

4 Typology of Uranium Deposits

A number of global and regional classifications of uranium deposits have been proposed in the past by Heinrich (1958), Ruzicka (1971), Ziegler (1974), Kazansky and Laverov (1977), Mickle and Mathews (1978), Mathews et al. (1979), Dahlkamp (1980), Nash et al. (1981), Barthel et al. (1986), and others. Although they remain in principle valid, recently published descriptions of uranium deposits discovered during the past exploration boom, and new research data on earlier established and defined types of uranium deposits justify a rearrangement and refinement of the classification scheme. Many open questions still exist with respect to specific provenance of the ore forming uranium and solutions, the conditions of uranium mobilization, transport and redeposition, and repetitive redistribution in many cases. Therefore a classification scheme based purely on metallogenetic criteria does not appear feasible. Instead, for all practical purposes, a typology based more on descriptive data has been given preference here.

The principal recognition criteria used for the identification and definition of the individual types and subtypes of deposits include particularly lithologic and structural relationships, alteration, mineralogy, paragenesis, age constraints, and spatial geotectonic distribution of deposits. According to the chosen system, the terminology selected for types and subtypes refers primarily to the geotectonic setting or host environment of the discussed type.

On this basis sixteen principal types of uranium deposits are distinguished. They include almost forty subtypes and classes. All classes have certain principal parameters in common permitting their attribution to a specific type, but they also exhibit distinctive features justifying an individual status.

Each type is introduced by a type *Definition*, followed by *Principal Recognition Criteria* and *Metallogenetic Aspects* before presenting characteristics of subtypes. Inevitably, this kind of organization involves overlap and repetition, which is considered minor in order to achieve a better type- and subtype-related comprehension and precision and avoidance of confusion.

Complementing the selected type examples, a list of examples is added. The attribution of these examples is in many cases only tentative and the example may belong to another type, subtype or class than listed, or it may have characteristics of several subtypes or classes.

The description also includes selected references though not exclusively of authors who either reviewed comprehensively the given type of deposit or districts thereof and list extensive bibliographies for further reference, or of authors describing in detail a specific deposit taken as type example.

Those types of generally subeconomic order which are not complemented by a detailed deposit/district description in Chapter 5 are more extensively reviewed here to provide sufficient background for their understanding.

Cartoons (Figs. 4.1 to 4.15) are added to furnish a schematized presentation of the geological setting of the various types, subtypes, and classes of deposits.

Division and numbering of the presented typology corresponds to that of Table 1.1, which gives an overview and economic ranking of the types of deposits.

Table 4.1 summarizes the significant geological recognition criteria of the various types, subtypes, and classes of deposits.

4.1 Type 1: Unconformity-Contact (Fig. 4.1)

Definition

Unconformity-contact deposits are associated with and occur immediately below and above an unconformable contact that separates a crystalline basement intensely altered by lateritic weathering from overlying clastic red bed type sediments of either Proterozoic or Phanerozoic age.

The unconformity-contact type includes the following subtypes and classes:

Table 4.1.1. Classification and principal geological recognition criteria of principal types of uranium deposits and occurrences (for location of type examples of deposits see Fig. 1.1)

Type Subtype	Class	Principal Recognition Criteria	Type Example	Selected References
1. Unconformity-contact				
1.1 Proterozoic unconformity		Lower Proterozoic metasediments mantling Archean domes, overlain by Middle Proterozoic red bed sandstones, strong unconformity related alteration of metasediments and sandstone. Some small deposits associated with Phanerozoic unconformities		Dahlkamp and Adams 1981; Fogwill 1985; IAEA/Ferguson (ed.) 1984; Lainé et al. (eds.) 1985; Sibbald and Petruk (eds.) 1985; Sibbald 1988; Tremblay 1982
1.2 Phanerozoic unconformity (see text)				
1.1.1 Fracture-bound in altered metasediments immediately below unconformity		U disseminated to massive in structures within Lower Prot. metasediments containing graphitic horizons, vertical extension commonly less than 200 m below unconformity; ore often extends along fractures into overlying Middle Prot. sdst.; medium rarely very high grade; med. to large reserves, dominantly monometallic	Athabasca Basin, Rabbit Lake, Eagle Point, Canada	Heine 1986; Eldorado Resources Ltd 1987
1.1.2 Clay-bound upon unconformity		U disseminated to often massive in tabular to lenticular horizontal ore bodies in clay and argillaceous sandstone of (mixed) pedogenic and/or early Athabasca diagenetic origin, resting on Lower Prot. metasediments; very high grade (>1% U ₃ O ₈), large reserves, commonly polymetallic	Ath. Bas., Cigar Lake, Key Lake, Canada	Fouques et al. 1988; Ruhrmann 1986
2. Subunconformity-epimetamorphic				
Metasediments		Deposits occur in same environment as subtype 1.1 but under early Middle Prot. unconformity, and basement shows only mild to moderate paleoweathering; type 2 deposits may be transitional into class 1.1.1		Dahlkamp and Adams 1981; Ferguson and Goleby (eds.) 1980; IAEA/Ferguson (ed.) 1984; Needham et al. 1988
2.1 not albitized		U as fracture and breccia filling within distinct Lower Prot. metased. horizons, ± peneconcordant to strata attitude, strong wall rock alteration; nearby migmatitic-granitic complexes, cover by early Middle Prot. red bed sedim.; fairly continuous mineralization, med. (to high grade); often large reserves; all large deposits are monometallic, some small deposits polymetallic	Ex. 2.1 Alligator Rivers, Ranger, Australia	Ewers and Ferguson 1980; Hegge et al. 1980
2.2 albitized			Ex 2.2 Beaverlodge, Faya Verna, Canada	Beck 1986; Tremblay 1978
3. Vein				
		Vein deposits consist of U lodes in fractures, breccias, stockworks and occur spatially related or unrelated to a granitic pluton		IAEA/Fuchs (ed.) 1986; Kolektiv 1984; Poty et al. 1986; Rich et al. 1977

3.1 Granite-related

3.1.1 Intragranitic (Limousin type) - in leucogranite - in episyenite	Granite-related veins occur inside or outside of late magmatically or autometamorphically altered peraluminous leucogranite; only restricted wall rock alteration; mostly discontinuous mineralization; low to high grade, small to medium reserves Veins, networks, stockworks of limited vertical extension within a 300 m segment below intrusion contact	Massif Central, Fanay/Limousin, France	Leroy 1978a, 1978b
3.1.2 Perigranitic			
3.1.2.1 in (meta) sediments Monometallic (Bohemian type)	Open space filling in irregular pipe-like episyenite within leucogranite, often grading into veins in surrounding granite	Massif Central, Pierres Plantées, Margeride, France	Cariou 1964 Leroy and Cathelineau 1982
3.1.2.2 in (meta) sediments Polymetallic (Jachymov type)	Veins, networks, stockworks in (meta-) sedimentary mantle rocks, extensive vertical persistence in Bohemian type (<2000 m); low to high grade, low to high reserves	Bohemian Massif, Příbram, ČSFR	Petroš et al. 1986
3.1.2.3 in contact-metamorphics (Iberian type)	As above but U associated with Ag, Co, Ni, Bi, or Cu, Mo or other metals in noteworthy amounts	Erzgebirge, Jáchymov, ČSFR	Kominek and Veselý 1986
3.2 Not granite-related	Disseminations and fracture fillings along shear and breccia zones in contact-metamorphic aureole Not granite-related veins do not display any apparent link to granitic intrusions but occur in rocks within orogenic belts U as veins, stockworks discordant to strata but ore may spatially be restricted to sections within distinct strata (or to overprinted unconformities), restricted wall rock alteration; low to high grade, small to large reserves	Iberian Meseta, Alto Alentejo, Portugal	Basham and Matos Dias 1986
3.2.1 Metasediment-hosted		Ex. 3.2.1 Schwartzwalder, USA	Wallace 1986
3.2.2 Sediment-hosted		Ex. 3.2.2 Shinkolobwe, Zaire	Kolektiv 1984 Derrick and Vaes 1956

4. Sandstone

U as disseminations in dominantly continental fluvial (less commonly marginal marine) arkosic sandstone commonly interbedded with argillaceous horizons, and almost flat-lying (<5°) unless post-ore tilted. Frequently associated with tuffaceous sediments. A distinction is made between (a) Phanerozoic (post-Devonian) deposits associated with terrestrial plant derived organics and (b) Proterozoic deposits associated with marine derived organics

