12. VOLCANIC-ASSOCIATED URANIUM

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S.S. Gandhi and R.T. Bell

IDENTIFICATION

Deposits of this type consist of disseminations and veins of uraninite/pitchblende in volcanic rocks that are commonly felsic and subalkaline to peralkaline felsic in composition, but some potassic alkaline mafic to intermediate rocks also host uranium occurrences. The volcanic rocks are formed mainly in late- or postorogenic settings and continental extensional tectonic environments. They occur in all volcanic lithofacies, from proximal to distal in setting, including volcaniclastic sediments. Molybdenum, flourine, thorium, rare-earth elements, and lead-zinc, are commonly enriched in the deposits and may be of economic importance.

The best examples in Canada are the trachyte-hosted Rexspar deposit in British Columbia and the rhyolite-hosted Michelin deposit in Labrador (Fig. 12-1). The important foreign examples include the ignimbrite-hosted Sierra Pena Blanca deposits in Mexico, rhyolite-hosted Pleutajokk deposit in Sweden, Anderson deposit in moat sediments in southwestern United States, and deposits in a collapsed caldera complex in the Streltsov region in eastern Russia.

Felsic volcano-plutonic complexes also host genetically related, uraniferous polymetallic deposits characterized by abundant iron oxides that form the matrix of breccias, e.g. the giant Olympic Dam deposit in South Australia and the Sue-Dianne deposit in the Northwest Territories. These are treated separately under the Kiruna/Olympic Dam-type deposits (see Type 22), which include deposits that contain little or no uranium.

Gandhi, S.S. and Bell, R.T.
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IMPORTANCE

In Canada, mineable deposits of the volcanic-associated type account for less than 1% of the uranium resources in the 'reasonably assured' category. At present in the western world, they probably account for less than 5% of the 'reasonably assured' resources. However, in the Russian Republic and China they represent a significant proportion of the uranium resources.

No uranium has yet been produced from the Canadian deposits of this type, unless the U-Ag-Cu-Co-Ni veins (described as "Arsenide vein uranium-silver", subtype 14.2) of mined out deposits in the Great Bear Lake area in Northwest Territories are included. These veins are hosted by volcanic and volcaniclastic rocks, but are much younger (isotopic ages of 1870-1840 Ma for the host rocks versus 1775-1500 Ma for the veins), and hence apparently have no direct genetic relation to those discussed here.

SIZE AND GRADE OF DEPOSIT

The Michelin deposit in Labrador contains about 7000 t U at an average grade of 0.1% U. Several smaller deposits occur in this volcanic district, and together they contain an additional uranium resource of comparable magnitude. The Rexspar deposit in British Columbia contains about 700 t at an average grade of 0.077% U.

Foreign deposits commonly range between 500 and 10 000 t of contained uranium in ores grading from 0.04 to 4% U (Cox and Singer, 1986, p. 162-164). The Anderson deposit in U.S.A. contains 20 000 t. A cluster of deposits in the Streltsov district in the Russian Republic contains as much as 100 000 t of uranium.

GEOLOGICAL FEATURES

Geological setting

The deposits are associated with felsic volcanic complexes that developed in late- and postorogenic settings and extensional tectonic environments. Their local settings are varied: calderas, lava and ash flow fields, taphrogenic volcanic-sedimentary basins, domes, and breccias (including diatremes).

The deposits in Labrador and Sweden are hosted by areally extensive sequences of flows, tuffs, and volcaniclastic sediments that developed during the late- and post-tectonic stages of the Makkovikian-Svecofennian orogeny 1900-1700 Ma (Gandhi, 1978, 1986; Lindroos and Smellie, 1979; Gustafsson, 1981; Hålenius et al., 1986; Schärer et al., 1988). A number of uranium occurrences are also found in felsic volcanic rocks of the Great Bear magmatic zone, which was developed on the west side of the Wopmay

