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Varieties of Granitic Uranium Deposits and Favorable Exploration Areas in the Eastern United States

JOHN J. W. ROGERS, PAUL C. RAGLAND, RICHARD K. NISHIMORI,
JEFFREY K. GREENBERG, AND STEVEN A. HAUCK

Abstract

Primary uranium deposits formed by granitic magmas can be classified on two bases: petrologic process of ore formation and tectonic occurrence. The processes of ore formation can be subdivided as follows:

1. Syngenetic, orthomagmatic disseminations.
2. High-temperature, late-magmatic deposits, including pegmatite stage deposits, such as the pegmatite-alaskite deposits of Rössing, Bancroft, and Crocker Well; contact metasomatic deposits, including occurrences of garnetiferous skarns around pegmatite-alaskite bodies; high-temperature vein deposits, commonly associated with quartz-fluorite veins; and autometasomatic deposits, including many of the disseminated and local concentrations in albite-riebeckite granites.
3. Local pegmatites formed by in situ melting of country rocks.

Based on occurrence, granitic uranium deposits can be described in the context of two ideal end members: (1) anatectic, migmatitic, pegmatite-alaskite bodies formed by remobilization of preexisting basement—a type example is the Rössing deposit of Namibia (South West Africa)—limited geochemical information suggests that these deposits have very low Th/U ratios, are probably rich in elements that are concentrated by surface processes, and may have high initial $^{87}Sr/^{86}Sr$ ratios; and (2) post-tectonic, alkali-rich (including albite-riebeckite) granites in stocks probably derived directly from mantle or deep crustal levels in the form of diapiric magmas—limited geochemical evidence suggests that these deposits have Th/U ratios > 1 and are rich in elements that form late differentiates during magmatic and deuteric processes; some bodies have low initial $^{87}Sr/^{86}Sr$ ratios.

The preceding considerations permit the selection of seven areas in the eastern United States that are most favorable for the development of uranium deposits in crystalline, dominantly granitic, rocks: (1) the Lithonia Gneiss of Georgia; (2) the northern North Carolina Blue Ridge (Grandfather Mountain window and Crossnore plutons); (3) the central and northern Virginia Blue Ridge (Irish Creek tin district and Robertson River and Lovingston Formations; (4) the Raleigh belt of North Carolina and Virginia; (5) the 300-m.y.-old pluton belt of Georgia, South Carolina, North Carolina, and Virginia; (6) portions of the White Mountain Magma Series of New England; and (7) the molybdenum-copper province of Maine.

Introduction

THE expanding search for uranium ore in the United States has extended to many types of deposits in addition to the conventional sandstone ores that have been most productive in the past. A number of the different types of ore deposits, and the problems involved in their use, have been discussed in recent symposia and summaries (e.g., I.A.E.A., 1977; Jones, 1977; Ruzicka, 1977). In particular, the development of the massive Rössing deposit (Berning et al., 1976) of South West Africa (Namibia) has given impetus to the exploration of crystalline rocks. Armstrong (1974) predicts that low-grade porphyry-type deposits in igneous rocks will become major sources of uranium in the future. Some aspects of uranium in granites have recently been reviewed by Moreau (1977).

The present authors have conducted a 2-year investigation of economic uranium concentrations in igneous rocks. Two reports have been issued as a result of this work. Nishimori et al. (1977) discuss the theoretical basis for exploration for uranium in granitic rocks, and Greenberg et al. (1977) apply these criteria to the identification of zones of potential economic interest in the eastern United States.

Uranium is a mobile element. In internal processes in the earth (generally in the reduced, tetravalent, form) it is classified as a lithophilic element and tends to accumulate in the later differentiates of igneous melts. It may oxidize to the hexavalent

state as the complex uranyl ion (UO_2^{+2},) which generally permits even more extensive separation into fluid and volatile phases. The tendency of hexavalent uranium to form fluoride and carbonate complexes may enhance this accumulation. In sediments, these complex ions are easily moved, thus causing the ultimate formation of sedimentary uranium ores.

All metals pose geologic problems for the explorationist. The mobility of uranium, however, adds even more complexities. In fact, the adage that "ore is where you find it" may not be applicable to most surficial exploration for uranium owing to surface leaching, transportation, and redeposition, which can easily remove all indications of ore deposits at depth and leave no ground or air radiometric or rock sample anomalies. Conversely, shallow accumulations of surface uranium may yield false signatures of nonexistent buried deposits.

Thus, in the search for uranium in igneous rocks, the geologist gains an advantage with an understanding of the fundamental geologic and geochemical processes that concentrate uranium and the environments in which ore is most likely to occur. The absence of conventional surface anomalies cannot be used to condemn potential exploration area, nor can simple airborne radiometry maps be used as an indication of detailed location.

This paper is divided into three parts. First is an overview of the basic igneous processes that cause concentration of uranium and the types of rocks in which these deposits are most likely to occur. Second is a discussion of the source of uranium and the tectonic environments in which uranium-rich igneous rocks are likely to form. Third is an application of these principles to the delineation of favorable belts for uranium exploration in crystalline rocks in the eastern United States.

This paper is restricted to a discussion of those deposits in which high-uranium concentrations are caused by magmatic processes. These deposits include syngenetic occurrences in granites and occurrences in which extensive uranium mineralization in wall rocks is presumably caused by fluids formed during the magmatic crystallization process. The paper does not cover the closely related topic of vein deposits, including such well-known suites as the Hercynian massifs of France and various deposits of central Europe. Hydrothermal deposits have been reviewed by Rich et al. (1977).

Uranium in Igneous Processes

There are two practical reasons why it is necessary to understand the mode of formation of a uranium deposit. One is that the method of formation has a major influence on the shape and magnitude of the deposit. Primary crystallization of uranium minerals within an igneous body will obviously restrict the ore to the pluton. In homogeneous plutons the ore may be distributed throughout much of the body, allowing the entire pluton to be mined, generally for low-grade, large-tonnage ore. In differentiated plutons the ore may be restricted to specific rock types, generally the more siliceous and alkali-rich varieties. Similarly, contact metasomatic, pegmatitic, hydrothermal, etc., deposits all have specific shapes, tenors of ore, and relationships to pluton and country rocks.

A second major reason for understanding the origin of a uranium deposit is connected with the surface mobilization of uranium mentioned in the Introduction. If surface measurements of uranium concentrations are not reliable indicators of ore at depth, then it is necessary to discover some elements associated with uranium that are less readily leached during weathering and may remain as pathfinders for economic concentrations of uranium at depth. The metals associated with uranium clearly depend on the process of deposition. For example, primary uranium in normal members of batholithic sequences should be closely associated with high concentrations of thorium; thus, high Th concentrations in surface rocks may indicate U enrichment at depth. Conversely, vein and pneumatolytic deposits might show a close association of U and Mo (which is also an accompaniment of U in some sedimentary ores), in which case Mo anomalies might be a useful pathfinder for uranium.

General geochemistry of uranium

Uranium geochemistry has been summarized in a variety of places (Rogers and Adams, 1969a and b; I. A. E. A., 1970, 1974). The most important aspects from the standpoint of the ore geologist are:

1. The uranous (U^{+4}) ion has a radius of 0.89 A and fits very poorly into the lattices of major rock-forming minerals. Thus, it tends to accumulate in residual magmas during igneous differentiation. The uranium may then crystallize in late-stage primary minerals such as zircon, allanite, sphene, xenotime, pyrochlore, or, where sufficiently concentrated, in some member of the uraninite-pitchblende (UO_2-UO_{2+x}) series. Some primary deposits also contain uranothorianite, $(U, Th)O_2$; davidite (a complex hydrous iron-uranium-rare earth-titanium oxide); and brannerite (principally uranium titanate).

