	1-4	<1.5	<1-<2
Ni	<20		-	-	-	-
Mo	13.5	<5-30	18.3	<10-40	-	<20-400
Sc	2.1	<1-16	0.5	0.2-0.7	-	<1-3
Zn	422.7	110-2000	162.5	130-200	2400	1900-2900
n =	11		4		2	

* Agpaitic ratio calculated from $\frac{na+k}{al}$, where na, k, and al are molecular abundances of sodium, potassium, and aluminum.

Table B-7
(continued)

	LUJAVRITES POÇOS DE CALDAS		IJOLITES NEMEGOS	
PERCENT	$\bar{X}$	Range	$\bar{X}$	Range
SiO_2	53.6	52.6-54.2	43.0	38.8-47.1
Al_2O_3	14.9	13.0-17.0	14.9	14.2-15.5
FeO	8.3	6.7-9.9	7.8	6.1-9.4
MgO	0.19	<0.1-0.4	2.3	1.2-3.4
CaO	2.5	2.4-2.5	7.4	4.3-10.5
Na_2O	7.9	7.9-8.0	6.3	5.3-7.2
K_2O	6.1	5.5-6.9	4.3	3.5-5.1
TiO_2	0.5	0.4-0.6	0.1	0.1
MnO	0.5	0.3-0.8	0.5	0.3-0.7
TOTAL	94.5		86.6	
Agpaitic Ratio*	1.29	1.18-1.44	0.97[5]	0.97-0.98
PPM				
U	13.3	11-18	5.7	4.1-7.3
Th	54.0	17-82	25.5	20-31
Zr	6766.7	3800-9200	615	610-620
Ta	12.1	8.3-17	6.5	5-8
Nb	458.3	314-616	127.0	107-147
Hf	137.3	72-190	7.0	7
La	313.3	160-410	72.5	50-95
Ce	348.7	125-546	140.0	80-200
Nd	58.3	20-100	65.0	30-100
Sm	6.6	2-12	13.0	7-19
Eu	1.6	0.5-3.0	3.5	1.9-5
Tb	2.9	0.2-1.5	1.0	0.6-1.4
Yb	6.8	4.5-9.8	5.2	4.2-6.2
Lu	1.2	0.9-1.8	1.1	1.0-1.1
Rb	216.7	210-225	175	100-250
Sr	2410	1570-3700	875	720-1030
Cs	10.5	1.5-25	1.4	0.7-2
Ba	250	200-300	1050	600-1500
Cr	-	<10-26	-	-
Co	1.4	1.2-1.8	9.0	6.9-11
Ni	<15	<10-<20	-	-
Mo	<10	<10	<10	<10
Sc	<1.0	0.8-1.3	0.7	0.5-0.8
Zn	180	150-220	200	150-250
n =	3		2	

* Agpaitic ratio calculated from $\frac{na+k}{al}$, where na, k, and al are molecular abundances of sodium, potassium, and aluminum.

APPENDIX C

Glossary of Rock and Mineral Names

ACMITE, AEGIRINE (Aegirite)

Aegirine and acmite are essentially the same in chemical composition, which may be represented by the formula, $NaFe^3Si_2O_6$. In hand specimens they occur as black lustrous prisms, sharply pointed in acmite.

Monoclinic. Crystals are often polysynthetic, with enclosed twinning lamellae. Crystals long prismatic, vertically striated or channelled; acute terminations very characteristic. The above applies to ordinary acmite. For aegerine, crystals prismatic, bluntly terminated; twins not common; also in groups or tufts of slender acicular to capillary crystals, and in fibrous forms.

Composition - Essentially $NaFe^3 (SiO_3)_2$ or $Na_2 O.\ Fe_2O_3.\ 4SiO_2$ = Silica 52.0, iron sesquioxide 34.6, soda 13.4. The diopside-hedenbergite molecule ($Ca(Mg,Fe)(SiO_3)_2$) can apparently mix in all proportions with the acmite molecule. Various hyphenated names have been proposed to describe the intermediate varieties, such as aegirite-hedenbergite, jadeite-aegirite. Acmite proper seems always to contain a notable amount of zirconia and rare earths.

Aegirine occurs especially in igneous rocks rich in soda and containing iron, commonly in rocks containing leucite or nepheline; thus in aegirine-granite, nepheline-syenite, and some varieties of phonolite.

In the sub-variety of phonolite called tinguaite, the rock has often a deep greenish color due to the abundance of minute crystals of aegirine.

(Hatch 49, p. 57 Dana 58, p. 561. Deer 63, V. 2, p. 79-91.)

ADULARIA

$KAlSi_3O_8$, occasionally with Na. Usually in crystals, weakly triclinic. G. = 2.565. Transparent or nearly so. Often with a pearly opalescent reflection or schiller or a delicate play of colors; this variety is commonly known as *moonstone*, microperthite to sub-microperthitic intergrowth of orthoclase and albite. (Dana 1958, p. 538)

AEGIRINE - AUGITE

Varities of augite characterized by the presence of alkalies, especially soda, probably in the form of the acmite molecule, $NaFe(SiO_3)_2$. Known chiefly from rocks rich in alkalies, as nepheline-syenite, phonolite, leucitite, etc. (Dana 58, p.559).

AENIGMATITE

$(Na,Ca)(Fe^{+2},Ti,Al,Fe^{+3})_5(O_3Si_4O_{11})$(?). In prismatic triclinic crystals. Cleavage: prismatic, distinct (66°). Shows certain relations to the amphibole group in which it has commonly been included as a triclinic member. Occurs as reddish brown to black grains in naujaite and naujaite pegmatites. *Cossyrite* occurs in minute crystals embedded in the liparite lavas of the island of Pantellaria (ancient name Cossyra); also widespread in the rocks of East Africa. *Rhönite* is like aenigmatite but contains much less ferrous oxide and alkalies with increase in alumina, ferric oxide, etc. (Dana 1958, p. 579; Sørensen 1962, p. 216)

AGPAITIC

Rich in alkalis, especially Na_2O:

$$\frac{Na_2O + K_2O}{Al_2O_3} > 1$$

Main mafic minerals: aegirine, Na-amphibole and/or aenigmatite.

Main feldspathoid minerals: nepheline, sodalite.

Accessory elements: rich in Ti, Zr, Nb, rare earths (lanthanides), Sr, Th, P.