Crawley 1983;
Grutt 1972;
IAEA/Finch (ed.) 1985;
Rackley 1976

Table 4.1. Continued

Type Subtype	Class	Principal Recognition Criteria	Type Example	Selected References
4.1 <i>Tabular/ peneconcordant</i>		Mineralization occurs generally in tabular zones of uranium matrix impregnations that are peneconcordant to but also crosscut sandstone bedding. The zones are irregular in shape up to several meters thick and are bounded on all sides by pyrite-bearing sandstone		
	4.1.1 Extrinsic carbon (Grants type)	U associated with redistributed carbonaceous matter (e.g., humate) disseminated in lenses within continental sandstone. The host sandstone has deposited in a mid-fan environment within an extensive fluvial-lacustrine sedimentary system. Moderate quantities of volcanoclastics are present. Sand-shale proportions are typically 60–80% sandstone. Alteration includes destruction of ilmenite-magnetite and significant pyritization. Feldspar is moderately to strongly altered; large reserves, medium grade	Grants Uranium Region, USA	Adams and Saucier 1981; Granger and Finch 1988; Turner-Peterson et al. (ed.) 1986
	4.1.2 Vanadium-uranium (Salt Wash type)	U associated with vanadium ($V > U$) within fluvial sandstone. Associated sediments are of continental origin “red-bed” type with thin but widespread units of reduced sandstone with interbeds of grey clay and carbonaceous debris. Most favourable sandstone parallels an adjacent contact of red oxidized sandstone and is overlain, underlain or interbedded with grey lacustrine clays. Altered, reduced sediments show ilmenite and magnetite destruction and significant concentrations of pyrite; small to medium reserves, low to high grade	Colorado Plat., Uravan Mineral Belt, USA	Thamm et al. 1981
	4.1.3 Basal channel (Chinle type)	U associated with plant fragments in basal part of fluvial channel. Deposits may occur in (a) distinct fluvial channels or (b) extensive blanket sands formed in braided fluvial systems that either unconformably overly or are eroded into underlying sedimentary or crystalline rocks; mostly small reserves, low to medium grade	Colorado Plat., Monument Valley, USA Ningyo-Toge, Japan	Chenoweth and Malan 1973; Katayama et al. 1974
4.2 <i>Rollfront (or Roll-type)</i>		Mineralization occurs in arcuate zones of uranium matrix-impregnations that crosscut sandstone bedding. Zones extend from overlying to underlying less-permeable horizons. Zones are convex down hydrologic gradient and elongate and sinuous perpendicular to hydrologic gradient. Contacts of zones are sharp with hematite and/or limonite bearing sandstone on the up-gradient side (except in reduced sands) and diffuse with carbon and/or pyrite-bearing sandstone on the down-gradient side		

<p>4.2.1 Continental basin, associated with detrital carbon (Wyoming type)</p>	<p>U as disseminations at redox boundary at contact with detrital carbonaceous (generally plant) debris on the down-gradient side in arkosic and subarkosic sandstones deposited in intracratonic or intermontane basins in spatial proximity to rocks containing anomalous U concentrations such as tuffs or granites. Most deposits occur within interbedded sequences of fluvial sandstones and volcanic rich sediments. Alteration is variable and includes hematitic alteration or bleaching. The shape of the deposit is strongly controlled by the hydrology of the host rocks. Some deposits have long tabular rollfront limbs against overlying and/or underlying carbonaceous-rich sediments; small to large reserves, medium grades</p>	<p>Wyoming Basins, USA Lake Frome Emb., Beverley, Australia</p>	<p>Crew 1981; Harshmann and Adams 1981</p>
<p>4.2.2 Marginal marine, associated with extrinsic sulfide (South Texas type)</p>	<p>U is concentrated in roll-type deposits near faults and in contact with pyrite/marcasite bearing sandstone on their down-gradient side. Sandstone on the up-gradient side of deposits is hematite and/or limonite bearing except for some deposits which occur totally within reduced, pyrite bearing sandstone which probably reflects the post-ore introduction of H₂S along faults. H₂S introduced before ore formation prepared the host for rollfront development. Host environments include point bars, lateral bars and crevasse splays deposited in a fluvial environment and barrier bars and offshore bars in a marine environment; small to medium reserves, low to medium grades</p>	<p>South Texas Coastal Plains, USA Crow Butte (Wyoming Basins) USA</p>	<p>Adams and Smith 1981; Galloway 1985</p>
<p>4.3 Tectonic-lithologic</p>	<p>U (re)distributed into faults cutting through mineralized sandstone and permeating tongue-like into permeable sand horizons</p>	<p>Grants, USA Franceville Basin, Gabon</p>	<p>Diouly-Osso and Chauvet 1979; Gauthier-Lafaye et al. 1980</p>
<p>5. Collapse breccia Pipe</p>	<p>Circular collapse structure cutting through flatlying strata including permeable sandstone horizons. Pipes are filled with breccia fragments and matrix. U occurs predominantly as matrix impregnations and in annular ring structures; small reserves, high grade</p>	<p>Arizona Strip, USA</p>	<p>GSA/Wenrich and Billingsley (eds.) 1986; Wenrich and Sutphin 1987</p>
<p>6. Surficial</p>	<p>U almost exclusively as uranyl minerals as disseminations, void filling, coating, or adsorbed on host constituents (organics, clay, etc.) in surficial depressions, dissolution caverns, at near-surface fractures, joints within or near uraniferous source rocks</p>		<p>Carlisle 1983; IAEA Toens (ed.) 1984</p>
<p>6.1 Duricrust (nonpedogenic)</p>	<p>Fluvial valley fill cemented by nonpedogenic calcrete, silcrete, gypcrete of recent age in arid region, often incised into granitic basement, U principally as uranyl minerals or adsorbed; small to med., exceptionally large resources mostly low grade</p>	<p>Yilgarn/Yeelirrie, Australia Namib Desert, Langer Heinrich, Namibia</p>	<p>Cameron 1984; Butt et al. 1984; Hambleton-Jones 1984; Mann and Deutcher 1978</p>

Table 4.1. Continued

Type Subtype	Class	Principal Recognition Criteria	Type Example	Selected References
	6.1.2. Lacustrine or playa	Similar to above but assoc. with shallow lake sediments; small resources, low grade	Yilgarn/Lake Maitland, Australia	Cavaney 1984
6.2 Peat and Bog		Organic-rich sediments/swamps, bogs filling shallow depressions, valleys; organic material often composed of sphagnum peat, U adsorbed on organic matter; small reserves, low grade	Stevens County, Washington, USA	Johnson et al. 1987
6.3 Karst cavern		Floor cover in caverns within limestone, dolomite by uranyl minerals; small reserves, low to med. grade	Pryor Mtns., USA	Bell 1983
6.4 Surficial Pedogenic and Structure Fill		U as dissemination, coating, filling of near surface permeable cataclastic zones (shears, fissures, joints) in igneous, metamorphic, sedimentary rocks, and soils, can be found associated with all deposit types in and near their outcropping parts; small resources, low grade	Daybreak, USA	US-AEC 1959
7. Quartz-pebble Conglomerate		U as disseminations in fluvial to deltaic oligomictic, pyritic quartz-pebble conglomerate, typically trough cross-bedded, of lowermost Proterozoic age on or peripheral to Archean shields. 2.2 to 2.7 M.Y. appears to be the most favorable age. Generally low grade, but large reserves		Button and Adams 1981 Pretorius 1981; IAEA/Pretorius(ed.) 1987;
7.1 U-dominant with REE	Basal conglomeratic beds in single stratigraphic unit	U mineralization concentrated in the basal section of a clastic sequence	Blind River - Elliot Lake Lake, Canada	Robertson 1989; Ruzicka 1988;
7.2 Au > U dominant	Conglomerate beds in multi-stratigraphic units	Au > U mineralization concentrated in several successive conglomeratic horizons, commonly only few cm to some ten cm thick with partly redistributed ore; U is by-product of Au production	Witwatersrand, S. Africa	Hallbauer 1986; Pretorius 1976; Anhaeuser and Maske (eds.) 1986
8. Breccia Complex		Matrix-poor bedded granite breccia and matrix-rich polymict breccias mineralized with Cu, Au, Ag, REE and U ore minerals as disseminations and fracture and void fillings; low grade, large U reserves, U is by-product	Olympic Dam, Australia	Roberts and Hudson 1984; Roberts 1988
9. Intrusive		U disseminations, distributed regularly in mostly unaltered acidic or alkaline massive magmatic or anatectic intrusion; commonly very low grade but large resources in 9.1		
9.1 Alaskite		As above, in anatectic alaskite	Rössing, Namibia	Berning 1986; Berning et al. 1976; Brynard and Andreoli 1988