2. Instead of crystallizing in primary minerals within the magmatic rock itself, the uranium may be sufficiently segregated into volatile phases so that it is distributed by late-stage processes or escapes from the magma chamber in pegmatitic, pneumatolytic, and high-temperature hydrothermal fluids. Minerals commonly associated with this stage of deposition

are pitchblende, brannerite, davidite, uranophane, and other uranyl silicates in minor amounts.

3. In late-stage, water-rich fluids, uranium is wholly or partly oxidized to the hexavalent form. Deposition of partially oxidized material commonly forms pitchblende (UO_{2+x}) in veins or hydrothermally disseminated deposits. Veins and broader disseminations may also contain uranyl minerals similar to those of sedimentary deposits and include various silicates, phosphates, carbonates, etc.

4. Uranium and thorium are closely associated in most primary magmatic rocks, but separation gradually occurs during igneous differentiation. Thus, the Th/U ratio commonly increases from 2 to 3 in mafic rocks to values of 5 to 6 in the more differentiated plutons of an igneous sequence. Some of this separation may be the result of uranium loss into late-stage fluids, in part because of oxidation of the uranium. Thorium is less efficiently separated into vein fluids, and thus primary igneous deposits tend to have Th/U ratios much higher than pegmatites and veins.

Classification of processes

Based on the preceding considerations, Table 1 shows the possible types of igneous processes that could lead to an economic concentration of uranium. The table also predicts the general form of the deposit and indicates examples of actual deposits.

Syngenetic uranium deposits in igneous rocks (type 1 in Table 1) form during the orthomagmatic stage of crystallization of magmas, the stage during which approximately 90 percent of the magma crystallizes. Uranium-bearing minerals crystallize at or about the same time as the other mineral components of the host rock and are distributed in a disseminated fashion.

Uranium deposits formed from late magmatic differentiates and associated fluids and vapors are subdivided into four genetic types in Table 1. Deposits formed during the pegmatite stage of crystallization (type 2A) comprise deposits in pegmatites, alaskitic pegmatites, or aplites that apparently crystallized after the main body of magma from late-stage, volatile-rich differentiates. In many cases, these deposits are concentrated near the margins of the bodies. This group includes some of the largest igneous uranium deposits in the world, such as Rössing, Bancroft, and Crocker Well.

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

Metasomatic deposits of uranium (type 2B) associated with intrusive igneous rocks are most likely formed by the action of ore-carrying fluids or vapors emanating from magmas. Used here, the term metasomatic uranium deposit applies mainly to carbonate or mafic igneous country rocks that have undergone metasomatic replacement during ore deposition; an equivalent term would be contact replacement deposit. The deposit at Mary Kathleen, Australia, has been proposed as an important example of this type of deposit (Hughes and Munro, 1965), although Hawkins (1975) suggests that the uranium in the deposit may have been mobilized from preexisting sedimentary rocks during metamorphism. Other examples of contact replacement are the uranium-rich skarns at Bancroft and Rössing.

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

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

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

Uranium deposits at the contact of some igneous intrusives are composed entirely of secondary uranium minerals, as at Austin, Nevada (Sharp and Hetland, 1954). At the Midnite mine, Washington (Nash and Lehrman, 1975; Nash, 1977), ore-grade concentrations are caused largely by secondary processes, but soaking of the contact area around the principal igneous intrusive body may have caused high-temperature formation of protore from magmatically derived fluids. These deposits are not discussed in this paper because so much of the concentration process appears to have been caused by low-temperature fluids.

Relationship of processes to experimental studies

The deposits discussed in the preceding classification have formed through a considerable spectrum

TABLE 1. Genetic Classification of Uranium Deposits in Intrusive Igneous Rocks

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

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

   Form of deposit: Has shape of igneous body; may be localized in specific zones if body is differentiated.

   Examples:
   - Granites
     - Conway Granite, New Hampshire (Billings and Keevil, 1946; Hurley, 1956; Rogers, 1964; Rogers et al., 1965); Granite Mts., Wyoming (Malan, 1972; Stuckless, 1977); Silver Plume Granites, Colorado (Phair and Gottfried, 1964); and granitic and alkalic rocks in the eastern Seward Peninsula, Alaska (Miller and Bunker, 1976)
   - Alkaline rocks
     - Lovozero massif, Kola Peninsula, USSR (Gerasimovsky et al., 1968); Ilimaussaq, Greenland (Sorenson, 1970; Bohse et al., 1974); and Pocos de Caldas, Brazil (Ramos and Fraenkel, 1974)
   - Carbonatites
     - Oka and Lake Nippising, Canada (Rowe, 1958); Phalaborwa, South Africa (Verwoerd, 1967; von Backström, 1974); and Tapira (Sobrinho, 1974) and Araxa (Maciel and Cruz, 1973), Brazil

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

   A. Deposits formed during the pegmatite stage of crystallization

      Characteristics: Pegmatites, aplites, alaskitic pegmatites ranging in texture from pegmatitic to aplitic; may show evidence of replacement (metasomatism) due to attack by late-stage magmatic fluids and vapors; primary uranium minerals such as uraninite, davidite, uranothorianite, or brannerite disseminated through host rock; uraniferous Zr, Ta, Nb, etc., minerals in alkaline pegmatites.

      Form of deposit: May have shape of pluton; commonly localized along contacts, cupolas, etc.

      Examples:
      - Granites
        - Rössing, South West Africa (Berning et al., 1976); Bancroft, Ontario (Satterly, 1957; Cunningham–Dunlop, 1967; Robinson, 1960); Olary district including Crocker Well, Australia (Campana, 1956; Rayner, 1960); Wheeler Basin, Colorado (Young and Hauff, 1975); and Currais Novos, Brazil (Ramos and Fraenkel, 1974)
      - Alkaline rocks
        - Pegmatites and lujavrites at Ilimaussaq, Greenland (Sorenson, 1970; Bohse et al., 1974)

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

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

      Form of deposit: Irregular bodies along contacts.

      Examples:
      - Deposits in pyroxenites and skarns at Bancroft, Ontario (Satterly, 1957); skarns at Rössing, South West Africa (Berning et al., 1976); and Mary Kathleen, Australia (Hughes and Munro, 1965)

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

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

      Form of deposit: Veins

      Examples:
      - Quartz-fluorite veins at Rössing, South West Africa (Berning et al., 1976); calcite-fluorite-apatite veins at Bancroft, Ontario (Satterly, 1957); brannerite-rich quartz veins at Crocker Well, Australia (Campana and King, 1958); carbonate-hematite-fluorite veins at Bokan Mt., Alaska (MacKevett, 1963); and carbonate-fluorite veins at Oka carbonatite, Canada (Rowe, 1958)

   D. Autometasomatic deposits

      Characteristics: Disseminations of primary uranium minerals in nonpegmatitic igneous host rocks; crystallization of uranium minerals is speculated to be approximately contemporaneous with autometasomatic alteration by magmatic vapors or fluids.

      Form of deposit: May have shape of pluton, but commonly localized near contacts.