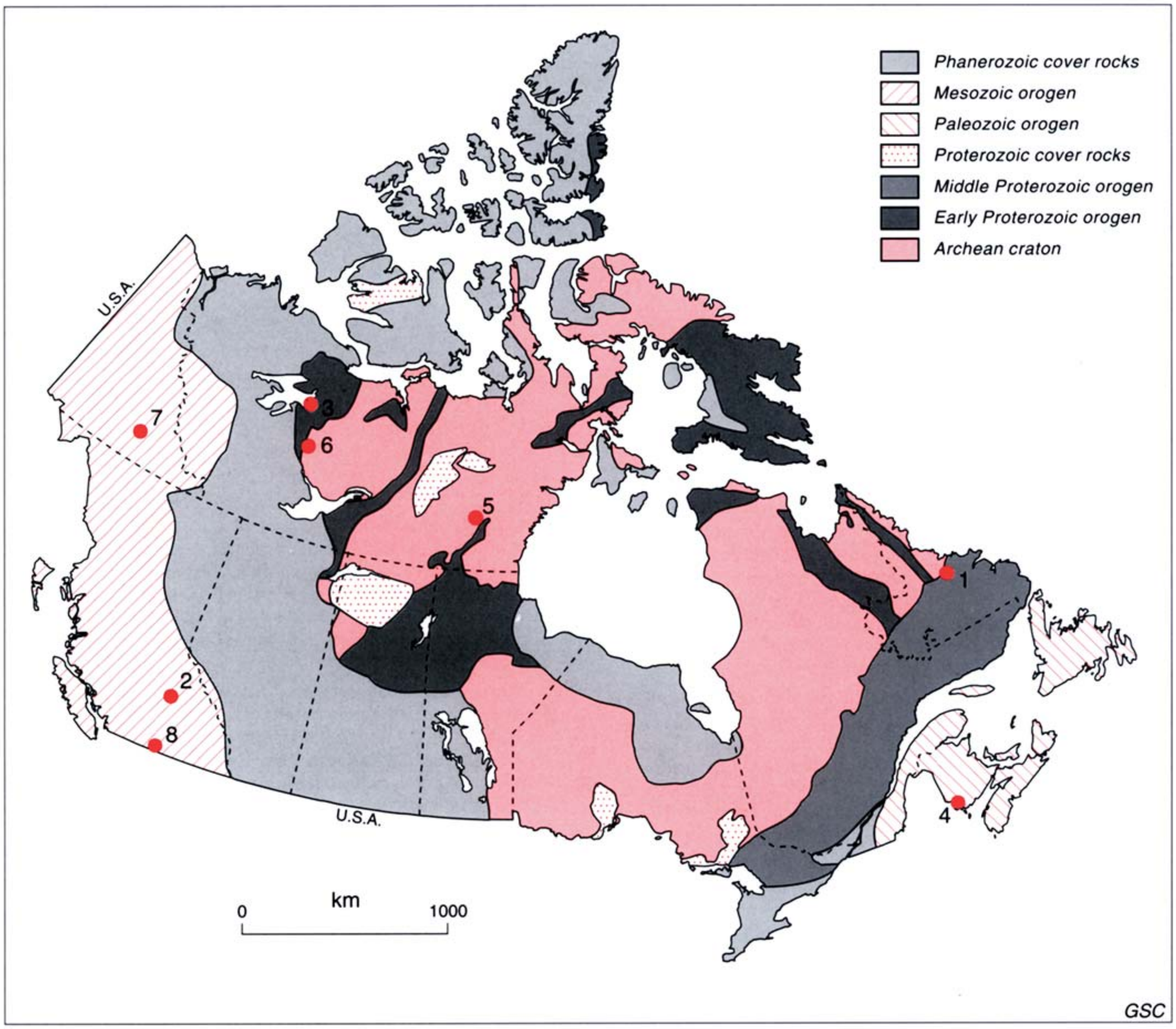

Figure 12-1. Volcanic-associated uranium deposits and main occurrences/districts in Canada. *Deposits:* 1 – Michelin, Labrador; 2- Rexspar, British Columbia; 3 – Eldorado, Great Bear Lake area, Northwest Territories (U-Ag-Cu-Co-Ni-As-bearing veins hosted by volcanic rocks but genetically unrelated to them). *Occurrences/districts:* 4 – Mount Pleasant, New Brunswick (Curtis, 1981); 5 – Lower Dubawnt Group volcanic rocks, Baker Lake area, Northwest Territories (Curtis, 1981; Miller and LeCheminant, 1985; LeCheminant et al., 1987); 6 – UGI-DV, Devries Lake, Northwest Territories (Gandhi and Prasad, 1993); 7 – Nokluit, Yukon Territory (Bell, 1985); 8 – Marron volcanic rocks, British Columbia (Bell, 1985).

orogen 30 to 60 million years after the peak of the orogeny about 1900 Ma (Hoffman, 1980; Hildebrand et al., 1987). Most of these are vein-type and much younger than the host rocks, but a few at DeVries Lake are of disseminated type such as the Michelin deposit, and are approximately of the same age as the host rocks (Miller, 1982; Gandhi and Prasad, 1993). Another Canadian uranium district, about 1840 Ma in age, is the intracratonic extensional Baker Lake basin in Northwest Territories which contains an areally extensive and voluminous assemblage of subaerial potassic to ultrapotassic trachyandesite and trachyte flows, related bostonite and other intrusions, continental clastic sediments, and a 1760 Ma, high silica, fluorine-rich, rhyolite-granite assemblage (Miller, 1980; Miller and LeCheminant, 1985; Miller et al., 1986; LeCheminant et al., 1987). Syngenetic U-Th mineralization occurs in bostonite dykes, which represent a highly fractionated phase of alkalic potassic magma, and epigenetic uranium and uranium-polymetallic (Cu+Pb±Zn±Au±Ag±Se±Mo) occurrences are associated with the mafic to intermediate volcanic rocks. Anomalous radioactivity is also noted in a high silica, topaz-bearing rhyolite.