Accessory Minerals: complex silicates of Ti and Zr, rinkite, rinkolite, lamprophyllite, eudialyte, eucolite; RE phosphates, (britholite, belovite), perovskite.

Volatile Elements: F, Cl, H_2O.

Volatile-bearing Species: Na-amphiboles, sodalite, rinkolite, eudialyte, villaumite.

(Heinrich 66, p. 19; Sørensen 74, p. 22-23).

ALKALINE (ALKALIC) IGNEOUS ROCKS

1. Igneous rocks of Atlantic or alkaline series.
2. Igneous rocks with alkali feldspar as predominant feldspar; that is, with more alkalis than average for their clans.
3. Igneous rocks with feldspathoids.
4. Igneous rocks with alkali-lime index less than 51.
5. Igneous rocks with feldspathoids and/or soda-pyroxenes and/or-amphiboles.

(Sørensen 74, p. 3).

ALKALI GRANITE AND RHYOLITE

Granites and rhyolites containing sodic pyroxenes and/or-amphiboles.

(Sørensen 74, p. 560).

ALLANITE, ORTHITE (Cerium Epidote)

Monoclinic. Crystals often tabular. Also massive and in embedded grains. Fracture uneven or subconchoidal.

Composition-like epidote, H(Ca, Fe)(Al,Fe, rare earths)Si_3O_{13}. Some varieties contain considerable water, but probably by alteration.

Allanite. The original mineral was from East Greenland, in tabular crystals or plates. Color black or brownish black. G. = 3.50-3.95.

Bucklandite is anhydrous allanite in small black crystals.

Bagrationite occurs in black crystals which are like bucklandite.

Orthite included, in its original use, slender or acicular prismatic crystals, containing some water but these graduate into massive forms, and some orthites are anhydrous, or as nearly so as most allanite.

Occurrence-Allanite is most characteristically found as an accessory mineral in the deep-seated igneous rocks, as granite, syenite, diorite as well as in pegmatites. It also occurs in metamorphic rocks that have been derived from igneous rocks, as gneiss, amphibolite, etc. Occurs in volcanic ejections and has been noted in limestone as a contact mineral, with magnetite bodies, and is sometimes enclosed as a nucleus in crystals of the isomorphous species, epidote.

(Dana 58, p. 624-625; Hatch 49, p. 113)

ALNÖITE

One-third each of melilite and biotite, the remainder of the rock being made up of pyroxene, calcite and olivine in order of importance, with various minor accessories.

(Hatch 49, p. 344-348)

ANALCIME, ANALCITE

Isometric. Usually in trapezohedrons; also cubes.

Composition-$NaAlSi_2O_6.H_2O = Na_2O.Al_2O_3.4SiO_2.2H_2O$ = Silica 54.5, alumina 23.2, soda 14.1, water 8.2.

Occurrence - Occurs frequently with other zeolites, also prehnite, calcite, etc., in cavities and seams in basic igneous rocks, as basalt, diabase, etc.; also in granite, gneiss, etc. It also may occur as replacing nepheline, leucite, sodalite, etc., and is found, therefore, as a constituent of rocks that originally contained these minerals.

(Dana 58, p. 562-563, Hatch 49, p. 110-111; Deer 63, V. 4, p. 338-350)

ANKERITE

$CaCO_3.(Mg,Fe,Mn)CO_3$, or for normal ankerite, $2CaCO_3.MgCO_3.FeCO_3$. In rhombohedral crystals; also crystalline massive, granular, compact. Minerals that may be classed as ankerite are fairly common, having in general the same mode of occurrence and associations as dolomite; frequently associated with iron ores.

(Dana 58, p. 517)

ARFVEDSONITE

Monoclinic. Crystals long prisms, often tabular, but seldom distinctly terminated, angles near those of amphibole; also in prismatic aggregates.

Composition-A slightly basic metasilicate of sodium and ferrous iron chiefly with smaller amounts of aluminum and ferric iron. $Na_3Fe_4Al(OH)_2Si_8O_{22}$.

Occurrence-Arfvedsonite and amphiboles of similar character, containing much iron and soda, are constituents of certain igneous rocks which are rich in alkalies, as nepheline-syenite, certain porphyries, etc.

(Dana 58, p. 578-579; Deer 63, V. 2, p. 364-374)

ASTROPHYLLITE (see TITANITE)

AUGITE

Aluminous pyroxene. Composition chiefly $CaMgSi_2O_6$ with $(Mg,Fe)(Al,Fe)_2SiO_6$, and occasionally also containing alkalies and then graduating toward acmite. Titanium is also sometimes present. Greenish or brownish black and black varieties, occurring mostly in eruptive rocks. It is usually in short prismatic crystals, thick and stout, or tabular.

(Dana 58, p. 559; Deer 63, V. 2, p. 109-142)

BADDELEYITE

Zirconium dioxide, ZrO_2. Contains a small amount of hafnium oxide. In tabular monoclinic crystals.

(Dana 58, p. 500)

BASTNÄSITE

(Hamartite) A fluorocarbonate of the cerium metals $(RF)CO_3$. Hexagonal, trigonal symmetry. Prismatic crystals. Basal parting.

(Dana 58, p. 526)

BETAFITE

A niobate and titanate of uranium, etc. Isometric with octahedron and dodecahedron.

(Dana 58, p. 699)

BOSTONITE

A light-colored hypabyssal rock, characterized by *bostonitic* texture and composed of albite and microcline, with accessory pyroxene; an alkalic syenite with few or no mafic components. Leucocratic microsyenite, generally as dikes, "intrusive trachytes".

(Gary 1972, p. 85; Hatch 1949, p. 246)

CANCRINITE

Cancrinite is related to nepheline in composition, and in a sense may be regarded as "nepheline-carbonate" with a rather doubtful formula, perhaps $3NaAlSiO_4.(Ca,Na,H)CO_3$.

This mineral is hexagonal, but rarely forms definite crystals. Occasionally it is a primary constituent of nepheline-syenites, and in so-called cancrinite-syenites is an essential component. More often it fills a minor role, as an alteration product of nepheline, or arises by reaction between the latter and included grains of calcite.

(Hatch 49, p. 101; Deer 63, V. 4, p. 310-320

CARBONATITE

A carbonate rock of apparent magmatic origin, generally associated with kimberlites and alkalic rocks.