9.2 <i>Granite, monzonite</i>	As above, in granite or monzonite/copper porphyry	Bingham, USA	John 1978; Lanier 1978
9.3 <i>Carbonatite</i>	As above in carbonatite, associated with REE	Phalaborwa, S. Africa	Camisani-Calzolari et al. 1985; IAEA 1986a
9.4 <i>Peralkaline syenite</i>	As above, in alkaline intrusion	Kvanefjeld, Greenland	Sørensen et al. 1974
9.5 <i>Pegmatite</i>	U as mainly uraninite in pockets and lenses, host rocks of similar origin as acidic magmatic stocks, but U distribution very erratic/limited in extension & resource; grade highly variable, generally low	Madawaska/Bancroft, Canada	Alexander 1986
10. Phosphorite	Syngentic U in phosphatic sediments; large resources, very low grade, U is byproduct		Heinrich 1958
10.1 <i>Phosphoria</i>	Oolitic marine phosphate beds	Idaho, USA	McKelvey et al. 1956
10.2 <i>Land-Pebble (Florida type)</i>	Uraniferous apatite within land-pebble phosphatic sandstone	Florida, USA	Altschuler et al. 1958
11. Volcanic	Felsic to intermediate volcanics mainly of rhyolitic composition and high U background; low grade and small resources		Chen Zhaobo 1981; Goodell and Waters 1981; IAEA 1985
11.1 <i>Structure-bound</i>	U as veins and fracture fillings associated with ring dike intrusions or resurgent domes	McDermitt, Moonlight USA Peña Blanca, Nopal I, Mexico	Dayvault et al. 1985; George-Aniel et al. 1985; Leroy et al. 1987
11.1.1 Intrusive vein in rhyolite intrusion		Cotaje; Bolivia	Leroy et al. 1985; Pardo-Leyton 1985
11.1.2 Surficial fracture fill	U as disseminations in surface-near fractures and breccias	McDermitt, Aurora-Cottonwood, USA	Dayvault et al. 1985
11.2 <i>Strata-bound</i>	U as disseminations in outflow volcanics and lacustrine facies	Peña Blanca, Margaritas, Mexico Date Creek Basin, USA	Goodell 1985; Sherborne et al. 1979
11.2.1 Intracaldera			
11.2.2 Exocaldera			
12 Metasomatite	U as fissure filling, partially to totally Na-metasomatized (albite) granitic and adjacent country rocks (albitization, Na-amphibole/pyroxene formation); mostly small resources, low to med. grade		Belevtsev et al. 1984; Fritsche 1988; Collot 1981; Fuchs et al. 1981; Kazansky and Laverov 1977; Mineeva 1984
12.1 <i>Metasomatized granite</i>		Krivoy Rog, Ukraine, Ross Adams, Alaska, USA Espinharas, Brazil	
12.2 <i>Metasomatized metasediments</i>			
13. Symmetamorphic	U as dissemination, (pene-)concordant to metamorphosed strata, minor to no alteration; commonly low to med. grade, small resources Dominantly (semi-)mafic metasediments with graphitic interbeds and in mixed sedimentary/volcanogenic rocks	Forstau, Austria	Dahlkamp and Scivetti 1981

Table 4.1. Continued

Type Subtype	Class	Principal Recognition Criteria	Type Example	Selected References
14. Lignite		Syn-epigenetic U in lignites often associated with adjacent tuffaceous sediments		Kolektiv 1984
14.1 Stratiform		U disseminations (mostly adsorbed) regularly through lignite sedm.; small to med. resources very low grade	Williston Basin, USA	Denson and Gill 1965
14.2 Fracture/Joint Fill		U filling fractures, joints within lignite seams underlying uraniferous strata (rhyolitic volcanics, sandstones); small resources, low to medium (locally) grade	Williston Basin, USA	Denson and Gill 1965
15. Black Shale		Syngenic U uniformly distributed in marine black shale. Sometimes with bentonite interbeds		Bell 1978
15.1 Bituminous sapropelic		U disseminations regularly distributed ubiquitously throughout black shale beds; large resources, very low grade	Chattanooga, USA	Mutschler et al. 1976
15.2 Humic/Kolm		As above but higher in grade in alum shale/kolm; med. to large resources	Ranstad, Sweden	Carlsson and Nojd 1977

Deposit size: small reserves = <5000 mt U308
 medium -"- = 5000-20000 mt U308
 large -"- = >20000 mt U308

Ore grades: low grade = <0.15% U308
 med. -"- = 0.15%-0.5% U308
 high -"- = >0.5% U308

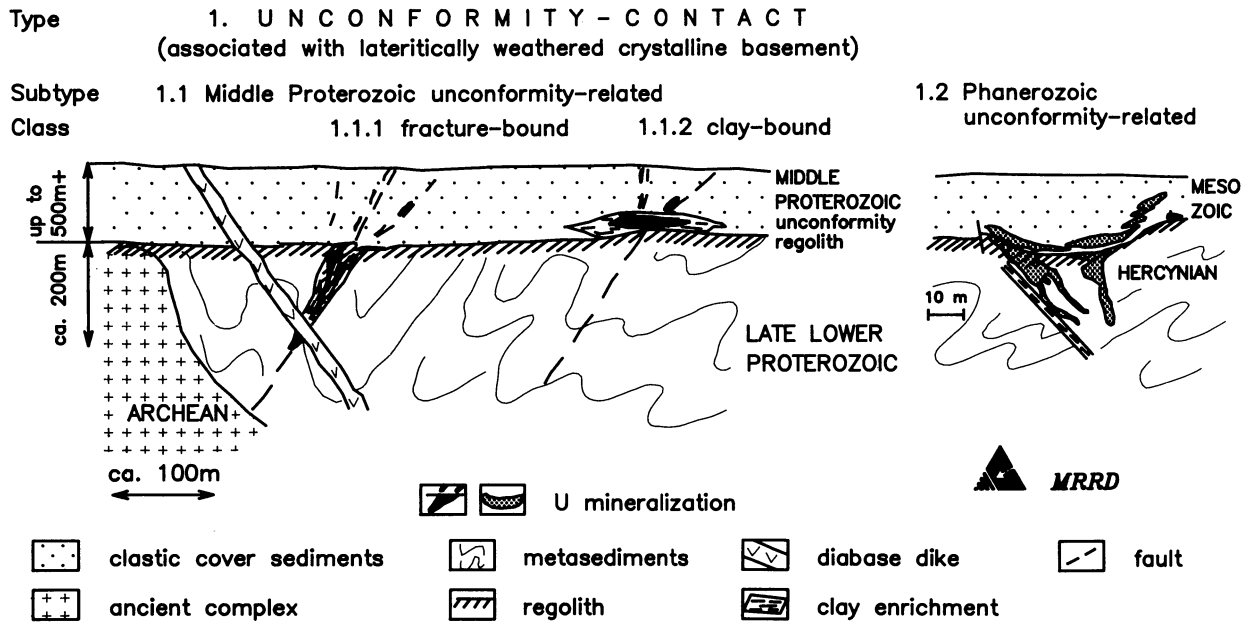


Fig. 4.1

Subtype 1.1: Proterozoic unconformity related

Class 1.1.1: Fracture-bound

Type Example: Rabbit Lake, Eagle Point, Athabasca Basin, Canada

Class 1.1.2: Clay-bound

Type Example: Cigar Lake, Athabasca Basin, Canada

Subtype 1.2: Phanerozoic unconformity related

Type Example: Bertholène, Aveyron, France

References: Dahlkamp and Adams 1981; Evans (ed.) 1986; Fogwill 1985; IAEA/Ferguson (ed.) 1984; Lainé et al. (eds.) 1985; Sibbald and Petruck (eds.) 1985; Tremblay 1982

The two classes of Proterozoic unconformity-contact deposits are defined by their setting with respect to the unconformity, host rock, paragenesis, and ore grade. *Fracture-bound deposits* (class 1.1.1) occur in metasediments immediately below the unconformity. Mineralization is commonly monometallic and of medium grade (0.3–1% U₃O₈). *Clay-bound deposits* (class 1.1.2) occur associated with clay at the base of the sedimentary cover directly above the unconformity. Mineralization is commonly polymetallic (U + Ni + Co + As) and associated with bitumen and of high to very high grade (1–14% U₃O₈). Principal uranium phases in both classes are pitchblende and uraninite.