      Examples:
      - Ross–Adams deposit, Bokan Mt., Alaska (MacKevett, 1963); and Kaffo Valley, Nigeria (McKay et al., 1952; Bowden and Turner, 1974)

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

   Characteristics: No associated comagmatic pluton; pegmatites apparently formed by partial melting of layers of biotite gneiss.

   Form: Localized concentrations in metamorphic sequences.

   Examples: Mt. Laurier, Canada (Allen, 1971; Kish, 1975); and Thackaringa belt, New South Wales (Willis and Stevens, 1971)

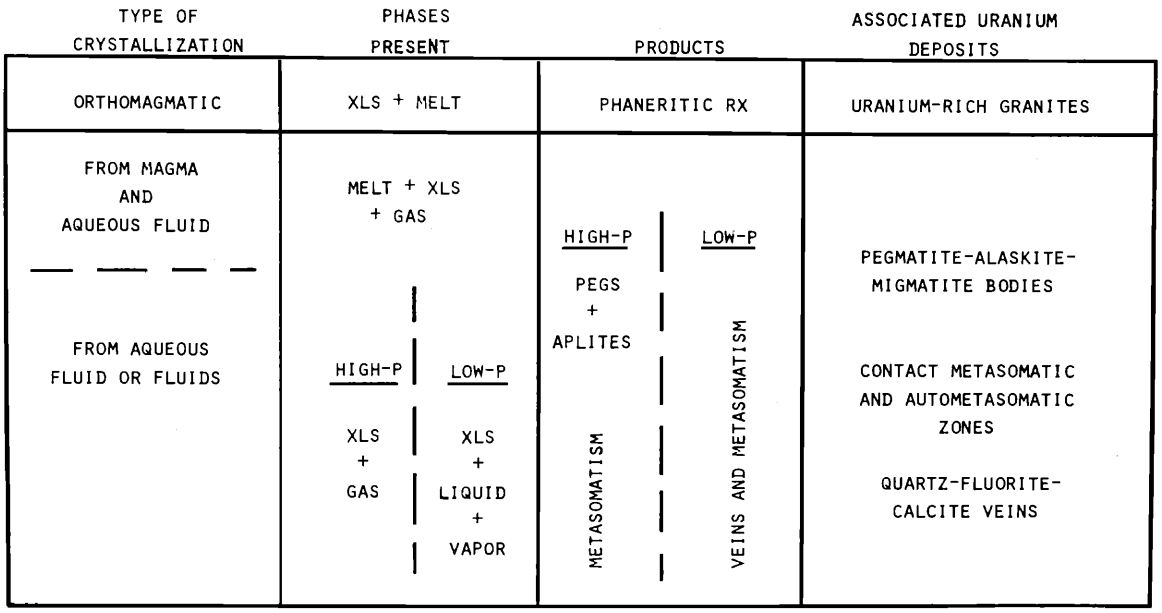

FIG. 1. Relationships between processes of uranium ore formation and cooling of granitic melts. Portions of the diagram are modified from Jahns and Burnham (1969). The subdivision between high-pressure generation of a homogeneous gas phase and low-pressure fractionation into separate vapor and liquid phases is about 1 kb (Luth and Tuttle, 1968). Progressive change with cooling is shown from orthomagmatic, high-temperature crystallization to low-temperature precipitation from hydrous phases. Uranium deposits are formed primarily during high-temperature, high-pressure crystallization from hydrous gas phases in pegmatite-alaskite-migmatite bodies and also during hydrothermal (vein and autometasomatic) activity at lower temperatures and pressures.

ranging from magmatic crystallization through pegmatitic and pneumatolytic processes to vein-type deposition. This spectrum can be explained in terms of evidence obtained from a variety of studies on the relationships between silicate melts and volatile phases.

Experimental studies by Tuttle and Bowen (1958), Luth and Tuttle (1968), Jahns and Burnham (1969), and Whitney (1975) subdivide granite crystallization into three general stages: (1) crystallization of liquidus crystals from the silicate melt (liquid + crystals); (2) crystallization of liquidus minerals and active generation of an aqueous fluid or vapor phase (hereafter called the fluid phase) from the coexisting melt (liquid + crystals + fluid); and (3) subsolidus stage reactions, after completed crystallization of the silicate melt (crystals + fluid).

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

Variations in pressure, temperature, water content, and volatile content of the magma cause differences in the duration and timing of these three stages of granite crystallization. At low pressures (less than 1 kb), granites with 3 to 4 percent initial water content will exsolve a fluid phase at sufficiently high temperatures above the solidus so that crystals, liquid, and fluid coexist over a large temperature range (Whitney, 1975). Second boiling, the early release of hydrothermal fluids from magmas, is believed to explain certain features of porphyry copper deposits and is probably important for uranium ore formation. At higher pressures (5–10 kb), the behavior of water-undersaturated granites is quite different; the following are some of the differences between high- and low-pressure granite crystallization.

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

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

3. At pressures in excess of about 1 kb and water-undersaturated conditions, the fluid phase is not exsolved until the melt and crystals are at a temperature that is approximately 20°C above the solidus. Crystals, liquid, and fluid thus coexist over a narrow temperature range above this pressure. However, crystals, liquid, and fluid coexist over a large temperature range at pressures below about 1 kb (Whitney, 1975).

Uraniferous pegmatitic granites at deposits such as Bancroft and Rössing may have formed as a consequence of stage 2 of granite crystallization (crystals + liquid + vapor). The Rössing deposit is discussed more completely in a later section, but several features which may be explained by high-pressure crystallization of hydrous granite magma should be mentioned here.

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

2. The fluid phase at higher pressures (greater than 5 kb) can contain only about 10 percent granitic solids (Luth and Tuttle, 1968, p. 544). Furthermore, Luth and Tuttle state that "the vapor changes from granite composition to 96+ percent silica as the temperature drops a few degrees." Thus, once voided of these granitic solids, the remaining fluid at lower temperature could constitute a more "normal," quartz-rich, hydrothermal solution, giving rise to hydrothermal vein deposits; hydrothermal vein deposits grade into pegmatite deposits at Bancroft. While the granitic solids are still in solution, the fluid phase could act as a granitizing, metasomatizing agent. At Rössing, the alaskites allegedly grew as a consequence of metasomatism (Berning et al., 1976); moreover, the wall rocks surrounding the alaskites apparently were altered by a granitizing, metasomatizing fluid, and it has been suggested that "granitizing fluids saturated and replaced already migmatized country rock" (Berning et al., 1976, p. 361).

3. The narrow temperature range (less than 20°C) that separates the magmatic, pegmatitic, and hydrothermal stages of crystallization of granites at pressures in excess of about 1 kb may account for the affiliation of pegmatitic, metasomatic, and vein deposits in the vicinity of batholiths at Bancroft.

Source and Tectonic Environments of Uranium Deposits

A knowledge of the petrologic processes described above is necessary in order to predict the detailed location of uranium in and around specific intrusive bodies. In order to determine broad regions which might be fruitful for reconnaissance exploration, it is necessary to understand the relationship between uranium concentration, the source of the uranium, and the tectonic environment in which the igneous body occurs. Among the most important distinctions to make is the one between those areas in which uranium has been released directly from the mantle into the igneous sequence and those areas in which uranium has been derived by remobilization of earlier crustal materials.