(Heinrich 66; Gary 72, p. 107)

CERITE

A silicate of the cerium metals chiefly, with water. Tetragonal or orthorhombic. Crystals rare; commonly massive; granular.

(Dana 58, p. 634)

CHKALOVITE

$Na_2BeSi_2O_6$. It occurs in amygdules in albititic rocks and in veins composed of analcime and natrolite. It is generally partially replaced by beryllium sodalite; occasionally associated with analcime and villiaumite. The occurrences of the mineral in Lovozero and Ilímaussaq are very similar, the chkalovite being restricted to amygdules, etc. and being formed in a late stage of the development of the pegmatites and hydrothermal veins.

(Sørensen 1963, p. 220)

COFFINITE

A black mineral: $U(SiO_4)_{1-x}(OH)_{4x}$. It is an important ore of uranium and occurs in many sandstone deposits and in hydrothermal veins.

(Gary 1972, p. 138)

CONE SHEET

A dike that is arcuate in plan and dips gently (30-45^0) toward the center of the arc. It occurs in concentric sets which presumably converge (by projection) at the magmatic center. It is associated with *ring dikes* to form a *ring complex*.

(Gary 72, p. 149)

ELEOLITE

A synonym of nepheline, especially of a translucent, massive or coarsely crystalline, and dark (grayish, bright-green, or brown to brownish-red) variety having a greasy luster and sometimes used as an ornamental stone.

(Gary 72, p. 225)

ELEOLITE SYENITE

An obsolescent synonym of *Nepheline Syenite*, especially of coarse-grained variety containing eleolite.

(Gary 72, p. 225)

EPISTOLITE (See also murmanite)

(Na,Ca)(Nb,Ti,Mg,Fe,Mn)(OH)SiO_4. Monoclinic. In rectangular plates, also in aggregates of curved folia. Basal cleavage perfect. G. = 2.9. Color white, grayish, brownish. Flakes of epistolite occur in the albititic rocks and also in some lujavrites. There may be transitions into murmanite. Murmanite has the composition NaTi(OH)SiO_4 and occurs in Lovozero under similar conditions as the epistolite of Ilímaussaq. (Dana 1958, p. 699; Sørensen 1962, p. 221)

ESSEXITE

An alkali gabbro primarily composed of plagioclase, hornblende, biotite, and titanaugite, with lesser amounts of alkali feldspar and nepheline. Essexite grades into theralite with a decrease in potassium feldspar and an increase in the feldspathoidal minerals. (Gary 72, p. 239; Hatch 49, p. 306-308)

EUDIALYTE

Essentially a metasilicate of Zr,Fe(Mn),Ca,Ce,Na,Cl, etc. The formula $(Na,Ca,Fe)_6Zr(OH,Cl)(SiO_3)_6$ has been proposed. In pink, red to brown tabular or rhombohedral crystals; also massive. *Eucolite* is similar but optically negative. Eudialyte and eucolite occur in nepheline-syenites and in their pegmatite facies. The name *mésodialyte* has been proposed for an intermediate member of the eudialyte-eucolite series.

Eudialyte is one of a number of complex zircono-silicates which occur as accessory minerals in nepheline-syenites, particularly of pegmatic facies. It increases in amount in more basic nepheline-bearing rocks and may attain to the status of an important essential constituent, as in the so-called eudialyte-syenites in southern Greenland.

(Dana 58, p. 581; Hatch 49, p. 128)

EUDIALYTE-NEPHELINE-SYENITE

Named *Khibinite* or *Chibinite* from a locality on the Kola Peninsula, USSR.

(Hatch 49, p. 240)

EUXENITE

A niobate and titanate of yttrium, erbium, cerium, and uranium. Pseudo-orthorhombic. Crystals rare; commonly massive.

(Dana 58, p. 698)

FELDSPATHOID

(a) A group of comparatively rare rock-forming minerals consisting of aluminosilicates of sodium, potassium, or calcium and having too little silica to form feldspar. Feldspathoids are chemically related to the feldspars, but differ from them in crystal form and physical properties; they take the places of feldspars in igneous rocks that are undersaturated with respect to silica or that contain more alkalies and aluminum than can be accommodated in the feldspars.

(b) A mineral of the feldspathoid group, including leucite, nepheline, sodalite, nosean, hauyne, lazurite, cancrinite, and melilite.

(Gary 72, p. 256)

FENITE

Alkali syenite formed by contact metasomatic processes around some alkaline intrusions and carbonatites. Leucometasomatites of altered country rock around alkalic complexes; up to 25% aegirine-augite, minimum of 52% SiO_2.

(Sørensen 74, p. 564; Heinrich 66, p. 12)

FOYAITE

Nepheline syenite, agpaitic to intermediate between agpaitic and miaskitic. Foyaitic (intergranular) texture because of arrangement of plates and tables of microperthite. Often used as group name for nepheline syenites.

Roughly one-quarter of rock is nepheline; potassic-sodic feldspar makes up about 62%, a sodic pyroxene some 10%, and sphene and other accessories 5 to 6%.

(Sørensen 74, p. 564; Hatch 49, p. 238-239)

IJOLITE

Nepheline-pyroxene rock, mesocratic, feldspar-free.

A series of plutonic rocks containing nepheline and 30-60% mafic minerals, generally pyroxene, and including sphene, apatite, and melanite; also, any rock of that series. *Melteigite* and *jacupirangite* are more mafic members of the series; *urtite* is a type rich in nepheline.

....a combination of nepheline and pyroxene with accessories...

(Sørensen 74, p. 565; Gary 72, p. 353; Hatch 49, p. 311)

(see Urtites-Ijolites-Melteigites)

ILVAITE

Lievrite. Yenite. Orthorhombic. Commonly in prisms, with prismatic faces vertically striated. Columnar or compact massive.

$CaFe_2^{+2}Fe^{+3}(SiO_4)_2(OH)$. It is related to epidote, and usually contains manganese in small amounts.

Cleavage: rather distinct. Fracture uneven. Brittle. G. =3.99-4.05. Luster submetallic. Color iron-black or dark grayish black.

Occurrence: Ilvaite occurs with magnetite ore bodies; with zinc and copper ores; in contact deposits; also with zeolites.