Phanerozoic unconformity-contact deposits are of similar setting as Middle Proterozoic deposits but are small and of low grade.

Principal Recognition Criteria

Host Environment

- Basement is similar to type 2 subunconformity-epimetamorphic deposits and consists of middle to upper Lower Proterozoic metasediments including graphitic horizons and strata with elevated U content surrounding Archean granitic domes, cut by various pegmatites
- Cover of middle Middle Proterozoic continental red bed facies sandstone (Athabasca Group ca. 1500 m.y.) above markedly weathered crystalline rocks below an unconformity
- Diabase dikes, and sills cutting both basement and cover
- Ancient lineaments and mylonite zones in basement
- Tensional repeatedly reactivated structures in the basement with extensions into the sandstone

Alteration

- Intense regional paleoweathering of basement

- Intense alteration halos around deposits in basement and sandstone

Mineralization

- U present dominantly as pitchblende or uraninite in disseminated to often massive accumulations
- Mineralization of class 1.1.1 mostly monometallic, of class 1.1.2 polymetallic
- Mostly sharp ore-waste boundaries
- Redistribution of uranium and sulfides into fractures in the sandstone within the alteration halo above the deposits

Age Constraints

- Formation of major deposits of subtype 1.1 tends to be restricted to middle Middle Proterozoic (see following Remarks)
- U-Pb minimum ages of first generation pitchblende of Athabasca deposits: 1200 to 1400 m.y.

Metallogenic Aspects

Processes leading to mineralization and related alteration are only partially established. The most obvious are products of diagenetic-hydrothermal activity indicating the critical role of these processes as the essential step in the formation of the deposits as they exist today. It remains unclear, however, whether or not polyphase processes have developed this type of deposit. The open question is whether (a) the diagenetic hydrotherms have also introduced the uranium (and other metals) or (b) have only finally concentrated and recrystallized (and redated) preexisting mineralization formed by supergene surficial (paleoweathering) or perhaps early diagenetic processes. A surficial type deposit (type 6) may be envisioned as a precursor stage transformed by diagenetic-hydrothermal overprinting to a Proterozoic unconformity type deposit.

Remarks

- a) Middle Proterozoic unconformity deposits commonly are high-grade and have large resources constituting about one third of the western world's low-cost uranium reserves.

- b) Although all large unconformity type deposits known are restricted to the above listed environment and belong to subtype 1.1, deposits of equivalent type also occur in comparable geological environments of younger age (subtype 1.2, Phanerozoic unconformity related) but are of smaller magnitude (see also Remarks in Section 4.1.2 subtype 1.2).

For more details see Chapter 5.1.

4.1.1 Subtype 1.1: Proterozoic-unconformity related

Class 1.1.1: Fracture-bound

Type Example: Rabbit Lake and Eagle Point, Saskatchewan, Canada

References: Heine 1986; Eldorado Resources Ltd. 1987

Host Rocks/Structures

Altered gneisses, schists, with intercalations of graphitic horizons, metacarbonates (dolomitic marble etc.) and calc-silicate rocks originally metamorphosed to amphibolite-granulite facies. Locally migmatites. Often abundant pegmatitic, microgranitic and/or granitic dikes or segregations (pegmatitic and granitic segregations constitute 15 to 20% of host rocks at Eagle Point). Diabase dikes. Host rocks are strongly fractured, sheared and/or brecciated along repeatedly reactivated faults including old mylonite zones. Deposits tend to occur in subsidiary structures in the hanging wall of major thrust faults.

Unmetamorphosed red bed arenites may overlie the basement.

Alteration

Three principal types of alteration are distinguished:

- early Na- and/or Mg-metasomatism (albitization, dolomitization) of the basement;
- pre-cover sandstone (Meso-Helikian in Saskatchewan) paleoweathering extending in excess of 50m below the unconformity (hematitization, chloritization, sericitization, argillitization);
- post-sandstone early diagenetic, and later ore-related diagenetic hydrothermal alteration

overprinting the former alteration zones by illitization, chloritization, carbonatization, tourmalinization (dravite), silicification, sulfidation, destruction of graphite, and corrosion of quartz. This alteration is intensely developed within a deposit but forms only a narrow aureole around it.

Ore and Associated Minerals

Uraninite/pitchblende and alteration products thereof. Quartz and carbonates in minor amounts. Fe-chlorite, Mg-chlorite, illite-sericite, kaolinite, dravite and hematite. Base metal minerals in trace amounts. Ore and associated minerals are present in several generations.

Mode of Mineralization

Uranium minerals occur disseminated to massive and fairly continuous in moderate to steep dipping fractures and breccia zones in the basement. These zones are commonly best developed proximal below the unconformity but may extend to a depth exceeding 400 m. Mineralization may persist upward along fractures into the overlying sandstone. These deposits are commonly monometallic with moderate to high uranium grades and contain only traces of other metallic elements.

Age Constraints

Class 1.1.1 deposits are restricted to areas affected by early Middle Proterozoic orogeny (Hudsonian in Canada), followed by a warm-humid climate changing into an arid climate as reflected by lateritic paleosol (regolith) development, then succeeded by sedimentation of red bed arenites (Athabasca Group ca. 1500 m.y.). Minimum U/Pb ages of earliest uranium oxide generation are 1400 m.y. at Eagle Point (Eldorado Resources Ltd. 1987) and ca. 1280 m.y. at Rabbit Lake (Cumming and Rimsaite 1977).

Dimensions/Resources

Individual deposits may be up to 1000 m long, a few meters to several 10 m wide and several 10 m to more than 400 m deep, containing up to >50 000 mt U_3O_8 at grades ranging from 0.3 to 1.0%, rarely a few percent U_3O_8 . Districts may contain up to 100 000 mt U_3O_8 .

Remarks

Fracture-bound deposits of the Rabbit Lake area (Rabbit Lake, Eagle Point) display peculiar geological features resembling those of subunconformity-epimetamorphic deposits such as found in the Beaverlodge district (subtype 2.2), e.g., albitization, migmatitization, and essentially monometallic mineralization. An explanation may be that the class 1.1.1 deposits originated from preexisting Beaverlodge-type deposits by unconformity-type overprinting.

Examples of Middle Proterozoic Unconformity-contact, Class 1.1.1 Fracture-bound Deposits/ Occurrences

Australia: ? Nabarlek/Alligator Rivers, Northern Territory, ? Kintyre, West Australia
 Canada: Dominique-Janine, Dominique-Peter, Horseshoe, Raven/Athabasca Basin, Saskatchewan, Kiggavik/Thelon Basin, NWT
 Guyana-Venezuela: Roraima region

Class 1.1.2: Clay-bound

Type Example: Cigar Lake and Key Lake, Saskatchewan, Canada

References: Fouques et al. 1986; Ruhmann 1986

Host Rocks/Structures

Argillaceous facies (clay, mudstone, argillic sandstone), locally containing carbonaceous material (bitumen) resting along the unconformity upon paleoweathered crystalline basement. The clay is mostly concentrated at slight basement ridges and grades upwards and laterally into ubiquitously oxidized sandstone. Basement under or near overlying deposits is disturbed by faulting including ancient lineaments (mylonite zones). The clay may have originated from pedogenic or lacustrine deposits of outwashed lateritic paleosol, or from fault gouge or diagenetic alterations, or from a combination of several of these features.

Alteration

Paleoweathering, diagenetic and mineral-related alteration corresponds to that of class 1.1.1, but

the latter forms a far larger halo. In contrast to subtype 1.1.1, albitization of basement rocks is practically absent.

Ore and Associated Minerals

Uraninite/pitchblende and alteration products thereof. Al-, Mg- and Fe-chlorite, illite, kaolinite, dravite, quartz and hematite. Veinlets of quartz, carbonates, and dravite. Associated metallic minerals may include sulfides and arsenides of Ni, Co, Cu, Pb, Zn, Mo, Bi, Sb, and V, locally Te, Se, Au, Ag, and Pt-group elements, some in appreciable amounts (up to several percent). Ore and associated minerals are present in several generations.

Mode of Mineralization

U minerals occur in the clay envelop as disseminated to often massive, continuous mineralization forming linear, pipe or cigar-shaped, more or less horizontal deposits, composed of a high grade core surrounded by a lower grade halo. The deposits exhibit a rather sharp ore-wall rock boundary. Mineralization may extend along cataclastic zones higher up into sandstone and downward into the basement. These deposits consist almost always of polymetallic mineralization of high to very high grades (>1% U₃O₈). Ni is commonly the most notably enriched associated metal.