The Rexspar deposit occurs in an areally restricted volcanic centre in Paleozoic rocks of the Canadian Cordillera (Preto, 1978; Morton et al., 1978). This deposit and those in the Labrador district have been affected by postmineralization deformation that has imparted schistosity to their host sequences. A collapsed caldera of Jurassic age, developed at the margin of a Paleozoic granitic dome, hosts deposits in the Streltsov district, eastern Russia (Ruzicka, 1992). Another Paleozoic uranium district is in northern Italy, where the Permo-Carboniferous Collio basin or half-graben, has abundant

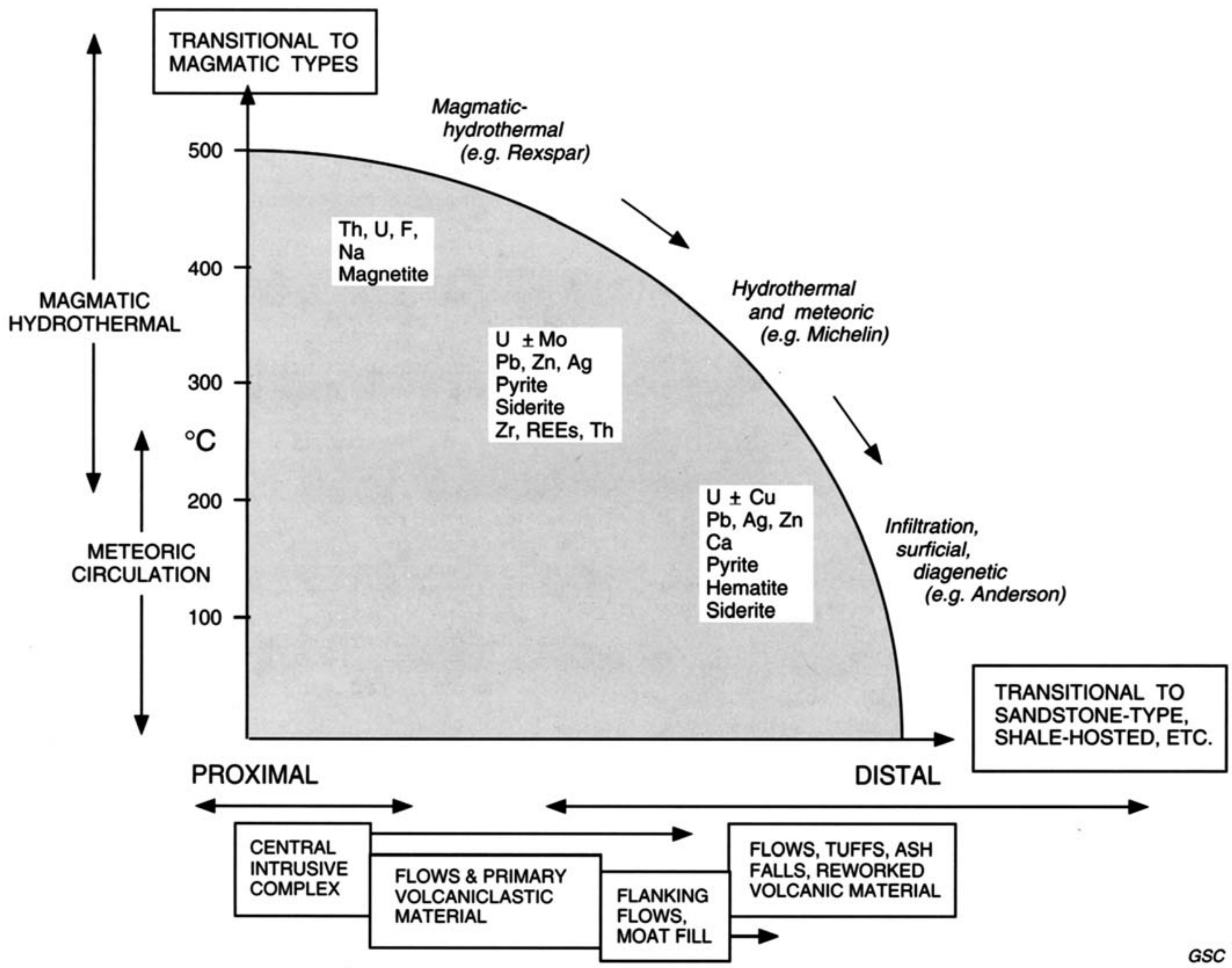

Figure 12-2. Diagram of felsic volcanic-associated uranium deposits in relation to magmatic source, mixing of magmatic fluids and meteoric waters, and temperature of mineralizing solutions.

felsic volcanic rocks which host stratabound and fracture-controlled polymetallic uranium deposits (Cadel, 1986; Cadel et al., 1987; Fuchs, 1989). In southeast China, numerous epigenetic uranium occurrences are hosted by rhyolites and granites that were formed at late stages of subduction of the Pacific plate under mainland China during Jurassic-early Cretaceous time (Xu, 1990). The uranium mineralization is believed to have occurred during the extensional tectonic stage that followed the end of subduction, and the mineralizing solutions may have been derived from deep crustal anatexis (Chen and Fang, 1985; Yao et al., 1989).

The Anderson deposit in organic-rich tuffaceous shales, and other felsic volcanic-associated deposits in the southwestern U.S.A. (e.g., those in the McDermitt caldera), and the ignimbrite-hosted Pena Blanca deposits in Mexico, are in the extensional Basin and Range Province-Rio Grande Rift Zone of Tertiary age (Sherborne et al., 1979; Rytuba and Glazman, 1979; Cárdenas-Flores, 1985; Dayvault et al., 1985; Goodell, 1985; Wenrich, 1985). Quaternary volcaniclastic rocks and vitric tuffs of the potassic volcanic Roman Province, controlled by a graben structure, contain exhalative-supergene concentrations of uranium, thorium, and iron (Locardi and Mittemperger, 1971).

Age of host rocks and mineralization

For this type of uranium deposits in general, the host rocks range in age from early Proterozoic to Cenozoic. No Archean examples have been documented to date.