(Dana 1958, p. 631; Gary 1972, p. 354)

JACUPIRANGITE

Composed chiefly of sodic clinopyroxene with a smaller amount of nepheline. Alkali pyroxenite; titanaugite, titanomagnetite, nepheline, apatite, perovskite, melanite.

(Hatch 49, p. 311; Sørensen 74, p. 566)

JUVITE

Nepheline syenite having orthoclase as the only feldspar.

(Sørensen 74, p. 566)

KAKORTOKITE

Eudialyte-arfvedsonite-nepheline syenite. Agpaitic. Leuco- to mesocratic, igneous lamination, distinct gravitative layering with black, red and white layers.

(Sørensen 74, p. 566)

KATAPLEITE (Catapleite)

$Na_2ZrSi_3O_9 \cdot H_2O$. Small plates of katapleite, 0.01-0.1 millimeter across, are commonly found as a secondary mineral after eudialyte.

(Sørensen 1962, p. 223)

KHIBINITE (Chibinite)

Nepheline syenite, leucocratic, agpaitic to intermediate between agpaitic and miaskitic nepheline syenites. Granular or trachytoid texture. Eudialyte-bearing.

(Sørensen 74, p. 566)

LEUCITE GROUP

Leucite (Amphigéne)

Isometric at about 600°C.; pseudo-isometric under ordinary conditions. Commonly in crystals varying in angle but little from the trapezohedron. Faces often showing fine striations due to twinning. Also in disseminated grains; rarely massive granular.

Composition - $(KAl(SiO_3)_2$ or $K_2O.Al_2O_3.4SiO_2$ = Silica 55.0, alumina 23.5, potash 21.5.

Soda is present only in small quantities, unless as introduced by alteration; traces of lithium, also of rubidium and cesium, have been detected. Leucite and analcite are closely related chemically as is shown by the fact that the two species can be converted into each other when heated with sodium or potassium chlorides or carbonates.

Occurrence-Leucite occurs only in igneous rocks, and especially in the recent lavas, as one of the products of crystallization of magmas rich in potash and low in silica, and is associated with minerals having a high content of alumina and alkalies or with the ferromagnesian minerals. It is rarely observed in deep-seated rocks, evidently because it is easily altered and because under conditions of high pressure orthoclase is the more stable mineral. Its former presence in such rocks is indicated by pseudomorphs, often of large size (pseudoleucite), consisting of nepheline and orthoclase, of analcite, etc.

Pollucite. Essentially $H_2O.Cs_2O.Al_2O_3.9SiO_2$.

Ussingite. $HNa_2Al(SiO_3)_3$. Triclinic. Three cleavages. Found in rolled masses from pegmatite at Kangerdluarsuk, Greenland; also from Kola Peninsula.

(Dana 58, p. 549-551; Hatch 49, p. 95-98; Deer 63, V. 4, p. 276-288)

LUJAVRITE

Agpaitic nepheline syenite, mesocratic (aegirine and/or arfvedsonite), having trachytoid texture (igneous lamination). Fine- to coarse-grained. Rich in rare minerals such as eudialyte. Hypersolvus with microperthite or subsolvus with separate microcline and albite.

(Sørensen 74, p. 568)

MALIGNITE

(see shonkinite)

MELILITE

This name is applied to a series of uncommon, somewhat complex silicates of calcium, aluminum and magnesium. Any one specimen may be regarded as having a composition that can be expressed in terms of the two end-members of the series, akermanite ($Ca_2MgSi_2O_7$) and gehlenite ($Ca_2Al_2SiO_7$).

Tetragonal. Usually in short square prisms or octagonal prisms, also in tetragonal tables.

Composition- The composition is complex but can usually be expressed as varying isomorphous mixtures of two molecules, that of gehlenite, $Ca_2Al_2SiO_7$, and that of akermanite, $Ca_2MgSi_2O_7$.

Occurrence-Melilite is a component of certain recent basic eruptive rocks formed from magmas very low in silica, rather deficient in alkalies, and containing considerable lime and alumina. In such cases melilite appears to crystallize in the place of the more acid plagioclase. Found in such rocks as basalts, leucite and nepheline rocks, etc., also in the intrusive rock called *alnöite*.

(Hatch 49, p. 101-102; Dana 58, p. 606-607)

MELTEIGITE

(see Urtites-Ijolites-Melteigites)

MIASKITE

Biotite-nepheline monzosyenite, miaskitic, leucocratic, with albite-oligoclase and potash feldspar (=nepheline plagisyenite).

(Sørensen 74, p. 569)

MIASKITIC

Main elements:

$$\frac{Na_2O + K_2O}{Al_2O_3} < 1 \qquad \text{(in molecular proportions)}$$

Ca and Mg are significant elements.

Main mafics: biotite, diopside, augite, hornblende

Main feldspathoids: nepheline, cancrinite

Accessory elements: Ti, P, Ba, Sr, Nb

Accessory minerals: sphene, ilmenite, rutile, Ti-magnetite, zircon, apatite, pyrochlore

Volatile elements: H_2O, CO_2

Volatile-bearing species: biotite, hornblende, cancrinite, calcite, apatite

(Heinrich 66, p. 19; Sørensen 74, p. 6)

MONAZITE

Monoclinic. Crystals commonly small, often flattened or elongated; sometimes prismatic; also large and coarse. In masses yielding angular fragments; in rolled grains.

Composition-Phosphate of the cerium metals, essentially $(Ce,La,Di)PO_4$. Most analyses show the presence of ThO_2 and SiO_2, usually, but not always, in the proper amount to form thorium silicate; that this is mechanically present is not certain but possible. It has been suggested that the thorium silicate is in solid solution with the cerium phosphate.

Occurrence-Monazite occurs as an accessory mineral in acidic igneous rocks and gneisses, and is found in relatively large crystals in pegmatites. It also occurs as a heavy detrital mineral in sands derived from the weathering of such rocks.

(Dana 58, p. 700-701; Deer 62, V. 5, p. 339-346)

MONZONITE

A group of plutonic rocks intermediate in composition between syenite and diorite, containing approximately equal amounts of orthoclase and plagioclase, little or no quartz, and commonly augite as the main mafic mineral.

(Gary 72, p. 463)

MURMANITE (See also epistolite)

$Na_2(Ti,Nb)_2Si_2O_9 \cdot nH_2O$. In tabular masses. Micaceous cleavage. Color violet.