Age Constraints

Correspond to those of class 1.1.1.

Dimensions/Resources

Individual deposits are a few 10 m to ca. 1500 m long, a few meters to ca. 100 m wide and a few meters to 25 m thick, containing a few 100 to >125 000 mt U₃O₈ at grades ranging from ca. 1 to 14% U₃O₈. Districts may contain up to 200 000 mt U₃O₈ and more.

Examples of Middle Proterozoic Unconformity-contact, Class 1.1.2 Clay-Bound Deposits/Occurrences

Canada: Cluff Lake "D", Collins Bay, Dawn Lake, Maurice Bay, Midwest, McClean, P2-North/Athabasca Basin, Saskatchewan

4.1.2 Subtype 1.2: Phanerozoic unconformity-related

Type Example: Bertholène and Le Roube/Brousse Broquies, Aveyron, France

References: Schmitt et al. 1984; George 1985

Host Rocks/Structures

Permo-Carboniferous clastic sediments with some volcanic components resting along the post-Hercynian unconformity on altered Upper Proterozoic to Lower Paleozoic schists and gneisses containing minor graphitic horizons. Faults transect basement and sediments. Redox conditions in the cover sediments are variable.

Alteration

Two types of alteration are distinguished:

- pre-mineralization: albitization, Fe-chloritization, sideritization;
- syn- to post-mineralization: silicification, argillitization (smectite, illite, minor kaolinite), carbonatization, pyritization, hematitization.

Ore and Associated Minerals

Coffinite, minor pitchblende and tetragonal α -U₃O₇, and alteration products thereof (uranyl vanadates).

Gangue or similar minerals: Illite, smectite, dolomite, calcite, siderite.

Metallic minerals: Pyrite, minor marcasite, galena, sphalerite, hematite replacing pyrite.

Mode of Mineralization

U minerals occur as disseminations and fine veinlets forming small ore bodies. The ore bodies straddle along the post-Hercynian unconformity most commonly where the unconformity is transected by faults. Mineralization occurs either in the basement (Bertholène) or cover sandstone (Bennac) or in both (Le Roube).

Age Constraints

Mineralization in the type examples formed in Jurassic time, contemporaneously with intrusion of basic dikes and approximately time-equivalent to global tectonics marked by the incipient stage of the opening of the North Atlantic ocean.

Dimensions/Resources

Individual deposits may be up to 1000 m long, a few meters to 50 m wide and may extend up to ca. 30 m above and ca. 30 m below the unconformity. Resources are a few tens to ca. 2000 mt U₃O₈ at (average) grades of 0.1 to 0.15% U₃O₈.

Remarks

Differences between subtype 1.1 deposits in Saskatchewan and those of subtype 1.2 in Aveyron, France include (a) well-developed albitization in Aveyron attributed to diagenesis of cover sediments. Albitization is practically absent in class 1.1.2 deposits in Saskatchewan. (b) Clay minerals associated with mineralization are dominantly illite and smectite in Aveyron, and illite and Al-, Mg-chlorite in Saskatchewan. (c) Metal association is more simple in Aveyron than in Saskatchewan. (d) Cover sediments have contrasting redox environments in Aveyron, whereas those in Saskatchewan are uniformly oxidized. (e) Graphite horizons are of only minor importance in Aveyron. (Pagel 1989).

4.2 Type 2: Subunconformity-Epimetamorphic (Fig. 4.2)

Definition

Subunconformity-epimetamorphic deposits are strata-structure-bound in metasediments below an unconformity on which clastic sediments rest. Type example deposits occur below an early Middle Proterozoic unconformity that is overlain by early Middle Proterozoic clastic sediments and volcanics.

Deposits consist of peneconcordant lenses or tabular mineralizations emplaced in fractures and breccias within distinct stratigraphic units. Host strata are predominantly pelitic (subtype 2.2 or carbonatic (2.1) sediments with intercalated carbonaceous horizons of late Lower Proterozoic age metamorphosed to amphibolite grade facies and superimposed by retrograde (greenschist) metamorphism. Granitic-migmatitic complexes occur discordantly in the metasediments. Paleoweathering of the crystalline rocks was only mild (in contrast to areas of “unconformity-contact”

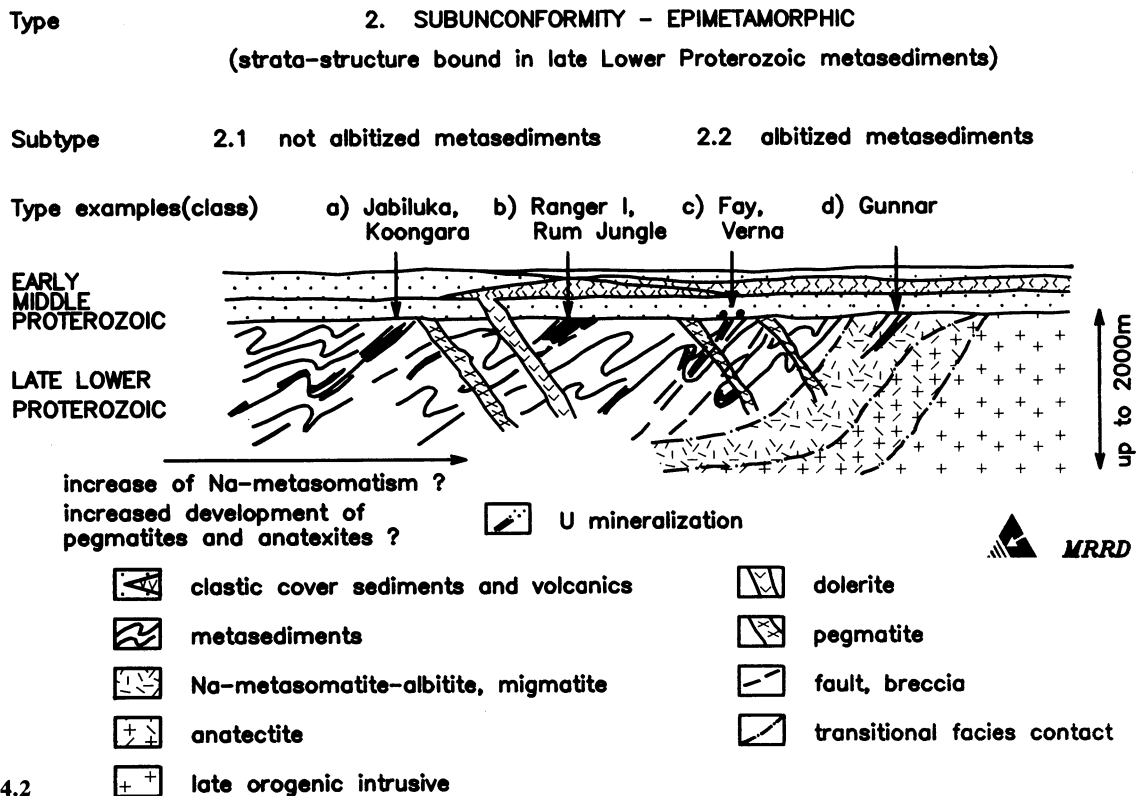


Fig. 4.2

deposits). Principal uranium phases are pitchblende and uraninite. Intense and extensive host rock alteration surrounds mineralization.

Two settings of mineralization are recognized on the base of Na-metasomatism of the host metasediments and other features:

Subtype 2.1: not albitized metasediments

Type Example: a) Jabiluka, Koongara,
b) Ranger,
Alligator Rivers district, Australia

Subtype 2.2: albitized metasediments

Type Example: c) Fay-Verna,
d) Gunnar,
Beaverlodge district, Canada

References: Beck 1986; Dahlkamp and Adams 1981; Ferguson and Goleby (eds.) 1980; IAEA/Ferguson (ed.) 1984; Needham et al. 1988; Tremblay 1978

a), b), c), and d) refer to type examples shown in Fig. 4.2.

Subtype 2.1 does not display albitization but extensive Mg-, Li-, and B-metasomatism of both host metasediments and overlying sediments. Subtype 2.2 exhibits albitization of host rocks partly of high intensity up to albitite formation and also shows a stronger structural control and contains relative abundant gangue minerals as compared to subtype 2.1.