The mineralization may be synvolcanic in the case of magmatic-hydrothermal deposits in volcanic vents and proximal exhalative settings, or it may be epigenetic resulting from the action of circulating heated meteoric waters, and/or by groundwaters during weathering processes. The epigenetic mineralization ranges in age from close to that of the host rocks to significantly younger. It may occur anywhere in the volcanic region, but appears to be more important in the distal facies.

Most of the deposits in the Labrador uranium district have yielded isotopic ages in the range 1800-1750 Ma, and their felsic volcanic host rocks, which dominate the bimodal upper part of the Aillik Group, are between 1860 and 1805 Ma (Gandhi, 1978, 1986; Schärer et al., 1988). In Sweden, the Pleutajokk and other deposits in its vicinity, and their host rocks are essentially coeval with those in Labrador (Gustafsson, 1981; Hålenius et al., 1986). They are in an early Proterozoic terrane which was conterminous with Greenland and Labrador prior to the birth of Atlantic Ocean (Gower et al., 1990, Gower, 1992; Gandhi and Bell, 1993). Some younger occurrences are also found in this terrane, a notable one being the Duobblon deposit in about 1725 Ma ignimbrite in northern Sweden (Lindroos and Smellie, 1979). Fracture-controlled occurrences in the Baker Lake basin have yielded discordant pitchblende ages between 1800 and 1700 Ma (Miller and LeCheminant, 1985). The Rexspar deposit is Paleozoic, and no younger than Permian (Morton et al., 1978; Bell, 1985). Most of the other foreign examples are Phanerozoic, as mentioned above.

Associated structure

Block faulting, breccia development, weak to moderately intensive folding and shearing related to volcanic activity, and late tectonic structural adjustments are common prior to, during, and after mineralization. No major orogenic deformation, however, occurred immediately before or after the mineralization.

Relation of ore to host rocks

Ore zones are stratabound away from the volcanic vent, as in the case of the Michelin and Rexspar deposits, as well as the foreign deposits in lava and ash flow fields mentioned above. In proximal deposits, ore zones are primarily discordant veins, although breccia fillings and disseminations also occur.

The Michelin deposit is hosted by rhyolitic, nonwelded ash-flow and air-fall crystal tuffs, which are about 250 m thick, have a strike length of more than 4 km, and dip 55° to the south-southeast. The host rocks are part of the much thicker and extensive, rhyolite-dominated, upper Aillik Group, deposited about 1860 Ma and deformed during the Makkovikian 'orogeny' about 1800 Ma (Gandhi, 1978, 1986; Bailey, 1979; Schärer et al., 1988). They are layered, and the layering is defined by abrupt textural changes across strike from coarse feldspar-porphyritic to subporphyritic (with relatively smaller and less abundant phenocrysts) to nonporphyritic rhyolites. The mineralized zones are as much as a few metres thick and several hundred metres long, and are concordant with the layering in the host sequence. Four main mineralized zones and a few subsidiary zones occur in, but are not restricted to, coarse feldspar porphyritic units within the 40 m thick lower part of the host crystal tuffs, and within a strike length of 1 km. The host rocks are variably foliated and sheared, and the mineralization predates at least the final stages of deformation. A number of other smaller occurrences similar to the Michelin deposit occur in the Aillik Group (Gandhi, 1978, 1986).

The Rexspar mineralized zones occur in metamorphosed potassium-rich, feldspar-porphyritic trachyte and tuff units, whose stratigraphic tops are not known with certainty, although they are most likely overturned (Bell, 1985). The three main mineralized zones are widely separated, and occur in pyritic, tuffaceous, argillaceous lenses containing pyroclastic fragments. Mid-Mesozoic deformation has rendered the host rocks schistose. The mineralized zones are as much as 20 m thick and 200 m long, and dip less than 30°.

Form of deposits

The stratabound disseminated-type deposits are lenticular to tabular. Discordant veins and fracture-fillings are common in volcanic vents and proximal deposits. They also occur in the districts that contain stratabound deposits, but are relatively subordinate in importance; they may be primary fracture fillings or may have resulted from remobilization of uranium during geological events post-dating the primary mineralization.

Ore composition

The ores may be either compositionally simple or complex. The Michelin deposit is of simple type, and contains only traces of other elements. Some complex deposits with high Th/U ratios include significant amounts of other elements, in particular REEs, Mo, F, Pb, and Zn, as in the Rexspar deposit. In some cases proximal vein deposits with low Th/U ratios also contain significant amounts of Mo, F, Pb, and Zn.

Alteration

Hematitization, carbonatization, and albitization are common. Hematitization is distinctive in the Michelin ore, but not in the sulphide-rich ore of the Rexspar deposit. Hematite occurs as very fine grains or interstitial films in the Michelin ore, but does not represent a significant addition of iron to the host rock. Magnetite and ilmeno-magnetite in the rhyolitic host rock have been hematitized to a variable degree.

Carbonatization is reflected in widely distributed calcite in and around ore zones as interstitial grains, fracture-coatings, and veins. Pink calcite is typical of the uranium deposits. Purple fluorite is a common associate of the calcite.