(Dana 1958, p. 582; Gary 1972, p. 471)

NAUJAITE

Poikilitic sodalite-nepheline syenite and sodalite syenite, agpaitic, leucocratic. Crystals of sodalite are poikilitically enclosed in other rock-forming minerals. Up to 70% sodalite. Eudialyte-rich. (Sørensen 74, p. 570)

NAUJAKASITE

A silvery-white or grayish mineral: $(Na,K)_6(Fe,Mn,Ca)(Al,Fe)_4Si_8O_{26}\cdot H_2O$

(Gary 1972, p. 475)

NEPHELINE, (Nephelite, Elaeolite)

Hexagonal. The structure of nepheline corresponds to normal hexagonal symmetry.

In thick six - or twelve - sided prisms with plane or modified summits. Also massive compact, and in embedded grains; structure sometimes thin columnar.

Composition-$NaAlSiO_4$. Natural nepheline always contains silica in varying excess and also small amounts of potash. The composition usually approximates to $Na_8K_2Al_8Si_9O_{34}$.

Occurrence-Nepheline is rather widely distributed in igneous rocks as the product of crystallization of a magma rich in soda and at the same time low in silica. It is thus an essential component of the nepheline-syenites and phonolites where it is associated with alkali feldspars chiefly. It is also a constituent of more basic augitic rocks such as nephelinite, nepheline-basalts, nepheline-tephrites, theralite, etc., most of which are volcanic in origin.

Alteration- Nepheline is easily altered and in various ways. It frequently changes to various zeolites, to analcite, sodalite, or cancrinite.

Further, the alteration may produce micaceous material.

Eucryptite - $LiAlSiO_4$. In symmetrically arranged crystals (hexagonal), embedded in albite and derived from the alteration of spodumene at Branchville, Connecticut.

Kaliophilite - $KAlSiO_4$. Commonly contains small amounts of isomorphous $NaAlSiO_4$. In hexagonal prisms or bundles of slender acicular crystals, also in fine threads, cobweb-like.

(Dana 58, p. 585-587; Hatch 49, p. 98-99; Deer 63, V. 4, p. 231-270)

NEPHELINE SYENITE

Group name for feldspathoidal syenites with nepheline predominant. Divided into agpaitic and miaskitic types which are connected by transitional forms. Varieties: foyaite, lujavrite, miaskite, etc.

Nepheline-syenites and more particularly the pegmatitic facies are noteworthy on account of the wide variety of accessories they contain. Many of these are titanium and zirconium silicates. One of the most striking is eudialyte, which in some rocks is obvious in the hand specimen, and which rarely ranks as an essential component.

(Sørensen 74, p. 570; Hatch 56, p. 240)

OKAITE

The okaite of Oka, Quebec, is a coarse-grained melilite-rich rock with biotitic, nephelinitic, or calcitic variants.

(Heinrich 66, p. 44)

PANDAITE (See also pyrochlore)

A mineral of the pyrochlore group: $(Ba,Sr)(Nb,Ti)(O,OH)_7$.

(Gary 1972, p. 513)

PANTELLERITE

A green to black extrusive rock (an alkalic rhyolite) characterized by acmite-augite or diopside, anorthoclase, and cossyrite phenocrysts in either a pumiceous, partly glassy, fine-granined holocrystalline trachytic, or microlitic groundmass composed of acmite and feldspar; plagioclase is typically absent and quartz, rare. Its name is derived from Patelleria, an island in the Mediterranean Sea south of Sicily.

(Gary 1972, p. 514)

PERALKALINE (see agpaitic)

Igneous rocks in which

$$\frac{Na_2O + K_2O}{Al_2O_3} > 1 \quad \text{(molecular proportions)}$$

(Sørensen 74, p. 22; Gary 72, p. 527)

PERIDOTITE

Peridotites of alkaline ultramafic massifs are dominated by titanaugite, olivine (more than 40%), titanomagnetite, perovskite and apatite. May contain nepheline.

(Sørensen 74, p. 571)

PEROVSKITE (Perofskite)

Isometric or orthorhombic pseudo-isometric. Crystals generally cubic in habit and often highly modified, but the faces often irregularly distributed. Cubic faces striated parallel to the edges and apparently penetration-twins.

Composition-Calcium titanate, $CaTiO_3$ = titanium dioxide 58.9, lime 41.1. Iron is present in small amount replacing the calcium.

Occurrence-Perovskite is most commonly found in chlorite, talc, or serpentine rocks. Also, usually as a microscopic constituent, in melilite-, nepheline-, and leucite-basalts. Perovskite occurs as an accessory mineral in basic igneous rocks, often in association with melilite or nepheline. It is also found in thermally metamorphosed calcareous rocks in contact with basic or alkaline igneous rocks.

Loparite. A titanate of cerium, calcium and sodium, perhaps $(Na, Ce, Ca)_2 (Ti,Nb)_2O_6$. In pseudo-cubic twins. Member of the perovskite group. Occurs associated with eudialyte, aegirine, ramsayite, and sphene, on Kola Peninsula.

A related mineral, which has also long passed as perovskite, occurs with magnetite, brookite, rutile, etc., at Magnet Cove, near Hot Springs, Garland Co., Arkansas. It is in octahedrons or cubo-octahedrons, black or brownish black in color and submetallic in luster.

Zirkelite - $(Ca,Fe)(Zr,Ti,Th)_2O_5$. Isometric. Octahedral habit. In twins according to spinel law and in polysynthetic twinning.

Delorenzite. A titanate of iron, uranium and yttrium of uncertain composition. Orthorhombic. Prismatic habit.

Yttrocrasite. A hydrous titanate of the yttrium earths and thorium.

Brannerite. Essentially $(UO,TiO,UO_2)TiO_3$. Prismatic crystals or granular.

(Dana 58, p. 692-693; Deer 62, V. 5, p. 48-55)

PHLOGOPITE

Monoclinic. In form and angles near biotite. Crystals prismatic, tapering; often large and coarse; in scales and plates.

Composition- A magnesium mica, near biotite, but containing little iron; potassium is prominent as in all the micas, and in most cases fluorine. Typically phlogopite is $H_2KMg_3Al(SiO_4)_3$.

Occurrence-Phlogopite is especially characteristic of crystalline limestone or dolomite and is also found in serpentine. It is a product of both regional and contact metamorphism. It is often associated with pyroxene, amphibole, serpentine, etc. It more rarely occurs as a constituent of igneous rocks, being occasionally found in those that are rich in magnesia and poor in iron.