Separation of uranium from the mantle

The mechanism by which uranium is released from the mantle is unclear and has many puzzling aspects. Much of the problem can be demonstrated by a brief discussion of Th-U-Pb systematics in volcanic rocks. Most basalts (and gabbros) of island arcs, mid-ocean ridges, and other areas of direct mantle derivation contain Pb isotope ratios that have evolved in mantle regions in which the Th/U ratio has attained a present value of 3.5 to 4 (e.g., Tatsumoto, 1966, 1969; Church and Tatsumoto, 1975); this Th/U ratio is also characteristic of chondritic meteorites and appears to be the primordial ratio for the entire earth. Oceanic and arc tholeiitic rocks, however, commonly have Th/U ratios of 1 to 2, thus signifying a preferential release of uranium relative to thorium from the mantle into the derived melt during partial melting.

Preferential release of uranium relative to thorium may be explainable by a comparison of the relative bonding energies between oxygen and the two cations. Although the U^{+4} ion is slightly smaller (0.89 A) than the Th^{+4} (0.95 A), and thus might be expected to remain selectively in solid phases, there are major differences in electronegativity of the U^{+4} (1.7) and Th^{+4} (1.3); (Pauling's electronegativity values). Assigning the O^{-2} ion a radius of 1.40 A and an electronegativity of 3.5 permits the use of the following equation (Damon, 1968) for the calculation of bonding energy:

$$BE = \frac{330\ Z_c(1 - e^{-0.25\Delta^2})}{R}$$

where BE = bonding energy, Z_c = charge on cation, Δ = electronegativity difference between cation and

anion, and R = sum of cation and anion radii (interatomic distance). The results of this calculation are bonding energies of 320 kcal/mole for U^{+4} and 394 kcal/mole for Th^{+4}. If the bonding energy with oxygen is the critical factor in determining the release of elements from solid phases, the uranium would be expected to be released preferentially to thorium, thus explaining the relatively low Th/U ratios in primary mafic rocks. The tendency of the Th/U ratio to increase toward the later differentiates of igneous sequences is opposite to the prediction that would be made on the basis of bonding energy calculations, but the ratio may be largely controlled by loss of hexavalent uranium from the magma chamber during igneous differentiation.

In short, there is a poorly understood mechanism by which uranium is released from the mantle into liquid and fluid phases. Where these phases are mafic magmas, the concentration in the crystallized rocks is generally low (1 ppm or less), and significant concentration of uranium must depend on crystallization differentiation or possibly even liquid immiscibility (Philpotts, 1976). This differentiation produces rocks with uranium concentrations up to a maximum of a few tens ppm and having Th/U ratios in the vicinity of 5. Concentrations of uranium high enough to be economic probably can be obtained in such rocks only by separation of uranium into late-stage volatile phases and localized deposition from hydrothermal fluids.

It is possible that uranium may be released from the mantle not only into magmas but directly into volatile phases. This possibility is supported by the evidence cited above for the ease of separation of uranium from the mantle. Such broad release of uranium might be expected to yield areas of regional, moderate uranium mineralization, with the possibility of high concentration in localized zones of favorable structure or wall-rock lithology.

Mobilization of uranium by crustal reactivation

Mobilization of uranium from preexisting crustal rocks is the second likely possibility for a source of mineralizing fluids. In particular, sedimentary processes have the ability to concentrate uranium into certain rocks (e.g., organic-rich shales) and to separate it from thorium (e.g., into organic-rich shales and other rocks of low Th/U ratios). Anatectic processes may then operate either on primary, felsic igneous rocks containing moderate levels of uranium enrichment or on sediments, which may contain moderate to high initial uranium concentrations. These anatectic processes may either produce volatile, mineralizing phases or felsic magmas, which could later differentiate to fluids. In either case, there is the possibility for the development of regional or local hydrothermal deposits, plus the possibility that some silicic magmas may be sufficiently enriched in uranium that the primary, crystallized rock itself could be a source of low-grade, disseminated ore.

Relationship of uranium deposits to geologic age

Relationships of uranium deposits to geologic age and/or processes of crustal evolution have been discussed by a number of writers (e.g., Robertson, 1974; Nishimori et al., 1977; Robertson and Tilsley, 1977). One of the best examples of an age relationship is the concentration of uranium in basal Proterozoic conglomerates, which has been attributed to a variety of processes, such as change in atmospheric composition at the end of the Archean or release of uranium from the earth's interior during an end-of-Archean orogenic pulse. Uranium deposits are also common in Grenville-age terranes (e.g., Bancroft, Ontario) and in Pan-African orogenic belts of 500 to 600 m.y. age (e.g., Rössing, Nambia; eastern Egypt; Currais Novos, Brazil). The reasons for the concentration of uranium deposits at a particular time are unknown, but they may be related to the necessity for accumulating radioactive elements in the upper mantle and lower crust for considerable periods of time in order to supply the energy needed for worldwide orogenic pulses.

One very significant observation has been the absence of uranium deposits from Archean terranes. This absence correlates with the generally less lithophilic composition of the Archean crust than of the Proterozoic crust (e.g., Eade and Fahrig, 1971). One explanation for this observation could be that mantle differentiation and crustal evolution occurred only to a limited extent in the Archean and generally did not produce lithophile-rich, granitic crust in significant amounts. An alternative explanation is that Archean crust was originally as uraniferous as younger crusts but lost mobile elements such as uranium during later orogenic activity.

Tectonic classification of igneous uranium deposits

Based on these general concepts for the generation of uranium-rich materials, a classification can be proposed for igneous uranium deposits that places the process of uranium mineralization in its tectonic setting. For this purpose, two end members of igneous deposits have been established: the Bokan Mountain deposit of southern Alaska, which is considered to be an ideal example of mantle-derived uranium; and the Rössing deposit of South West Africa (Namibia), which is considered to be an ideal example of anatectic remobilization of preexisting sialic crustal material. The identifying characteristics of these deposits are shown in Table 2.

Bokan Mountain: The Bokan Mountain deposit of

TABLE 2. Summary of Principal Differences between the Rössing and Bokan Mountain Models for Granitic Uranium Deposits

Characteristic	Rössing Model	Bokan Mt. Model
Lithology	Pegmatite-alaskite-gneiss; anatectic granite and migmatite	Alkaline and/or peralkaline granite; associated syenites; commonly albite-riebeckite granite
Derivation	Reworked and recycled sialic crust	Mantle or lower crust
Initial Sr isotope ratios	Generally greater than 0.710	Generally less than 0.710
Th/U ratios	Generally less than 1.0	Generally greater than 1.0
Levels of erosion	Deep	Shallow
Levels of emplacement	Catazonal	Epizonal
Tectonic stage	Syntectonic	Post-tectonic
Age	Commonly Proterozoic to early Paleozoic	Any age (post-Archean)
Tectonic setting	Orogenic	Anorogenic or post-orogenic
Metamorphic rank of country rocks	Middle- to upper-amphibolite	Any rank (including unmetamorphosed)

southeastern Alaska is associated with a Mesozoic intrusion of peralkaline albite-riebeckite granite. The pluton is a post-tectonic plug intruding geosynclinal sediments of upper Proterozoic and lower Paleozoic age (Churkin and Eberlein, 1977). Four types of uranium deposits have been recognized by MacKevett (1963) in the Bokan Mountain area: (1) primary disseminations and segregations of uranium minerals in the peralkaline granite—it appears that the minerals became more concentrated in the later phases of crystallization, possibly as a result of magmatic hydrothermal activity; (2) primary mineralization (syngenetic) in the aplites and pegmatites associated with the granite; (3) secondary hydrothermal deposition (epigenetic) in veins and fractures with some replacement; and (4) secondary hydrothermal deposition in pores of clastic sedimentary rocks.