Albitization of the host rock is an important feature of many of these deposits. It is strongly developed at the Michelin deposit, where mineralized rhyolites contain 7% to 11% Na_2O and less than 0.5% K_2O, in contrast to the unmineralized rhyolites which contain 4% to 6% Na_2O and 5% to 7% K_2O. The strongly metasomatized rocks also show, in addition to alkali exchange and alkali enrichment, some desilication (White and Martin, 1980). In the Rexspar deposit, some albite-rich rocks have been noted, but albitization is apparently not extensive.

Mineralogy

Uranium occurs mainly as pitchblende, and to a lesser extent as coffinite in the thorium-poor occurrences, such as the Michelin deposit and many high grade veins and disseminated deposits. In the thorium-rich Rexspar deposit and the Nokluit occurrence in Yukon Territory (Fig. 12-1), the dominant uranium minerals are uraninite, uranoan thorite, and uranothorite (Bell, 1985).

Associated minerals at the Michelin deposit are nearly pure albite (99% Ab), sodic pyroxene, sodic amphibole, zircon, sphene, calcite, and fluorite (Gandhi, 1978, 1986). In the Rexspar deposit, a great variety of minerals are present: pyrite, fluorophlogopite, apatite, fluorite, celestite, galena, sphalerite, molybdenite, scheelite, siderite, calcite, barite, quartz, albitic plagioclase, bastnaesite, and monazite (Preto, 1978). Fluorite, celestite, and rare-earth elements are abundant enough to be of economic interest.

Texture

Uranium-bearing minerals are commonly finely disseminated. In the Michelin deposit, they occur as grains less than 10 μm in diameter that are interstitial to other minerals, as inclusions in sphene and in mafic silicate minerals, and as small aggregates with mafic silicate grains, zircon, and sphene. In the Rexspar deposit, uranium-bearing minerals are tiny, discrete grains, from less than a micrometre to a few tens of micrometres in diameter, and commonly occur as inclusions in fluorphlogopite.

DEFINITIVE CHARACTERISTICS

1. The host rocks are commonly felsic volcanic and associated clastic sediments of post-Archean age.
2. The host rocks were deposited in an extensional tectonic environment, during late- and post-tectonic stages in orogenic zones or in continental anorogenic settings.
3. The hosting volcanic suites are generally felsic dominated or bimodal, are meta- or peraluminous, and have a mildly to highly alkaline character.
4. Fluorine and molybdenum are commonly associated with uranium.
5. Hematitization, carbonatization, and albitization of the host rocks are associated features of the deposits.

GENETIC MODEL

Two stages are involved in the model:

a) an initial enrichment of uranium in the felsic magma source, and
b) a later concentration of the metal at the deposit site, during and after extrusion of the felsic magma, by magmatic hydrothermal fluids and/or meteoric waters circulating through the volcanic pile.

The main debate is whether or not the primary magmatic enrichment in uranium and associated incompatible elements is of deep-seated mantle origin (Locardi, 1985; Treuil, 1985) or of metamorphic and anatectic origin from the middle or lower regions of a thick sialic crust (Chen and Fang, 1985). Adherents to both schools of thought agree that a dilational (viz., taphrogenic) geological regime is important regionally in the formation of volcanogenic uranium deposits, and that the volcanic rocks are enriched in uranium substantially above normal crustal levels.

An important dilatant geological regime is that of the rising metamorphic core complex, e.g. the Basin and Range Province in the southwestern U.S.A. and its extension in the Rio Grande Rift (Wenrich, 1985), and the Shuswap terrane in British Columbia (Bell, 1985). Rise of the complexes allow for a regional structural ground preparation through progressive mylonitization, development of detachment zones, listric faults, brittle deformation, and brecciation. These are coupled with intrusion of deep-seated alkali-rich melts, possibly mantle-derived, with or without underplating and delamination as visualized by Wyborn et al. (1987) and Wyborn (1988). The surface expressions of the phenomenon are fault-bounded, terrestrial clastic-volcanic basins.

A lower crustal derivation of the felsic magma is favoured here, but it is possible that this felsic magma is derived by remelting of previously underplated igneous bodies in the manner visualized by Wyborn et al. (1987) and Wyborn (1988). The silicate melts and the accompanying hydrous fluids were enriched in the incompatible elements through partial melting of the source rocks. Further enrichment occurred through differentiation during crustal residence and during ascent of the magma. Although this process is considered adequate by most workers, input of additional uranium in these melts and fluids by mixing with meteoric waters is suggested by Chen and Fang (1985) in their "double mixing" model. This model involves deep circulation of oxygenated uraniferous meteoric waters in volcanic terranes.