Principal Recognition Criteria

Host Environment

- Orogenic belts
- Metasediments (schist, gneiss) with interbedded graphitic horizons of pelitic and psammitic eugeosynclinal or lacustrine origin
- Regional metamorphosed to amphibolite grade locally up to granulite grade facies
- Retrograde greenschist facies metamorphic overprint
- Presence of granitic-migmatitic complexes and pegmatite dikes in basement
- Cover by continental clastic sediments with intercalated and transgressive basic volcanics
- Post-sedimentary diabase/dolerite dikes
- Brittle deformation of host strata by intense faulting and brecciation often but not neces-

sarily developed adjacent to and at intersections of major faults (particularly evident in Beaverlodge district)

- Host structures are faults, fractures, breccias, stockworks arranged more or less peneconcordant to attitude of strata

Alteration

- Mild paleoweathering-related alteration of basement (in Beaverlodge district of more physical than chemical nature)
- Pervasive diagenetic alteration including Mg-, Li- and B-metasomatism of several generations imposed on both basement and overlying sediments and reflected by tourmalinization (dravite), carbonatization (calcite, dolomite), argillitization, sericitization etc.
- Intense mineral-related wall rock alteration including argillitization, chloritization, desilicification, silicification, sulfidization and hematitization
- Widespread pre-ore albitization of basement rocks hosting subtype 2.2 deposits

Mineralization

- Principal uranium minerals are pitchblende, uraninite and alteration products thereof (coffinite, etc.). For associated minerals and metals, see Table 4.2
- Gangue minerals are associated with subtype 2.2 but rare or absent in subtype 2.1
- Most deposits, particularly all large ones are monometallic except for some containing locally Au; some smaller deposits are polymetallic (Rum Jungle: Cu, Pb, Zn)
- Several generations of mineralization exist, mainly derived by redistribution of primary mineralization (locally into cover sandstone)
- Ore distribution consists of U disseminations or massive veinlets within host structures
- Mineralized structures are arranged \pm peneconcordant to attitude of host strata
- Type example (a) Jabiluka and Koongara display the most pronounced strata-bound structure correlation, whereas going from type examples (b) to (c) and (d) the strata-structure relationship becomes less evident
- Mineralization is fairly continuous
- Depth persistence is variable but can extend to great depth (>1600 m in Beaverlodge district)

Table 4.2. Associated minerals and metals

	Gangue minerals Vein fillings	Others (replacement, authigenic, etc.)		Metals
		Basement	Overlying sandstone	
a) ^a	–	Chlorite Sericite/illite Kaolinite Silica Quartz	Locally Mg-chlorite, tourmaline (in Kombolgie sandstone and basement)	Au
b)	–	Carbonate Hematite		Cu, Pb, Zn
c)	Calcite, dolomite, quartz, chlorite (?)	Hematite Epidote		Co, Ni, Pb Cu, Pt, Au, Ag As, Se, S
d)	Quartz (?) Calcite (?) Chlorite (?)	Albite Calcite		

^a a to d refer to type examples in Fig. 4.2

Age Constraints

- No age constraint except limitation to orogenies younger than late Lower Proterozoic
- All major deposits known are associated with upper Lower Proterozoic sediments metamorphosed during the Hudsonian or time equivalent orogenies (ca. 1900 to 1700 m.y. ago)

Metallogenic Aspects

Subunconformity-epimetamorphic uranium deposits have a complex, polyphase evolution. Deposits in the Alligator Rivers and Beaverlodge districts most likely have their roots in late Lower Proterozoic time when pelitic-psammitic sediments interbedded with carbonaceous horizons collected anomalous amounts of uranium and other metals. It is possible that pre-metamorphic relocation of uranium led to the formation of sandstone-type deposits such as those in the Franceville Basin, Gabon. During Lower to Middle Proterozoic times these sediments were regionally metamorphosed to amphibolite and locally to granulite facies. In regions of open systems, i.e., in tectonically active terrane characterized by anatexis, migmatism, metasomatism, acidic and mafic intrusions, and brittle deformation, uranium was locally mobilized by late metamorphic and/or metasomatic hydrothermal processes and reconcentrated in structures which

had opened within the uraniferous strata. In contrast, in areas of closed systems, i.e., those that lack the above listed criteria, uranium remained in situ and formed stratiform synmetamorphic mineralizations (Type 13). The position of more structurally dominated mineralization [type examples (c) and (d) at Beaverlodge] or more lithologically controlled mineralization [(a) and (b) in the Alligator Rivers district] may be related to zones influenced by Na-metasomatism, migmatization and/or palingenesis/anatexis. In regions where subunconformity-epimetamorphic deposits were covered by early Middle Proterozoic continental sediments, the cover protected the deposits against weathering and erosion. More or less intense diagenetically induced magnesium and boron metasomatism occurred in both crystalline basement and overlying sandstone as displayed in the Alligator Rivers district. These processes very probably created diagenetic modifications in the deposits including redistribution, partly into the overlying sandstone as at Beaverlodge, and recrystallization of the uranium and intense host rock alteration. Still younger processes led to further modifications, as reflected by several generations and isotope ages of uranium and associated minerals.

Remarks

- a) Monometallic subunconformity-epimetamorphic U deposits particularly those of Lower to

Middle Proterozoic age, often have medium to large resources (up to >200 000 mt U_3O_8) at low to medium grade (0.2–0.4% U_3O_8) but may also contain sections of very high grade (several % U_3O_8). In contrast, polymetallic deposits except those with gold (e.g., Jabiluka) have small resources.

- b) Although all large deposits of this category known are associated with Lower to Middle Proterozoic rocks, similar deposits may also occur in comparable geological environments associated with younger orogenic-metamorphic events.

4.2.1 Subtype 2.1: Not albited metasediments

Type Example: Pine Creek Geosyncline, Australia
Monometallic (except for local Au concentration): a) Jabiluka, Koongara, Australia;
b) Ranger One, Australia

Polymetallic: Rum Jungle

(a) and b) refer to Fig. 4.2)

References: Ewers et al. 1984; Ferguson and Goleby (eds.) 1980; IAEA/Ferguson (ed.) 1984; Needham et al. 1988

Host Rocks/Structures

Metasediments (schist, gneiss) with intercalated graphitic layers and carbonatic horizons derived from pelites and psammities of eugeosynclinal or lacustrine origin, regionally metamorphosed to amphibolite-granulite facies.

Migmatitic/anatectic complexes occur near deposits. Pegmatite and diabase/dolerite dikes intrude host sequences. Continental sandstone with intercalated and discordant basic volcanics, if not eroded, overlie mineralized areas.

Host rocks are deformed by intensive faulting and brecciation. Structures containing mineralization consist of fractures, breccias and stockworks arranged \pm peneconcordant to attitude of strata. Type examples (a) Jabiluka and Koongara display the most distinct strata-bound structure correlation whereas that of examples (b), Ranger One and Rum Jungle is more structure prominent.

Alteration

Strong wallrock alteration and extensive metasomatism (Mg, B, Li) of several generations. The latter affected both basement and sandstone cover and includes tourmalinization (dravite), chloritization (Mg and/or Fe-rich), carbonatization (calcite, dolomite), sericitization, argillitization, desilicification, and silicification and hematitization. Alteration related to mineralization is commonly very intense and may extend to variable distance (m to 10's m) into wall rocks.

Ore and Associated Minerals

Principal uranium minerals are pitchblende, rarely uraninite and alteration products thereof (coffinite, brannerite, sooty pitchblende). Associated minerals/metals see under main heading, Type 2.

Mode of Mineralization

U occurs as disseminations or massive veins filling fractures, breccias and stockworks, \pm peneconcordant to attitude of the strata. Mineralization is more or less continuous and may extend to more than 500 m below the unconformity. Most ore is monometallic except for some small deposits (Rum Jungle) and locally payable gold values (Jabiluka, Koongara). Several generations of uranium mainly derived by redistribution and recrystallization (rejuvenated U/Pb ages) of primary mineralization partly by diagenetic processes. Mineralization is controlled by both structure and lithology as reflected by emplacement in cataclastic zones \pm peneconcordant to folded metamorphosed strata and often adjacent to graphitic horizons. Other recognition criteria include intense, partly pervasive chloritization, sericitization, argillitization, and hematitization of wallrocks; wide-spread halos into cover sediments of tourmalinization, carbonatization, silicification, etc.; (former) presence of continental cover sediments and volcanics; minor paleosol development prior to sedimentation and numerous pegmatite and diabase (dolerite) dikes.

Age Constraints

All examples known are associated with upper Lower Proterozoic sediments metamorphosed during an orogeny at about 1700 to 1900 m.y. ago.