With very few exceptions, the uranium deposits are in or near the granite stock. The exceptions include prospects in an older series of pegmatites associated with quartz monzonite-granodiorite and one prospect in a fractured mafic dike. There can be little doubt, however, that the main source of the uranium is the peralkaline granite. The ore-forming process may have taken place in two stages or it may have acted in a continuous progression. MacKevett (1963) discussed a two-stage process in which a peralkaline granite of anomalous uranium content initially crystallized to form the types 1 and 2 concentrations. Sometime later, hydrothermal activity moved uranium-rich solutions into the surrounding country rocks and thus produced types 3 and 4 deposits, which are the principal uranium occurrences in the Bokan Mountain area. The contrasting continuous process requires the hydrothermal enrichment system from granite to country rock to be originally magmatic. That is, the same magmatic fluids that caused the primary uranium ore mineralization within the granite also produced mineralized aplites and pegmatites and enriched the country rock in uranium.

As indicated above, Bokan Mountain and many post-tectonic plutons are considered to be mineralization sites of uranium derived fairly directly from the mantle. There is, of course, no absolute proof of this source of uranium, and the proposal is based on the following considerations.

1. The Bokan Mountain pluton shows no evidence of having been produced by local anatexis, in strong contrast to the stratigraphically restricted migmatites of the Rössing area (described below). The nature of the crust into which the Bokan Mountain pluton was intruded is uncertain. Churkin and Eberlein (1977) cite limited evidence that the southern part of Prince of Wales Island, containing Bokan Mountain, contains trondhjemitic igneous rocks, as old as 700 m.y., intrusive into earlier geosynclinal sediments. This observation might indicate development of a sialic crust in late Proterozoic time, which would be consistent with the general tendency of alkaline igneous rocks to intrude areas of crustal stability. Eugeosynclinal activity in the area, however, continued at least through the lower Paleozoic, which raises questions as to the degree of crustal stability in any portion of the southeastern Alaska area. Thus, although it is conceivable that sialic crust was available for anatectic or sedimentary recycling to produce the Bokan Mountain magma, there is far less evidence for such an origin than there is for the Rössing area and similar migmatitic, syntectonic terranes. Therefore the present writers consider that the most likely origin for the Bokan Mountain magma is either a partial melting of the mantle or a partial melting of sediments formed by the erosion of eugeosynclinal, mantle-derived, volcanic and plutonic rocks. The lack of cratonic contribution and the mantle source of such eugeosynclinal assemblages has been discussed by Rogers and McKay (1972).

2. Insofar as chemical evidence is available, the Th/U ratio of the Bokan Mountain pluton appears to be high (greater than 1). A Th/U ratio greater than 1 is generally characteristic of such mantle-

derived volcanic rocks as mid-ocean ridge basalts and continental tholeiites (Rogers and Adams, 1969a). Conversely, Th/U ratios greater than 1 are not found in magmatic rocks produced by local anatexis, as at Rössing. Too much reliance should not be placed on Th/U ratios of surface samples, however, owing to the continual mobilization of uranium by ground water in near-surface rocks (e.g., Stuckless, 1977).

3. As discussed above, substantial release of uranium from the mantle appears to be a common process.

4. Some post-tectonic plutons with geochemical similarities to Bokan Mountain have initial $^{87}Sr/^{86}Sr$ ratios of 0.705 and lower (see Table 3 and discussion in next section). These low ratios indicate derivation of the magmas by partial melting of the mantle or primitive, possibly lower, crust with low Rb/Sr values. Strontium isotopic data, however, are not available for Bokan Mountain. Wenner et al. (1978) have found low $^{18}O/^{16}O$ initial ratios in some 300-m.y.-old, possibly mantle-derived, plutons of the Appalachian piedmont, which may be Bokan Mountain-type with respect to uranium potential. The low $^{18}O/^{16}O$ ratios are generally correlated with low initial $^{87}Sr/^{86}Sr$ ratios. Oxygen isotope data, however, are also lacking for Bokan Mountain, and the usefulness of this geochemical criterion is not yet clear.

Rössing: The Rössing deposit of South West Africa (Namibia) occurs in the Damaran orogen, a northeast-southwest-striking belt most recently deformed in Pan-African time, about 500 m.y. ago. (Cilfford, 1967; Jacob, 1974). The orogen extends between older cratons to the southeast and northwest. The belt is approximately 400 km wide, and the regional trend is northeast-southwest in all portions. The southeastern one-third of the width of the belt is a graywacke assemblage that may be ensimatic, but evidence of suturing between the cratons on either side has not been found within the exposed portions of the belt.

The northwestern two-thirds of the Damaran orogen contains a wide variety of rock types. The entire area appears to be underlain by preexisting (possibly Archean) sialic basement, now exposed at numerous places as mantled gneiss domes. The basement is overlain by quartzites, arkoses, marbles, and other shallow-water sediments that have now been metamorphosed to moderate- to high-rank gneisses and schists. The belt appears to pitch to the northeast, thus exposing deeper levels of the orogen toward the southwest, near the coast. High uranium concentrations occur in the more deeply eroded portions of the orogen, where basement rocks, high-rank metasedimentary rocks, and anatectic granites are closely intermingled.

The principal evidence that many of the granites in the deeply eroded portion of the Damaran belt are anatectic and/or syntectic is the stratigraphic restriction of two of the major intrusive types. One of the older granites (G_4) is the major host of the uranium deposits and is restricted primarily to the Nosib Metasedimentary Group, with some metamorphism of marbles in the overlying Rössing Formation and minor intrusion into younger metasedimentary rocks. The development of skarns along contacts of G_4 and the Rössing marbles, plus the conformity of overlying metasediments with the Rössing Formation, indicates that G_4 postdates most of the sedimentation in the area, and thus its restriction to the Nosib Group is presumably the result of very local anatectic derivation of the G_4 melt. The G_4 granite at Rössing also has a high $^{87}Sr/^{86}Sr$ initial ratio of 0.734 (Kröner and Hawkesworth, 1977).

High uranium concentrations are associated with the G_4 granites. These granites consist primarily of quartz and alkali feldspars with minor biotite. Mafic minerals are sufficiently scarce in most samples that the G_4 has been referred to as an alaskite. Anhedral textures predominate, and the grain size is highly variable, becoming pegmatitic in many places. There is no readily discernible pattern of grain-size variation.

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

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

least some of the secondary distribution is caused by late magmatic processes. A number of workers (e.g., Jacob and Hambleton-Jones, 1977), however, emphasize the importance of supergene activity.

Significance and examples

As indicated in the preceding discussion, recognition of the source of the igneous body and of tectonic conditions during its formation is important for exploration purposes. In general, only vein-type deposits will be of major importance in areas of post-tectonic plutons of the Bokan Mountain type, whereas disseminated deposits may be found in Rössing-type bodies.

Both the Rössing and Bokan Mountain types of deposits form only under conditions that permit considerable fractionation of uranium from initial source rocks. At Rössing, this fractionation has consisted of igneous differentiation following extensive crustal reworking during the complex history of the Damaran orogenic belt, which may involve several cycles of igneous crystallization, sedimentation, metamorphism, and anatexis. At Bokan Mountain, the fractionation has been accomplished by the production of a highly differentiated, alkali-rich, and peralkaline melt and an ultimate release of volatiles. Neither of these fractionation mechanisms appears to have been effective during the early history of the earth, and igneous uranium deposits are unknown in Archean rocks.