Lepidomelane. Near biotite, but characterized by the large amount of ferric iron present. H. = 3. G. = 3.1. Color black, brown. Lepidomelane occurs chiefly in feldspathic igneous rocks that are rich in iron content but low in magnesia, as certain granites, syenites and nepheline-syenites. It is commonly associated with aegirine or a soda amphibole.

(Dana 58, p. 665-666)

PHONOLITE

Volcanic (fine-grained) equivalent of feldspathoidal syenite, agpaitic to miaskitic, leucocratic. Consists essentially of nepheline, alkali feldspar, soda-rich mafic minerals. In leucite phonolite, leucite is only feldspathoid; leucite-nepheline phonolite contains less leucite than nepheline.

(Sørensen 74, p. 571; Hatch 49, p. 250-253)

PITCHBLENDE. Amorphous uraninite.

(see uraninite)

PYROCHLORE

Isometric. Commonly in octahedrons; also in grains. The natural mineral has a heterogeneous structure but recovers its normal structure on heating.

Composition-Chiefly a niobate of the cerium metals, calcium and other bases, with also titanium, thorium, fluorine. Probably essentially a metaniobate with a titanate, $RNb_2O_6.R(Ti,Th)O_3$; fluorine is also present. The formula suggested by X-ray study is $(Na,Ca)_2(N_b,Ti)_2(O,F)_7$.

Occurrence-Occurs in nepheline-syenite, in veins associated with carbonatites. A variety of pyrochlore from near Wausau, Marathon Co., Wisconsin, has been called *marignacite*.

Koppite. Essentially a pyroniobate of cerium, calcium, iron, etc., near pyrochlore. Has same atomic structure as pyrochlore.

Hatchettolite. A tantalo-niobate of uranium, near pyrochlore. Isometric, octahedral.

Ishikawaite. A niobate and tantalate of uranium, with ferrous iron and rare earths. Orthorhombic.

Ellsworthite. Approximately $CaO.Nb_2O_5.2H_2O$. Contains also uranium oxides, titanium, etc. Isometric. In rounded crystals or massive.

Neotantalite. A niobate and tantalate of iron, manganese, etc. Isometric, in octahedrons.

Chalcolamprite. $Na_4(CaF)_2Nb_2SiO_9$? Isometric. In small octahedrons.

Samirésite. A niobate and titanate of uranium, lead, etc. Isometric. In octahedrons.

Microlite. Essentially a calcium pyrotantalate, $Ca_2Ta_2O_7$, but containing also niobium, fluorine and a variety of bases in small amount. Isometric. Habit octahedral; crystals often very small and highly modified.

Pyrrhite. Probably a niobate related to pyrochlore. Has been classed variously with koppite and with microlite. Occurs in minute orange-yellow octahedrons.

(Dana 58, p. 693-694)

RAUHAUGITE

A carbonatite that contains ankerite. Dolomitic equivalent of sovite.

(Gary 72, p. 591; Heinrich 66, p. 12)

RIEBECKITE

Monoclinic, an amphibole. In embedded prismatic crystals, longitudinally striated.

Composition-Essentially $NaFe^{+3}(SiO_3)_2$ with $FeSiO_3$ in varying proportions.

It corresponds closely to acmite (aegirine) among the pyroxenes.

$Na_2Fe_3^{+2}Fe_2^{+3}Si_8O_{22}(OH)_2$

$Na_2Fe_3^{+2}Fe_2^{+3}[Si_8O_{22}](OH,F)_2$

(Dana 58, p. 577-578; Deer 63, V. 2, p. 333-351)

RING COMPLEX

An association of the ring-shaped igneous intrusive forms *ring dikes* and *cone sheets.*

(Gary 72, p. 611)

RING DIKE

A dike that is arcuate or roughly circular in plan and is vertical or inclined away from the center of the arc. It is associated with *cone sheets* to form a *ring complex.*

(Gary 72, p. 611)

RINKITE

$(Na,Ca,Ce)_3Ti(SiO_4)_2F$

Near johnstrupite in composition. Monoclinic. Crystals prismatic or tabular. Occurs in sodalite-syenite.

Johnstrupite. A silicate of the cerium metals, calcium and sodium chiefly, with titanium and fluorine. In prismatic monoclinic crystals.

(Dana 58, p. 691; Gary 72, p. 485)

SHONKINITE

Dark, coarse-grained rock; augite most abundant, lesser amounts of orthoclase, olivine and biotite, a little nepheline. In a similar rock, *malignite*, orthoclase and nepheline are in roughly equal amounts.

(Hatch 49, p. 311)

SILEXITE

An igneous rock composed essentially of primary quartz (60-100 percent). The term was first used to include a quartz dike, segration mass, or inclusion inside or outside its parent rock.

Syn: igneous quartz; peracidite; quartzfels.

(Gary 1972, p. 658)

SODALITE

Isometric.

Composition = $3NaAlSiO_4.NaCl$ = Silica 37.2, alumina 31.6, soda 25.6, chlorine 7.3. Potassium replaces a small part of the sodium.

Occurrence-Sodalite occurs only in igneous rocks of the nepheline-syenite and related rock groups, as a product of the crystallization of a magma rich in soda; also as a product associated with enclosed masses and bombs ejected with such magmas in the form of lava, as at Vesuvius. Commonly associated with nepheline, cancrinite and eudialyte. In some instances it occurs as a secondary mineral, having been formed through the alteration of nepheline.

(Dana 58, p. 588-589; Hatch 49, p. 99-100; Deer 63, V. 4, p. 289-309)

SODALITE-SYENITE

Sodalite, the only feldspathoid present. Near Julianehaab, Greenland, this rock contains no nepheline. Sodalite is interstitial between lath-shaped sections of microcline-microperthite, but some of it occurs in the form of euhedral rhombododecahedrons embedded in the feldspars.

Sodalite-rich syenites are rare; but an example from St. Hilaire Mt., Quebec, contains up to 70 per cent; while a facies of the sodalite-syenite in Greenland grades into an almost pure sodalite rock, of an intense blue color.

(Hatch 49, p. 239)

SODALITE TRACHYTE

(see Trachyte)

SØRENSENITE

A mineral: $Na_4Be_2SnSi_6O_{16}(OH)_4$.