The concentration of uranium at the deposit site may be brought about by magmatic hydrothermal fluids, or oxidized meteoric waters near surface or at shallow depths, with or without direct input of the metal from magmatic fluids. The volcanic-associated uranium deposits vary considerably in their characters, reflecting a variety of mechanisms for uranium transport and deposition in the complex volcanic-hypabyssal environment (Fig. 12-2). Some features suggest relatively higher temperatures of deposition, e.g. intense soda metasomatism at the Michelin deposit (Gandhi, 1978, 1986; White and Martin, 1980); other features, e.g., fluid inclusions and metal associations, indicate boiling off of volatiles, as in the case of the Rexspar deposit (Morton et al., 1978; Preto, 1978; Bell, 1985), and of the Moonlight mine in the McDermitt caldera complex in the southwestern U.S.A. (Rytuba and Glazman, 1979). Posteffusive, circulating oxidized meteoric waters may, if the volcanic heat supply persists, leach uranium from devitrifying glass (Zielinski, 1985) and from zones mineralized by magmatic fluids, and deposit it at favourable sites within the volcanic pile or in nearby sedimentary basins or lakes where reducing conditions are encountered. White and Martin (1980) and Gower et al. (1982) proposed such convection cells for the deposits in Labrador, and Marten (1977) and Evans (1980) suggested similar processes, but with mineralizing solutions of metamorphic and meteoric origin respectively, without input from a magmatic source, and with deposition controlled by permeable shear zones produced by premineralization deformation. Gandhi (1986) has, however, emphasized features indicating predeformation mineralization, and the role of a magmatic source at depth in generation of mineralizing solutions. In addition to synvolcanic hydrothermal mineralization, subaerial volcanism may contribute uraniferous tuffaceous sediments to the sedimentary basins in, or adjacent to, the volcanic field, and uranium from them may be concentrated during sedimentation and diagenesis. Examples of deposits formed by surface and groundwater transport of uranium in the volcaniclastic sedimentary environment are several occurrences in the tuffaceous beds in the upper part of the Aillik Group (Gandhi, 1978, 1986) and the Anderson deposit in organic-rich tuffaceous shales (Sherborne et al., 1979).

An interesting aspect of most felsic volcanic-associated uranium deposits is that they are in distinctly bimodal or felsic igneous suites that are late- and postorogenic and anorogenic, rather than in classical andesite-dominated volcanic suites associated with continental margin orogenies.

RELATED DEPOSIT TYPES

The upper Aillik Group underlies an area more than 130 km by 40 km and hosts, in addition to a number of volcanic-associated uranium occurrences which resemble the Michelin deposit, a few cogenetic molybdenite-pyrite-fluorite occurrences. The largest molybdenite deposit in the district is the Cape Makkovik deposit, and this contains mainly stratabound disseminated mineralization in a granulated and sheared zone (Gandhi, 1978, 1986). Veins carrying these minerals, with or without pitchblende, galena, and sphalerite, occur elsewhere in the Aillik Group in the vicinity of granite intrusions and hence are regarded as granite-related. The lower Aillik Group includes some argillaceous-mafic tuffaceous beds near the base of its rhyolite-dominated upper part, and these beds host disseminated and associated vein-type uranium occurrences, of which the best known is the Kitts deposit in pyrrhotite-rich graphitic argillite (Gandhi, 1978, 1986).

The boundaries of the host volcanic rocks with related plutonic suites, and with associated volcaniclastic sediments, which in some cases host uranium deposits (e.g., the tuffaceous sediments of caldera-fill at the Anderson mine, U.S.A.), are for the most part ill-defined and arbitrary. It is apparent, however, that the volcanic-associated uranium deposits encompass a wide spectrum of volcano-plutonic environments. They are most closely related to the continental sandstone-type deposits, and indeed many workers have regarded felsic volcanic rocks as a fertile source of uranium in the sandstone-type deposits, insofaras they are among the most uraniferous rocks and are associated with sandstones in many places. Among other related deposits are precious metal-bearing veins in caldera complexes, which contain little or no uranium. The granite-related polymetallic deposits, particularly those carrying uranium, appear in many cases to be deep-seated equivalents of the felsic volcanic-associated uranium deposits, e.g., the Mount Pleasant Bi-Mo-Sn-W deposits in New Brunswick (Curtis, 1981).

Within the felsic volcanic domain, the deposit classification by type seems somewhat arbitrary. Thus felsic volcanic-hosted uranium deposits have been separated from Kiruna/Olympic Dam-type deposits, although a broader category of deposits genetically related to felsic volcano-plutonic complexes would include both. Furthermore, the polymetallic veins of the Great Bear Lake area, although they are hosted by volcanic rocks, are distinguished on the basis of isotopic age constraints. These ages call for a genetic model different from that for the volcanic-associated deposits.

EXPLORATION GUIDES

Terranes of profuse post-Archean felsic volcanic rocks are favourable for volcanic-associated uranium deposits. Of particular interest are those that developed in continental, extensional tectonic environments. Such felsic or bimodal (basalt-rhyolite) suites were apparently deposited during the interval 2000 to 1500 Ma over large parts of the Canadian, Baltic, and Australian shields. Detailed stratigraphic mapping of felsic volcanic sequences will be helpful in the recognition of favourable horizons for stratabound deposits, and of the vent facies favourable for discordant deposits. Alkali metasomatism is a useful guide as it extends for large areas surrounding the deposits.

REFERENCES

References with asterisks (*) are considered to be the best source of general information on this deposit type.

Bailey, D.G.
1979: Geology of the Walker-McLean Lake area, (13K/9E, 13J/12), Central Mineral Belt, Labrador; Newfoundland Department of Mines and Energy, Mineral Development Division, Report 78-3, 17 p.

***Bell, R.T.**
1985: Overview of uranium in volcanic rocks of the Canadian Cordillera; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 319-335.

Cadel, G.
1986: Geology and uranium mineralization of the Collio basin (central southern Alps, Italy); Uranium, v. 2, no. 3, p. 215-240.