Dimensions/Resources

Individual deposits may be up to >1000 m long, several tens to more than 400 m wide and in excess of 500 m deep, containing up to 200 000 mt U₃O₈ at (average) grades ranging from 0.1 to 0.4% U₃O₈ occasionally to >1% U₃O₈. Districts may contain up to 400 000 mt U₃O₈.

Remarks

For more details see Chapter 5.2.1.

Examples of Subunconformity-Epimetamorphic, Subtype 2.1 Not Albitized Metasediments Deposits/Occurrences

Australia: Alligator Rivers district, Rum Jungle district, ? South Alligator River district/Pine Creek Geosyncline, Northern Territory, ? Kintyre, West Australia

4.2.2 Subtype 2.2: Albitized metasediments

Type Example: Beaverlodge, Uranium City region, Canada

monometallic: c) Fay – Verna; d) Gunnar

polymetallic: c) Nicholson

(c) and d) refer to Fig. 4.2)

References: Beck 1986; Evans (ed.) 1986; Tremblay 1978; Ward 1984

Host Rocks/Structures

Metasediments (schist, gneiss) with intercalated graphitic layers derived from pelites and psammites of eugeosynclinal or lacustrine origin, regionally metamorphosed to amphibolite-granulite facies and partly Na-metasomatized to albitite rocks.

Migmatitic/anatectic complexes and/or granitic intrusions occur near deposits. Pegmatite and diabase/dolerite dikes cut the host rocks. Continental sandstone with intercalated and discordant basic volcanics, if not eroded, overlie mineralized areas and may carry (redistributed) mineralization.

Host rocks are deformed by intensive faulting and brecciation, often but not necessarily developed adjacent to and at the intersection of major faults. Structures containing mineralization

consist of fractures, breccias, and stockworks arranged ± peneconcordant to the attitude of strata. Structural control is more prominent as in subtype 2.1.

Alteration

Extensive and locally intense Na-metasomatism and strong wall rock alteration of several generations modified the basement. Na-metasomatism is a pre-ore phenomena and locally achieved albitite formation. Host rock alteration of pre- to syn-mineralization age includes pervasive hematitization, chloritization, epidotization, carbonatization, and silicification.

Ore and Associated Minerals

Principle uranium minerals are pitchblende, rarely uraninite and alteration products thereof (coffinite, brannerite, sooty pitchblende).

Associated minerals/metals (see under main heading, Type 2).

Mode of Mineralization

U occurs as disseminations or massive veins filling fractures, breccias and stockworks, ± peneconcordant to attitude of the strata. Mineralization is more or less continuous and may extend to a considerable depth (>1600 m). Most ore is monometallic except for some small deposits (e.g., Nicholson). Several generations of uranium mainly derived by redistribution (locally into cataclastic cover sandstone) and recrystallization (rejuvenated U/Pb ages) of primary mineralization.

Mineralization is controlled by both structure and lithology as reflected by emplacement in structures ± peneconcordant to folded metamorphosed strata and often adjacent to graphitic horizons. Other recognition criteria include intense, partly pervasive chloritization, sericitization, argillitization, hematitization, carbonatization, silicification, etc. of the host rocks; (former) presence of continental cover sediments and volcanics; little or no paleosol (regolith) development prior to sedimentation and numerous pegmatite and diabase (dolerite) dikes.

Age Constraints

All major deposits known are associated with upper Lower Proterozoic sediments metamor-

phosed during the Hudsonian Orogeny (ca. 1700 to 1900 m.y.).

Dimensions/Resources

Individual deposits may be meters to 100 m long, several meters to more than 100 m wide and in excess of 1600 m deep, containing up to >15 000 mt U₃O₈ at (average) grades ranging from 0.1 to 0.4% U₃O₈. Districts may contain up to 25 000 mt U₃O₈.

Remarks

For more details see Chapter 5.2.2.

Examples of Subunconformity-Epimetamorphic, Subtype 2.2 Albitized Metasediments Deposits/Occurrences

Canada: Bolger, Dubyna, Hab, Lake Cinch/Beaverlodge, Saskatchewan

4.3 Type 3: Vein (Figs. 4.3a,b)

Definition

Vein deposits consist of uranium mineralization in lenses or sheets or disseminations filling joints, fissures, breccias and stockworks in deformed and fractured rocks. Size and complexity of vein sets are variable. Distribution and intensity of mineralization are irregular. Principal uranium phases are pitchblende, uraninite and coffinite. Gangue minerals are always present. Uranium may form monometallic mineralizations or polymetallic mineralizations. Associated metals include Co, Ni, Bi, Ag, Cu, Pb, Zn, Mo and/or Fe in form of sulfides, arsenides or sulfarsenides. Wall rock alteration is commonly restricted to a narrow margin (<1 m).

Two principal subtypes are recognized, veins spatially and genetically (?) related to granites (subtype 3.1) and veins not related to granites (subtype 3.2) which are further subdivided into the following classes:

Subtype 3.1: granite-related (Fig. 4.3a)

Class 3.1.1: intragranitic
(Limousin type)

Type Examples: 3.1.1.1 veins in granite: Fanay, France
3.1.1.2 disseminations in episyenite pipes: Pierres Plantées, France

Class 3.1.2: perigranitic

Type Examples: 3.1.2.1 veins in (meta-)sediments:
monometallic (Bohemian type)
Příbram, ČSFR
3.1.2.2 veins in metasediments:
polymetallic (Erzgebirge type)
St. Joachimsthal/Jachymov, ČSFR
3.1.2.3 in contact-metamorphics:
(Iberian type)
Alto Alentejo, Portugal

Subtype 3.2: not granite-related (Fig. 4.3b)

Class 3.2.1: in metamorphic rocks
Type Example: Schwartzwalder, USA

Class 3.2.2: in sediments (polymetallic)
Type Example: Shinkolobwe, Zaire

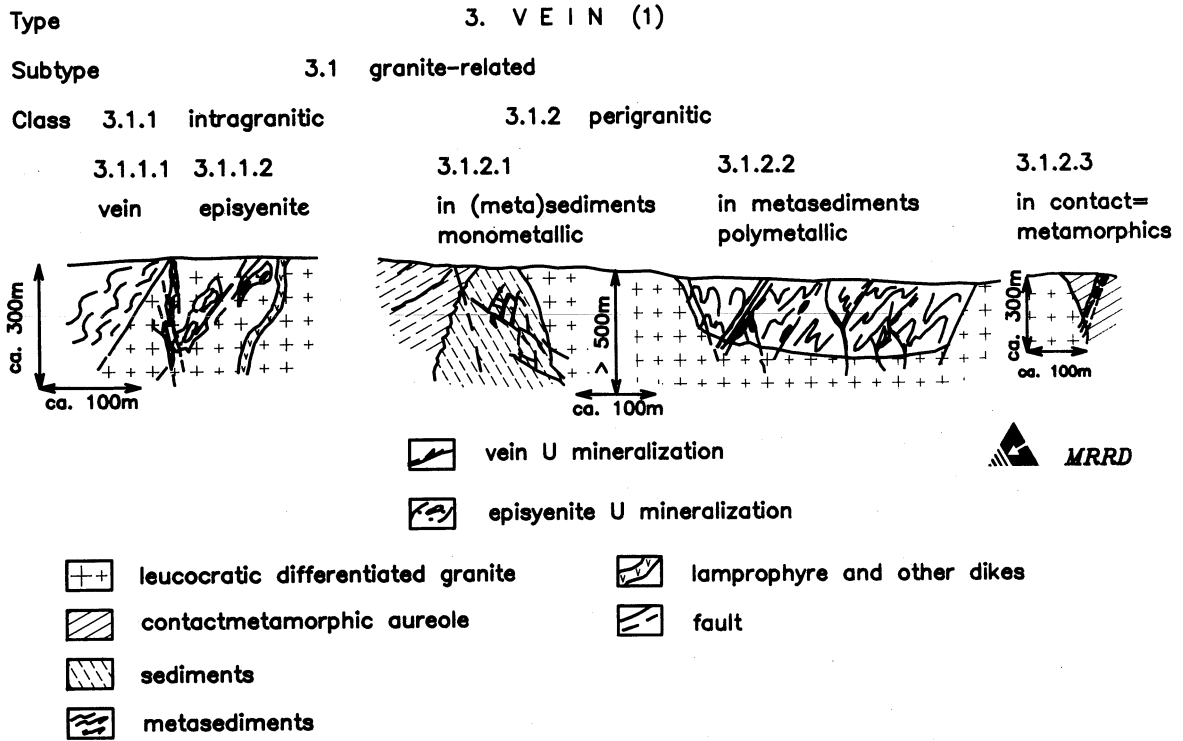
References: IAEA/Fuchs (ed.) 1986; Basham and Matos Dias 1986; Derricks and Vaes 1956; Friedrich et al. 1987; Kolektiv ČSSR 1984; Poty et al. 1986; Rich et al. 1977; Ruzicka 1971; Wallace 1986

Granite-related deposits are associated with highly differentiated peraluminous leucogranites and form veins either within (intragranitic, class 3.1.1) or around (perigranitic, class 3.1.2) the intrusion.