(Gary 1972, p. 675)

SOVITE

A carbonatite that contains predominantly calcite. Nearly pure calcitic carbonate. Maximum 10% of other species; medium-grained or coarse-grained.

(Heinrich 66, p. 12; Gary 72, p. 676)

SPHENE

(See Titanite)

(Hatch 49, p. 120-121)

STEENSTRUPINE

Rhombohedral. As well-developed crystals, irregular grains, often metamict.

Composition-$Na_2Ce(Mn,Ta,Fe^3)H_2(Si,P)O_4)_3$.

(Sørensen 62, Dana 58, p. 582)

SYENITE

Intrusive equivalent of trachyte.

Alkali feldspar rock, often with minor oligoclase. Sometimes quartz- or nepheline-bearing. Leucocratic with biotite, hornblende and augite. When sodic pyroxenes and amphiboles (and feldspathoids) are present: alkali syenite.

(Sørensen 74, p. 573; Gary 72, p. 717; Hatch 49, p. 231-235)

THORIANITE (See also uraninite)

Chiefly $(Th,U)O_2$. Isometric, cubic habit. G. = 9.3. Color black. Radioactive.

(Dana 1958, p. 746)

THORITE

Thorium silicate, $ThSiO_4$, like zircon in form and structure. Usually hydrated, black in color, and then with G. = 4.5-5; also orange-yellow and with G. = 5.19-5.40 (*orangite*). Commonly altered and isotropic. Orangite and a variety containing uranium oxide, *uranothorite*, have been found.

(See also zircon)

(Dana 58, p. 611)

THOROGUMMITE

A secondary mineral: $Th(SiO_4)_{1-x}(OH)_{4x}$, also with rare-earth elements. It is isostructural with thorite and may contain as much as 31.4% uranium. Syn: *mackintoshite*.

(Gary 1972, p. 738)

TINGUAITE

A textural variety of phonolite. Nepheline microsyenite, having tinguaitic texture; needles of aegirine occur interstitially in mosaic of alkali feldspar and feldspathoids, mainly nepheline.

(Sørensen 74, p. 574; Hatch 49, p. 252-253; Gary 72, p. 743)

TITANITE, SPHENE

Monoclinic. Twins rather common, both contact-twins and cruciform penetration-twins. Crystals very varied in habit; often wedge-shaped and flattened; also prismatic. Sometimes massive, compact; rarely lamellar. Transparent to opaque.

Varieties-Ordinary: (a) *titanite;* brown to black, the original being thus colored, also opaque or subtranslucent. (b) *sphene;* of light shades, as yellow, greenish, and often translucent; the original was yellow. *Ligurite* is an apple-green sphene. *Lederite* is brown, opaque, or subtranslucent. *Spinthère* is a green variety.

Titanomorphite is a white, mostly granular alteration-product of rutile and ilmenite, not uncommon in certain crystalline rocks; here also belongs most leucoxene.

Manganesian; *greenovite.* Red or rose-colored, owing to the presence of a little manganese.

Containing yttrium or cerium. Here belong *grothite, alshedite, eucolite-titanite. Keilhauite* or *yttrotitanite* contains about 12 per cent $(Y,Ce)_2O_3$.

Composition-$CaTiSiO_5$ or $CaO.TiO_2.SiO_2$ = Silica 30.6, titanium dioxide 40.8, lime 28.6. Iron is present in varying amounts, sometimes manganese and also yttrium in some kinds.

Occurrence-Titanite, as an accessory component, is widespread as a rock-forming mineral, though confined mostly to the igneous rocks of intermediate composition; it is much more common in the plutonic granular types than in the volcanic forms. Thus it is found in the more basic hornblende granites, syenites, and diorites, and is especially common and characteristic in the nepheline-syenites.

Molengraaffite. A titano-silicate of lime and soda. Monoclinic. In imperfect prismatic crystals. From a rock, "lujaurite", in the Pilands Berg, near Rustenberg, Transvaal, South Africa.

Fersmannite. $2Na_2(O,F_2).4CaO.4TiO_2.3SiO_2$. Monoclinic. Crystals show a pseudo-tetragonal habit. Found associated with feldspar and aegirine in veins in nepheline-syenite at Chibines Mts., Kola Peninsula, Russia.

Tscheffkinite. Chevikinite. A titano-silicate of the cerium metals, iron, etc., but an alteration product, more or less heterogeneous, and the composition of the original mineral is very uncertain. Usually massive, amorphous. In orthorhombic or monoclinic (pseudo-orthorhombic) crystals from Madagascar. Occurs in granitic rocks and apparently as an alteration product of other minerals.

Astrophyllite. Probably $^{1}R_{4}R^{2}_{4}Ti(SiO_4)_4$ with ^{1}R=H, Na, K, and ^{2}R=Fe, Mn chiefly, including also Fe_2O_3. Orthorhombic. In elongated crystals; also in thin strips or blades; sometimes in stellate groups.

(Dana 58, p. 688-691)

TRACHYTE

Alkali feldspar-rich fine-grained volcanic rock; often with subordinate oligoclase. May be quartz-,nepheline- or sodalite-bearing. Extrusive equivalent of syenite. When sodic pyroxene and amphibole present:

alkali trachyte. Often trachytic texture. Corresponds in mineral content with the syenites.

(Sørensen 74, p. 574; Hatch 49, p. 246-255)

TUGTUPITE

$Na_4BeAlSi_4O_{12}Cl$. It is related to sodalite; occurs with analcime and other Be minerals in veins at Ilímaussaq.

(Gary 1972, p. 759)

UNCOMPAHGRITE

A plutonic rock composed chiefly of melilite, along with pyroxene, opaque oxides, perovskite, apatite, calcite, anatase, melanite, and occasionally phlogopite.

The uncompahgrite of Iron Hill, Colorado (Larsen 1942) varies from a coarse-grained to a pegmatitic textured rock of intermediate structural position and relative age, and consists chiefly of melilite (68%) and diopside (15%). It has characteristically been beset by a multitude and variety of alterations.

(Sørensen 74, p. 575; Gary 72, p. 765; Heinrich 66, p. 43)

URANINITE

(Cleveite. Broggerite. Nivenite. Pitchblende.)

Isometric. In octahedrons (o), also with dodechedral faces (d); less often in cubes. Crystals rare. Usually massive and botryoidal; also in grains; structure sometimes columnar, or curved lamellar.