Cadel, G., Fuchs, Y., and Meneghel, L.
1987: Uranium mineralization associated with the evolution of a Permo-Carboniferous volcanic field - examples from Novazza and Val Vedello (northern Italy); Uranium, v. 3, no. 2/4, p. 407-421.

Cárdenas-Flores, D.
1985: Volcanic stratigraphy and U-Mo mineralization of the Sierra de Pena Blanca District, Chihuahua, Mexico; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 125-136.

Chen, Zhaobao and Fang, Xiheng
1985: Main characteristics and genesis of Phanerozoic vein-type uranium deposits; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 69-82.

***Cox, D.P. and Singer, D.M. (ed.)**
1986: Mineral deposit models; United States Geological Survey, Bulletin 1693, p. 162-164.

Curtis, L.
1981: Uranium in volcanic and volcaniclastic rocks - examples from Canada, Australia and Italy; American Association of Petroleum Geologists, Studies in Geology, no. 13, p. 55-62.

Dayvault, R.D., Castor, S.B., and Berry, M.R.
1985: Uranium associated with volcanic rocks of the McDermitt caldera, Nevada and Oregon; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 379-409.

Evans, D.
1980: Geology and petrochemistry of the Kitts and Michelin uranium deposits and related prospects, Central Mineral Belt, Labrador; PhD. thesis, Queen's University, Kingston, Ontario, 312 p.

Fuchs, Y.
1989: Hydrothermal alteration at the Novazza volcanic field and its relation to the U-Mo-Zn Novazza deposit, northern Italy; in Metallogenesis of Uranium Deposits, Proceedings of a Technical Committee Meeting, Vienna, March 1987; International Atomic Energy Agency, Vienna, p. 137-152.

***Gandhi, S.S.**
1978: Geological setting and genetic aspects of uranium occurrences in the Kaipokok Bay-Big River area, Labrador; Economic Geology, v. 73, p. 1492-1522.
1986: Uranium in Early Proterozoic Aillik Group, Labrador; in Uranium Deposits of Canada, (ed.) E.L. Evans; The Canadian Institute of Mining and Metallurgy, Special Volume 33, p. 70-82.

Gandhi, S.S. and Bell, R.T.
1993: Metallogenic concepts to aid exploration for the giant Olympic Dam-type deposits and their derivatives; Proceedings of the Eighth Quadrennial IAGOD Symposium, Ottawa, Canada, August 1990; International Association on the Genesis of Ore Deposits; (ed.) Y.T. Maurice; E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, p. 787-802.

Gandhi, S.S. and Prasad, N.
1993: Regional metallogenic significance of Cu, Mo, and U occurrences at DeVries Lake, southern Great Bear magmatic zone, Northwest Territories; in Current Research, Part C; Geological Survey of Canada, Paper 93-1C, p. 29-39.

Goodell, P.C.
1985: Chihuahua city uranium province, Chihuahua, Mexico; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 97-124.

Gower, C.F.
1992: The relevance of Baltic Shield metallogeny to mineral exploration in Labrador; in Current Research, Newfoundland Department of Mines and Energy, Report 92-1, p. 331-366.

Gower, C.F., Flanagan, M.J., Kerr, A., and Bailey, D.G.
1982: Geology of the Kaipokok Bay-Big River area, Central Mineral Belt, Labrador; Newfoundland Department of Mines and Energy, Report 82-7, 77 p.

Gower, C.F., Ryan, B., and Rivers, T.
1990: Mid-Proterozoic Laurentia-Baltica: an overview of its geological evolution and a summary of contributions made in this volume; in Mid-Proterozoic Laurentia-Baltica, (ed.) C.F. Gower, B. Ryan, and T. Rivers; Geological Association of Canada, Special Paper 32, p. 1-20.

Gustafsson, B.
1981: Uranium exploration in the N. Vasterbotten - S. Norbotten Province, northern Sweden; in Uranium Exploration Case Histories; Proceedings of an Advisory Group Meeting, November 1979; International Atomic Energy Agency, Vienna, p. 333-352.

Hålenius, U., Smellie, J.A.T., and Wilson, M.R.
1986: Uranium genesis within the Arjeplog-Arvidsjaur-Sorcelle uranium province, northern Sweden; in Vein Type Uranium Deposits, International Atomic Energy Agency, Vienna, IAEA-TECDOC-361, p. 21-42.

Hildebrand, R.S., Hoffman, P.F., and Bowring, S.A.
1987: Tectono-magmatic evolution of the 1.9-Ga Great Bear magmatic zone, Wopmay orogen, northwestern Canada; Journal of Volcanology and Geothermal Research, v. 32, p. 99-118.

Hoffman, P.F.
1980: Wopmay Orogen: a Wilson cycle of Early Proterozoic age in the northwest of the Canadian Shield; in Continental Crust and its Mineral Deposits; (ed.) D.W. Strangway; Geological Association of Canada, Special Paper 20, p. 523-549.

LeCheminant, A.N., Miller, A.R., and LeCheminant, G.M.
1987: Early Proterozoic alkaline igneous rocks, District of Keewatin, Canada: petrogenesis and mineralization; in Geochemistry and Mineralization of Proterozoic Volcanic Suites, (ed.) T.C. Pharoah, R.D. Beckinsale, and D. Rickard; Geological Society Special Publication, no. 33, p. 219-240.