TABLE 3. Examples of Granitic Uranium Deposits

Bokan Mountain

1. Cretaceous granites of Seward Peninsula, Alaska (Miller, 1972; Miller and Bunker, 1976; Staatz and Miller, 1976)
2. Early Tertiary and some Precambrian (Pikes Peak) plutons in Front Range, Colorado (Wells, 1960; Phair and Gottfried, 1964; Phair and Jenkins, 1975)
3. White Mt. Magma Series, New England (Billings and Keevil, 1946; Adams et al., 1962; Rogers, 1964; Rogers et al., 1965)
4. Younger Granite at Kaffo Valley, Nigeria (McKay et al., 1952; Bowden and Turner, 1974)
5. Younger Granites of Red Sea Hills, Egypt (Hussein et al., 1970; Hussein and El Kassas, 1970)

Rössing

1. Wheeler Basin, Colorado (Young and Hauff, 1975)
2. Charlebois Lake, Saskatchewan (Mawdsley, 1952; Lang et al., 1962; Beck, 1970)
3. Bancroft, Ontario (Satterly, 1957; Robinson, 1960; Lang et al., 1962; Cunningham–Dunlop, 1967)
4. North shore of St. Lawrence River, Quebec, including Sept Iles, Baie Johan Beetz, etc. (Baldwin, 1970)
5. Crocker Well, Olary district, Australia (Campana, 1956; Campana and King, 1958; Johnson, 1958; Rayner, 1960; Thompson, 1965)
6. Six Kangaroos area of Cloncurry–Mt. Isa District, Australia (Brooks, 1960; Carter et al., 1961)
7. Nanambu, Nimbuwah, and Rum Jungle complexes of Katherine–Darwin area, Australia (Dodson et al., 1974; Ayers and Eadington, 1975)
8. Currais Novos, Brazil (Favali, 1973; Ramos and Fraenkel, 1974)
9. Minor gneiss and migmatite in Laborador uranium area (Beavan, 1958; Gandhi et al., 1969)

Table 3 shows a number of igneous-related uranium deposits and their principal characteristics. Many of them compare closely with Bokan Mountain or Rössing, thus indicating the general validity of the two-fold classification. Some deposits, however, have characteristics intermediate between those of the two end-member varieties. In particular:

1. Deposits in Wheeler Basin, Colorado (Young and Hauff, 1975), show many elements of similarity to Rössing. They occur in gneiss-migmatite terranes, are concentrated in zones that have been highly injected by the 1.4-b.y.-old Silver Plume Granite, and occur in rocks in the upper amphibolite facies of metamorphism. Principal uranium concentrations are in biotitic masses scattered throughout the injection zone. The major uranium mineral is uraninite, with minor uranophane and other uranyl minerals. The only significant differences between Wheeler Basin and Rössing are that the Th/U ratio of the Silver Plume host rock at Wheeler Basin is high (as much as 10; Phair and Gottfried, 1964) in contrast with the very low Th/U ratio (<1) in the G_4 granites near Rössing; and that, whereas Rössing was formed in an area of ensialic crustal reactivation, this process has not been identified at Wheeler Basin.

2. The Conway Granite of New Hampshire is the principal member of the Mesozoic, post-tectonic White Mountain Magma Series, which occurs in a variety of ring dikes and plugs throughout New England. The granite has a number of similarities to Bokan Mountain, including its post-tectonic intrusion into a former geosynclinal terrane and a high Th/U ratio. The Conway Granite, however, is dominantly potassic, rather than sodic; also, peralkalinity is shown by other members of the series rather than by the Conway Granite. The Conway Granite is largely a potential thorium resource (Adams et al., 1962), and uranium concentrations rarely exceed 20 ppm. It is possible that some smaller bodies of the White Mountain Series, which are also more sodic and peralkaline, may be better potential uranium sources (e.g., four bodies in Vermont discussed in a later section).

3. The albite-riebeckite granites of Kaffo Valley, Nigeria, are similar to Bokan Mountain in virtually all petrologic respects, including post-tectonic intrusion, sodic and peralkaline character, vein and disseminated uranium deposits, and high Th/U ratios in host rocks. The Kaffo Valley granites, however, were intruded into a craton stabilized in Proterozoic time, whereas the Bokan Mountain pluton intruded a terrane of uncertain crustal characteristics;

eugeosynclinal activity, however, persisted in the Bokan Mountain area at least throughout lower Paleozoic time. Both the Kaffo Valley and Bokan Mountain areas were apparently crustally stabilized at the time of intrusion, which may be the only requirement for the development of the igneous host rock.

Another possibly anomalous characteristic of the Kaffo Valley pluton may be its initial $^{87}Sr/^{86}Sr$ ratio. The ratio has not been determined for Kaffo Valley itself, but measurements on an apparently correlative body (Amo) of the Nigerian Younger Granite suite yield an initial $^{87}Sr/^{86}Sr$ ratio of 0.7212 (Bowden and Turner, 1974). This high ratio contradicts the concept of mantle derivation of the pluton. Unfortunately, no strontium isotope work has been done on the Bokan Mountain pluton, and thus adequate comparisons cannot be made.

4. Uranium deposits associated with the Younger Granites of the Red Sea Hills of Egypt are enigmatic. The Younger Granites were formed in Pan-African time (500–600 m.y. ago), have low initial $^{87}Sr/^{86}Sr$ ratios of 0.702 to 0.706, are highly potassic, and range. from peraluminous to slightly peralkaline (Rogers et al., 1978). They are clearly post-tectonic and thus might be expected to compare with Bokan Mountain. Measured Th/U ratios, however, are approximately 2 (Rogers et al., 1978), which is clearly in the range of mantle-derived magmatic rocks but considerably lower than the 4 to 6 expected of highly potassic granites (Rogers and Adams, 1969a).

The lower-than-expected Th/U ratios in the Younger Granites lead to interesting speculations concerning the source of the uranium for the entire area. Complete mineralogical studies on the occurrence of the uranium have not been made, but radiometric surveys clearly show that uranium minerals are disseminated through the more felsic granites and in broad zones in the surrounding wall rocks. If the uranium mineralization in the wall rocks resulted from uranium-bearing fluids escaping from adjoining granites, then the Th/U ratio in the source granite should increase as a result of the uranium loss; this process has been proposed to explain the general tendency for more felsic igneous rocks to have higher Th/U ratios than more mafic varieties (Rogers and Adams, 1969a, b). Thus, Th/U ratios of 2, instead of the expected 4 to 6, in the Younger Granites presumably indicate that the uranium in the area was not derived from the plutons themselves. One explanation is that the entire area, including plutons and wall rocks, was soaked in uranium-bearing fluids structurally associated with the granites but derived from some source at depth. This process would explain both the comparatively low Th/U ratios of the granites and the dissemination of uranium in wall rocks. The area, then, may be an example of the direct release of uranium from the mantle in volatile phases.

Igneous Uranium in the Eastern United States

The preceding sections can be summarized in the form of a set of criteria that can be used to judge the favorability of an area for uranium exploration and the varieties of deposits that the area may contain. These criteria are the following.