Composition-A uranate of uranyl, lead, usually thorium (or zirconium), often the metals of the lanthanum and yttrium groups; also containing the gases nitrogen, helium and argon, in varying amounts up to 2.6 per cent. Calcium and water are present in small quantities; iron also, but only as an impurity.

It has been suggested that the UO_3 present in uraninite is due to oxidation and that the original isometric substance is UO_2 (*ulrichite*) with Isomorphous replacements of ThO_2. This is considered to be isomorphous with thorianite.

Variations

The minerals provisionally included under the name uraninite are as follows:

1. Crystallized. *Uranniobite* from Norway. In crystals, usually octahedral, occurs as an original constituent of coarse granites. The variety from Branchville, Connecticut, which is as free from alteration as any yet examined, contains chiefly UO_2 with a relatively small amount of UO_3. Thoria is prominent, while the earths of the lanthanum and yttrium groups are only sparingly represented.

Broggerite, as analyzed by Hillebrand, gives the oxygen ratio of UO_3 to other bases of about 1 : 1; it occurs in octahedral crystals.

Cleveite and *nivenite* contain UO_3 in larger amount than the other varieties mentioned, and are characterized by containing about 10 per cent of the yttrium earths. Cleveite is a variety from Arendal, Norway, region occurring in cubic crystals modified by the dodecahedron and octahedron. It is particularly rich in the gas helium. Nivenite occurs massive, with indistinct crystallization. It is more soluble than other kinds of uraninite, being completely decomposed by the action for one hour of very dilute sulphuric acid at 100°. Material stated to be UO_3 in composition occurring in canary-yellow crystals with uraninite and uranophane in quartzite near Lusk, Wyoming, has been named *lambertite*.

2. Massive, amorphorous or cryptocrystalline.

Pitchblende. Contains no thoria; the rare earths also absent. Water is prominent and the specific gravity is much lower than that of uraninite, doubtless largely due to alteration. Here belong the kinds of pitchblende which occur in metalliferous veins, with sulphides of silver, lead, cobalt, nickel, iron, zinc, copper.

Occurrence-As noted above, uraninite occurs either as a primary constituent of granitic pegmatites or as a secondary mineral with ores of silver, lead, copper, etc.

(Dana 58, p. 745-746)

URANOTHORIANITE

A variety of thorianite containing uranium; an intermediate member in the uraninite-thorianite isomorphous series.

(Gary 1972, p. 770)

URTITE

A light-colored member of the ijolite series. 0-30% mafic minerals, especially acmite and apatite. Nephelinolite with more than 70% nepheline; devoid of feldspar, differs from ijolite in smaller content of mafic minerals.

(Sørensen 74, p. 575; Gary 72, p. 770; Hatch 49, p. 311)

URTITES-IJOLITES-MELTEIGITES

(Quoted from Heinrich, 1966)

If any particular group of rocks may be considered especially characteristic of the carbonatitic ring complexes, the urtite-ijolite-melteigite series certainly qualifies. Ijolites in particular are widespread. Rocks of this series tend to occur in intermediate rings, or arcuate

> bodies, or as cores. The two essential minerals are nepheline and pyroxene, the latter ranging in composition from diopside to aegirine-diopside. A high Ca content in the pyroxene is characteristic. Melanite is a widespread constituent, not uncommonly essential... Apatite, perovskite, sphene, biotite, and calcite are common accessories. Cancrinite may replace nepheline, and hastingsite may replace the pyroxene.
>
> Texturally and compositionally the rocks are exceedingly variable and, indeed, over but very short distances. Not uncommonly urtites, ijolites, and melteigites, including several varieties of each (besides subordinate malignites and juvites in some cases) are closely intermingled in what must be treated as a single mappable unit.
>
> (Heinrich 66, p. 45)

VILLIAUMITE

NaF. Isometric. In small carmine colored grains. Abnormally birefringent and pleochroic. Heated to 300°C becomes isotropic. Soft. G. = 2.8. Found in nepheline syenites.

(Dana 1958, p. 461)

XENOTIME

A brown, yellow, or reddish tetragonal mineral: YPO_4. It is isostructural with zircon, and often contains erbium, cerium, and other rare earths, as well as thorium, uranium, aluminum, calcium, beryllium, zirconium, or other elements. Xenotime occurs as an accessory mineral in granites and pegmatites; sometimes in minute embedded crystals generally distributed in granitic and gneissoid rocks. Commonly associated with zircon and often encloses that mineral.

(Gary 1972, p. 798; Dana 1958, p. 700)

ZIRCON

Tetragonal. Twins. Commonly in square prisms, sometimes pyramidal. Also in irregular forms and grains. *Hyacinth* is the orange, reddish and brownish transparent kind used for gems.

Composition-$ZrSiO_4$ or ZRO2 . SiO_2 = Silica 32.8, zirconia 67.2. A little iron (Fe_2O_3) is usually present. Some varieties contain hafnium oxide up to 4 per cent. The rare earths occur in the variety *hagatalite* from Hagata, Iyo Province, Japan. *Oyamalite* is a variety containing considerable phosphorus from Oyama, Iyo Province, Japan.

Occurrence-A common accessory constituent of igneous rocks, especially those of the more acid feldspathic groups and particularly the kinds derived from magmas containing much soda, as granite, syenite, diorite, etc. Is generally present in minute crystals, but in pegmatitic facies often in large and well-formed individuals. In certain types of nepheline-syenites the zircons are large and have the status of an essential constituent, particularly in the coarse-grained "zircon-syenite-pegmatites." Occurs more rarely elsewhere, as in granular limestone, chloritic and other schists; gneiss; sometimes in iron-ore beds. Crystals are common in most auriferous sands. Sometimes found in volcanic rocks, probably in part as inclusions derived from older rocks.

Malacon is an altered zircon. *Cyrtolite* is related but contains uranium, yttrium and other rare elements.

Naëgite is apparently zircon with yttrium, niobium-tantalum, thorium, and uranium oxides. Occurs in spheroidal aggregates near Takoyama, Mino, Japan.

Orvillite is an altered zircon from Caldas, Minas Gerais, Brazil.

Orangite and variety containing uranium oxide, uranothorite, have been found.

(Dana 58, p. 610-611; Hatch 49, p. 127-128)

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APPENDIX D

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