Lindroos, H. and Smellie, J.
1979: A stratabound uranium occurrence within Middle Precambrian ignimbrites at Duobblon, Northern Sweden; Economic Geology, v. 74, no. 5, p. 1131-1152.

Locardi, E.
1985: Uranium in acidic volcanic environments; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, IAEA-TECDOC-490, p. 17-27.

Locardi, E. and Mittemperger, M.
1971: Exhalative supergenic uranium, thorium and marcasite occurrences in Quarternary volcanites of central Italy; Bulletin Volcanologique, v. 35, p. 173-184.

Marten, B.E.
1977: The relationship between the Aillik Group and the Hopedale Complex, Kaipokok Bay, Labrador; PhD. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 244 p.

Miller, A.R.
1980: Uranium geology of the eastern Baker Lake basin, District of Keewatin, Northwest Territories; Geological Survey of Canada, Bulletin 330, 63 p.

Miller, A.R. and LeCheminant, A.N.
1985: Geology and uranium metallogeny of Proterozoic supracrustal successions central District of Keewatin, N.W.T. with comparisons to northern Saskatchewan; in Geology of Uranium Deposits, (ed.) T.I.I. Sibbald and W. Petruk; The Canadian Institute of Mining and Metallurgy, Special Volume 32, p. 167-185.

Miller, A.R., Stanton, R.A., Cluff, G.R., and Male, M.J.
1986: Uranium deposits and prospects of the Baker Lake Basin and sub-basins Central District of Keewatin, N.W.T.; in Uranium Deposits of Canada, (ed.) E.L. Evans; The Canadian Institute of Mining and Metallurgy, Special Volume 33, p. 263-285.

Contents

Miller, R.G.
1982: The geochronology of uranium deposits in the Great Bear batholith, Northwest Territories; Canadian Journal of Earth Sciences, v. 19, no. 7, p. 1428-1448.

Morton, R.D., Aubut, A., and Gandhi, S.S.
1978: Fluid inclusion studies and genesis of the Rexspar uranium-fluorite deposit, Birch Island, British Columbia; in Current Research, Part B; Geological Survey of Canada, Paper 78-1B; p. 137-140.

Preto, V.A.
1978: Setting and genesis of uranium mineralization at Rexspar; The Canadian Institute of Mining and Metallurgy, Bulletin, v. 71, no. 800, p. 82-88.

***Ruzicka, V.**
1992: Types of uranium deposits in the former U.S.S.R.; Colorado School of Mines, Quarterly Review, v. 92, no. 1, p. 19-27.

Rytuba, J.J. and Glazman, R.K.
1979: Relation of mercury, uranium and lithium deposits of the McDermitt caldera complex, Nevada-Oregon; in Papers on Mineral Deposits of Western North America, Nevada Bureau of Mines and Geology, Report 33, p. 109-118.

Schärer, U., Krogh, T.E., Wardle, R.J., Ryan, A.B., and Gandhi, S.S.
1988: U-Pb ages of Lower and Middle Proterozoic volcanism and metamorphism in the Makkovik Orogen, Labrador; Canadian Journal of Earth Sciences, v. 25, no. 7, p. 1987-1107.

***Sherborne, J.E., Jr., Buckovic, W.A., DeWitt, D.B., Hellinger, T.S., and Pavlak, S.J.**
1979: Major uranium discovery in volcaniclastic sediments, Basin and Range Province, Yavapai County, Arizona; American Association of Petroleum Geologists, v. 63, no. 4, p. 621-646.

Treuil, M.
1985: A global geochemical model of uranium distribution and concentration in volcanic rock series; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984, International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 53-68.

Wenrich, K.J.
1985: Geochemical characters of uranium enriched rocks; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 29-51.

White, M.V.W. and Martin, R.F.
1980: The metasomatic changes that accompany uranium mineralization in the non-orogenic rhyolites of the Upper Aillik Group, Labrador; Canadian Mineralogist, v. 18, p. 459-479.

Wyborn, L.A.I.
1988: Petrology, geochemistry and origin of a major Australian 1880-1840 Ma felsic volcano-plutonic suite: a model for continental felsic magma generation; Precambrian Research, v. 40/41, p. 37-60.

Wyborn, L.A.I., Page, R.W., and Parker, A.J.
1987: Geochemical and geochronological signatures in Australian Proterozoic igneous rocks; in Geochemistry and Mineralization of Proterozoic Volcanic Suites, (ed.) T.C. Pharoah, R.D. Beckinsale, and D. Rickard; Geological Society of London, Special Publication No. 33, p. 377-394.

Xu, Zhigang
1990: Mesozoic volcanism and volcanogenic iron-ore deposits in eastern China; Geological Society of America, Special Paper 237, 46 p.

Yao, Z., Liu, Y., Zhu, R., Yang, S., and Li, D.
1989: Uranium metallogenesis in southeast China; in Metallogenesis of Uranium Deposits, Proceedings of a Technical Committee Meeting, Vienna, March 1987; International Atomic Energy Agency, Vienna, p. 345-357.

***Zielinski, R.A.**
1985: Volcanic rocks as sources of uranium: current perspectives and future directions; in Uranium Deposits in Volcanic Rocks, Proceedings of a Technical Committee Meeting, El Paso, Texas, April 1984; International Atomic Energy Agency, Vienna, IAEA-TECDOC-490, p. 83-96.

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