General (for all types of deposits):

1. Belts or regions of broadly similar geologic features in which uranium mineralization has already been reported in several (preferably numerous) areas. Although, as discussed above, the mobility of uranium makes it impossible to predict uranium concentrations at depth from surface measurements, geologically homogeneous areas that do not contain reported uranium occurrences somewhere must be considered less favorable than those that do.
2. Abundance of silicic and alkali-rich intrusive rocks. Uranium tends to concentrate in these highly differentiated rock types.
3. Presence of suitable structural traps and wall-rock lithology to promote deposition from volatile phases.
4. Abundance of fluorite or other fluorine-bearing phases. These minerals indicate the availability of fluorine, which apparently aids in the distribution of uranium because of the formation of uranium-fluoride complexes.
5. Post-Archean age of the magmatic activity. As discussed previously, for some reason Archean rocks are impoverished in lithophilic elements such as uranium.

Rössing-type deposits:

1. Occurrence in zones of crustal remobilization; ensialic belts deformed between cratons or craton fragments. The high concentration of uranium in these deposits apparently has its original source in sialic crustal rocks.
2. Medium- to high-rank metamorphic terranes (amphibolite facies). The deposits can form only in areas of migmatization and anatexis.
3. Pegmatitic, highly silicic granites and pegmatite dikes and veins, in which the uranium-bearing volatile phases can concentrate. Metasomatically altered pegmatites are of particular interest.
4. Contact zones of pegmatite-aplite-alaskite bodies. These zones are areas of particular concentration of volatiles; in some cases particularly high concentrations of uranium are associated with biotitic zones.
5. High initial $^{87}Sr/^{86}Sr$ ratios indicative of crustal remobilization.

6. Commonly associated fluorine (Greenberg et al., 1977).

Bokan Mountain-type deposits:

1. Post-tectonic plutons intruding any variety of wall rocks. Possibly most important in areas of former ensimatic geosynclinal activity.
2. Sodic plutons, generally with high concentrations of albite; possibly peralkaline (shown by presence of riebeckite, etc.).
3. Abundance of favorable structures and wall-rock lithologies. Most of these deposits are probably veins and hydrothermal disseminations.
4. Major pathfinder elements may be thorium, niobium, and fluorine.

Based on these criteria, a general survey has been made of crystalline terranes in the eastern United States; the details are reported by Greenberg et al. (1977). Seven areas have been chosen as having the greatest possible potential for further uranium exploration (Fig. 2).

Rössing types:

1. the Lithonia Gneiss of Georgia;
2. the northern North Carolina Blue Ridge (Grandfather Mountain window and Crossnore plutons);
3. the central and northern Virginia Blue Ridge (Irish Creek tin district and Robertson River and Lovingston Formations); and
4. the Raleigh belt of North Carolina and Virginia.

Bokan Mountain-type deposits:

1. the 300-m.y.-old pluton belt of Georgia, South Carolina, North Carolina, and Virginia;
2. portions of the White Mountain Magma Series of New England; and
3. the molybdenum-copper province of Maine.

As discussed below, the placing of some of these areas into the Rössing or Bokan Mountain category is problematical, and some areas appear to contain both types.

The Lithonia Gneiss is a layered granitic gneiss containing numerous pegmatites and showing fluidal structure. It is in the sillimanite grade of metamorphism. The gneiss probably represents metamorphism of Precambrian-early Paleozoic rocks about 450 m.y. ago (Butler, 1972); it has been intruded by the post-tectonic Stone Mountain Granite, which has an Rb-Sr isochron age of 291 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.725, indicating its probable derivation by anatexis of the Lithonia Gneiss (Whitney et al., 1976). A number of radioactivity anomalies are found in the Lithonia Gneiss and related rocks (Higgins and Zietz, 1975).

The northern North Carolina Blue Ridge contains two areas of particular interest: the Grandfather Mountain window, which seems to fit a Rössing model; and the Crossnore plutons, which have properties of both Rössing and Bokan Mountain.

The Grandfather Mountain window contains up to 6,000 m of arkoses, siltstones, shales, and conglomerates (Grandfather Mountain Formation) overlying a variety of granites, gneisses, and augen gneisses of Grenville age (about 1,000 m.y.). All rocks apparently underwent low-rank metamorphism about 350 m.y. ago and now appear as a window through the major Blue Ridge thrust sheet. A more complete description of the geology is given by Bryant and Reed (1970).

Uranium occurs in various ways in the Grandfather Mountain window. The Wilson Creek Gneiss contains uraninite-filled joints in sheared pegmatites localized along phyllonite zones. Heavy mineral beds in the Grandfather Mountain Formation (as well as the Chilhowee Group of an overlying thrust sheet) contain metamict zircon and allanite. Abundance of these minerals in generally arkosic rocks is one of the criteria listed by Dennison and Wheeler (1975) for potential sandstone-type uranium ores.

The Crossnore plutonic-volcanic group contains a series of peralkaline granites and gabbros intrusive into the Blue Ridge basement complex. The granites are chemically similar to volcanic rocks of the Grandfather Mountain and Mt. Rogers Formations (Rankin, 1975) and are characterized by the presence of aegerine and/or riebeckite with common accessory fluorite. The granites are also rich in Nb, Y, and rare earth elements. Although the granites have many of the properties of Bokan Mountain deposits, they also have initial $^{87}Sr/^{86}Sr$ ratios of 0.7125 (Odom and Fullagar, 1971), indicative of crustal reworking. Geochronologic studies of the granites are inconsistent (Rankin, 1970; Odom and Fullagar, 1971) but generally agree on a late Precambrian age. Rankin (1975) believes that the series was associated with crustal rifting.

The central and northern Virginia Blue Ridge contains two areas of potential uranium deposits: the Irish Creek tin district, Rockbridge County; and the Robertson River Formation and Lovingston Gneiss in Greene, Madison, and Rapahannock Counties.

The Irish Creek tin district is formed in a presumed Precambrian hypersthene granodiorite intrusive into quartz-feldspar gneisses. The granodiorite is older than the regional metamorphism. Tin occurs as cassiterite in quartz veins and greisens. Fluorine is abundant in the area, occurring as fluorapatite in the granite and as fluorite in the greisens and veins. A more complete description is given by Koschmann et al. (1942) and Glass et al. (1958).

The Robertson River Formation is a massive, fine-grained granite with variable amounts of hornblende

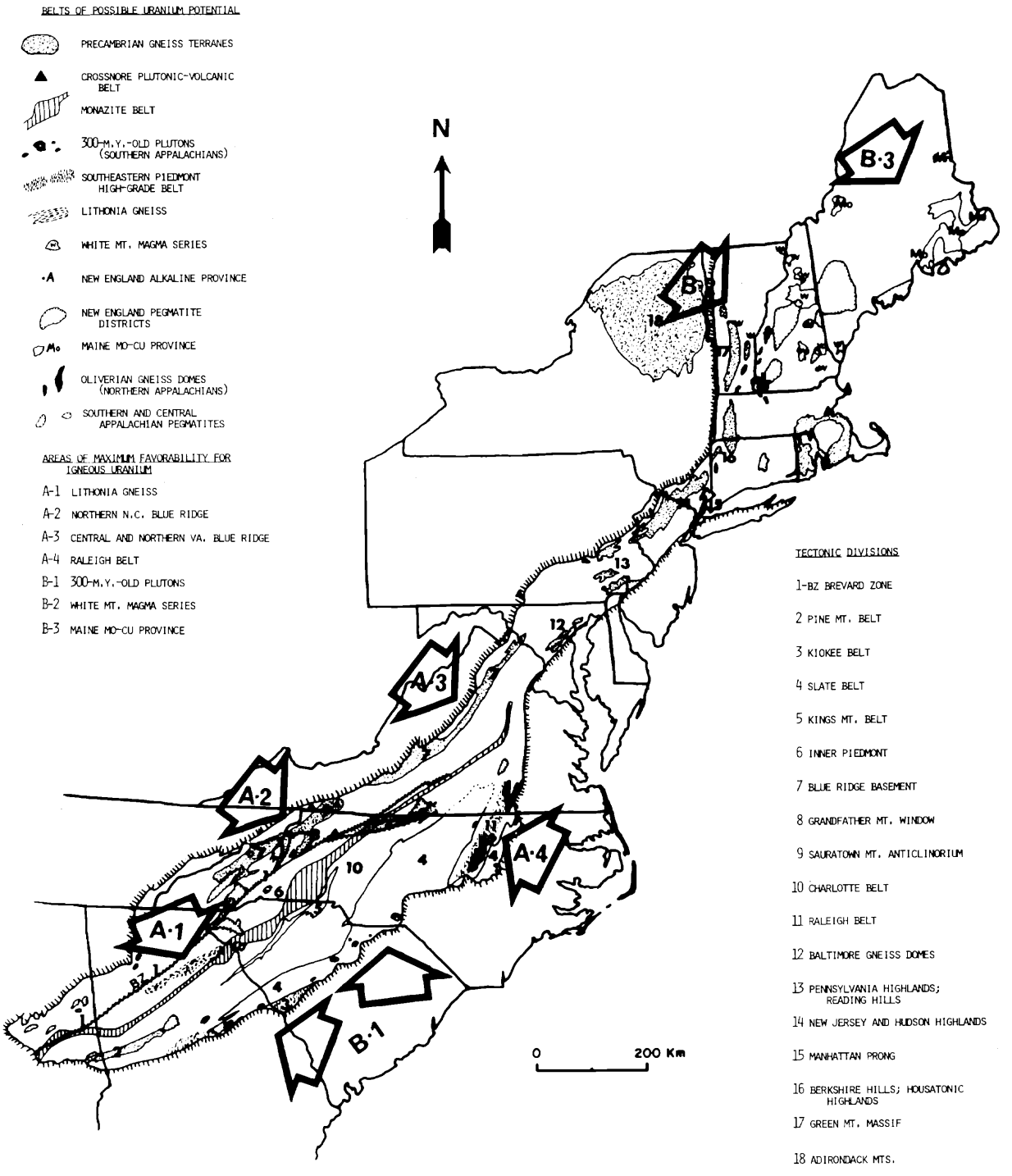

FIG. 2. Tectonic index map of the eastern United States showing areas of maximum favorability for igneous uranium deposits. The seven specific areas of principal interest are shown by arrows and are discussed more completely in the text. Belts of possible uranium potential investigated by the writers are shown by various symbols. Major, readily recognizable, tectonic divisions are shown by numbers.

and biotite (Allen, 1963) and an age of about 700 m.y. Some portions of the granite contain aegerine and/or riebeckite and abundant accessory fluorite (Rankin, 1975, 1976); thus it has some similarities to nearby Crossnore-type plutons. Its post-tectonic character might place it in the Bokan Mountain

category, but no information is available on Th/U or Sr isotopic ratios.

The Lovingston Gneiss is a quartz-biotite augen gneiss widely distributed in the northern Virginia Blue Ridge (Allen, 1963). It is foliated, gradational into many wall rocks, and clearly syntectonic. Monazite and allanite are disseminated in the unit, and radioactivity anomalies are known. Thus, the Lovingston Gneiss may fit fairly closely with a Rössing-type model.

The Raleigh belt of North Carolina and Virginia consists of high-rank (up to kyanite-grade) gneiss and schist intruded by several syntectonic granites. The plutons have been dated in the range of 300 to 450 m.y., and one pluton has an initial $^{87}Sr/^{86}Sr$ ratio of 0.7141 (Fullagar, pers. commun.), indicating possible origin by anatexis. Pegmatites are common throughout the belt. Most of the features of Rössing-type deposits are present.

The 300-m.y.-old plutons of Georgia, South Carolina, North Carolina, and Virginia are post-tectonic and represent the last major thermal event in the southern Appalachians (Fullagar and Butler, in press). There are approximately 20 plutons consisting of typical calc-alkaline, coarse- to medium-grained granite intrusive into rock types of all metamorphic grades. Most granites have initial $^{87}Sr/^{86}Sr$ ratios of 0.702 to 0.705 (Fullagar, 1971; Fullagar and Butler, in press), but a few plutons have initial ratios greater than 0.710. Molybdenum-copper mineralization is associated with four plutons (with low initial strontium isotope ratios), and uranium contents up to 12 ppm have been measured in the Sparta Granite of Georgia (Wanger, 1972; Garvey, 1975). Different portions of the Sparta pluton, however, have initial $^{87}Sr/^{86}Sr$ ratios as high as 0.744 (Fullagar and Butler, in press). The high strontium isotope ratios and calc-alkaline character of some bodies indicate that these plutons do not fit all aspects of the Bokan Mountain model.

The White Mountain Magma Series is a suite of Mesozoic, post-tectonic ring dikes and isolated plutons in New England. Rock types range from gabbro to granite; some of the rocks are peralkaline, containing riebeckite, and most rocks are alkali-rich. Initial $^{87}Sr/^{86}Sr$ ratios are low (about 0.706; Foland et al., 1971), and the Th/U ratios are high (Rogers, 1964). Ages of the various intrusive complexes range from 235 to 100 m.y., and Foland and Faul (1977) show that the distribution of ages does not support previous proposals that the White Mountain Series represents a Mesozoic plume track. The Conway Granite is the largest rock body in the series and has been proposed as a low-grade thorium resource on the basis of its average concentration of about 50 ppm thorium (Adams et al., 1962). Uranium is not particularly abundant in the Conway Granite (10–15 ppm; Rogers, 1964), but a number of isolated plutons in Vermont belonging to the White Mountain Series are more sodic, show minor molybdenum mineralization, and have radiometric anomalies. These smaller bodies may be very similar to Bokan Mountain and include: Mt. Monadnock (Wolff, 1929; Chapman, 1954); Mt Ascutney (Daly, 1903; Chapman and Chapman, 1940); Cuttingsville (Eggleston, 1918; Laurent and Pierson, 1973); and Barber Hill (Laurent and Pierson, 1973).

The molybdenum-copper province in Maine has formed in the vicinity of a number of granitic to quartz monzonitic intrusions. Magmatic activity in the area appears to have occurred throughout much of Ordovician to Devonian time (Spooner and Fairbairn, 1970). At the Catheart Mountain Mo-Cu deposit, Schmidt (1974) described an epizonal or subvolcanic type of igneous emplacement. Greenberg et al. (1977) list a number of high-level plutons in Maine that were apparently formed in the general age range and that show molybdenum mineralization associated with pegmatites and fluorite. The suite as a whole is hard to define, but many of the plutons appear to have characteristics similar to those of Bokan Mountain.

The various areas and rock types listed above are certainly not the only ones of promise for uranium exploration in the eastern United States. The writers feel, however, that they are where the present evidence indicates maximum potential for major discovery.

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Department of Geology
University of North Carolina at Chapel Hill,
Chapel Hill, North Carolina 27514

R. K. N. AND S. A. H. PRESENT ADDRESS:
UNION CARBIDE METALS DIVISION
GRAND JUNCTION, COLORADO 81501
July 25, 1978

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