Intragranitic deposits are commonly monometallic and occur either as (a) linear ore bodies in form of distinct veins or stockworks emplaced in fractured granite or (b) disseminations in pipes or chimneys of episyenite, a dequartzified, micaceous vuggy alteration product of granite. Depth extension of intragranitic veins is commonly less than 300 m.

Perigranitic deposits emplaced in (meta-)sediments are either monometallic consisting essentially of pitchblende and gangue minerals (3.1.2.1) or polymetallic (3.1.2.2) containing both U and Co, Ni, Bi and Ag minerals in economic quantities. The U and the other elements are not genetically related. Both monometallic and polymetallic veins can persist as much as 2000 m deep. Ore occupancy of host structures is generally low (in the order of 5 to 30%).

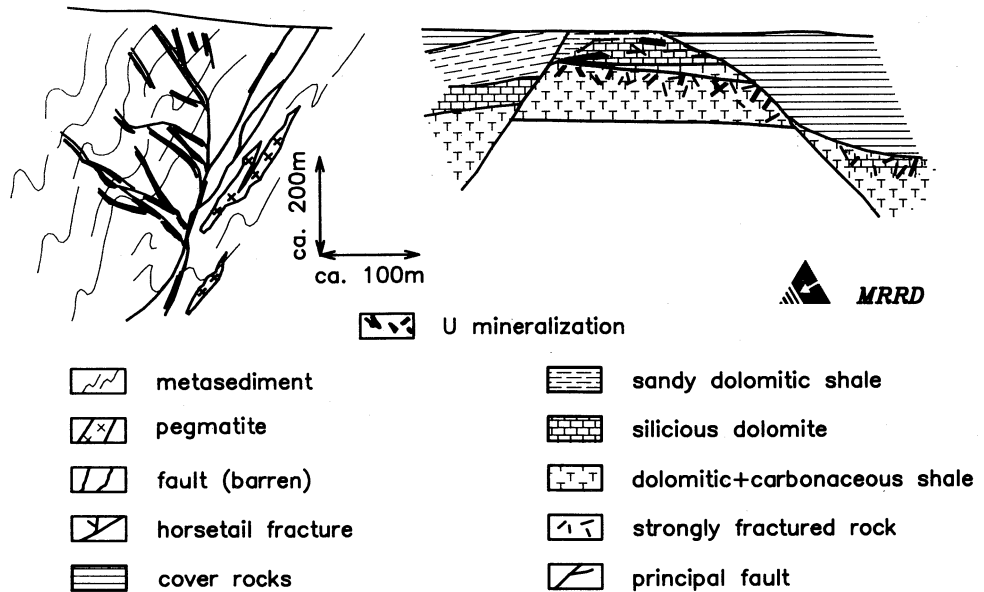
Perigranitic deposits emplaced in the contact-metamorphic aureole of the intrusion (3.1.2.3)



Type 3. VEIN (2)

Subtype 3.2 not-granite-related

Class 3.2.1 in metasediments¹⁾ 3.2.2 in sediments²⁾



1) idealized after Schwartzwalder, USA/Wallace 1986

2) idealized after Shinkolobwe, Zaire/Derrick & Oosterbosch 1958

Fig. 4.3a, b

have monometallic mineralization in form of veinlets and disseminations in intensely fractured hornfels, speckled andalusite-cordierite schist and similar rocks up to approximately 2 km wide around the granite. Host rocks are severely altered.

Not granite-related deposits (subtype 3.2) are similar in mineral composition and wall rock alteration to perigranitic veins in (meta-)sediments but do not reveal any apparent link to granitic intrusions.

Principal Recognition Criteria

Host Environment of Granite-related Deposits

- Orogenic belt
- Presence of highly differentiated igneous complex including peraluminous leucocratic granite of crustal origin derived by multistage magmatic and deuteric processes
- Uranium content in granite above Clark standard (>5 ppm)
- Uranium fixed in leachable phases (uraninite)
- Sufficient size of pluton (outcrop extension at least 100 km²)
- Presence of leucocratic (pegmatite, aplite) and mafic (lamprophyre) dikes
- Limited depth of erosion level (indicated by abundance of roof pendants in pluton, dikes, etc.)
- Structural vein control by commonly one, \pm parallel oriented dilational fracture system

Host Environment of Not Granite-related Deposits

- Orogenic belt
- Absence of nearby granites or other igneous uranium source rocks
- Host rocks are folded sediments or metasediments, the latter often of mafic composition and metamorphosed up to amphibolite facies
- Intense brittle deformation by major faults associated with abundant subsidiary fractures and breccias which may form stockworks or horsetail patterns
- Emplacement of mineralization preferentially in subsidiary structures

Regional Alteration (Subtype 3.1)

- Albitization, muscovitization
- Feldspar and mica episyenitization

Ore-Related Alteration (Subtype 3.1 and 3.2)

- Spatially restricted wall rock alteration commonly persisting for less than 0.5 m, rarely to 3 m, from veins into wall rock
- Type of alteration depends to some degrees on host rock composition
- Alteration types may include carbonatization, chloritization, argillitization, silicification, hematitization, K-feldspathization

Mineralization (Subtype 3.1 and 3.2)

- Principal uranium minerals: pitchblende, locally uraninite, coffinite, and alteration products thereof
- Associated metallic minerals: dominantly pyrite, marcasite, and minor Cu, Pb, Zn, Mo sulfides
- In some deposits either arsenides or sulfides of Ag, Co, Ni, Bi accompany pitchblende but not paragenetically
- Gangue minerals: quartz, chalcedony, carbonates, fluorite, baryte (in class 3.1.1 present in minor amounts and sometimes almost absent, in class 3.1.2 abundant)
- U and associated minerals are mostly present in several generations
- U and gangue minerals form irregularly shaped and discontinuous ore shoots separated by barren intervals
- Low frequency of uranium ore occupancy of host structures commonly in the range from 5 to 30% in subtype 3.1, more continuous in subtype 3.2
- U mineralization is often associated with inhomogeneities of veins (change in trend, thickness) and wall rock lithologies

Age Constraints (Subtype 3.1 and 3.2)

- No stratigraphic age constraint
- Restriction to late orogenic stages
- In Europe the dominant association of subtype 3.1 is with the waning stage of the Hercynian Orogeny

Metallogenic Aspects

Poty et al. (1986) suggest for *granite-related* pitchblende-vein deposits in the Hercynian orogenic belt in France (class 3.1.1) the following

metallogenetic model. Although largely based on research of intragranitic veins, the model appears, at least to some extent, to be also applicable to perigranitic vein deposits except for tectonic processes, creating the structural frame for vein emplacement, and, perhaps, incorporation of uranium from metasediments.

Evolution of granite-related vein uranium deposits started during the waning episode of the Hercynian Orogeny marked by general uplift, and intrusion of granite and a suite of leucocratic to mafic dikes. Certain peraluminous leucogranites contain uraninite as a primary magmatic rock constituent distributed in two modes (a) homogeneously throughout the granite and (b) accumulated (up to 100 ppm U) along synmagmatic shear zones.

In zones of intense faulting, high heat flow, in response to tectonism (?) generated deep reaching convective circulation of mixed connate-meteoric waters in late to post-magmatic time. The fluids leached the uraninite and transported uranium as uranyl-carbonate complexes to the marginal zones of the pluton. Precipitation of pitchblende occurred in either dilational fractures (vein mineralization) or vesicular, vuggy episyenite bodies (disseminated mineralization). Precipitation supposedly resulted as a response to boiling of the hypogene convective hydrothermal fluids triggered by either a pressure drop, and/or by reactions with mafic rocks. Pitchblende crystallization was accompanied by deposition of pyrite and gangue minerals (mainly quartz, carbonate) and by K-metasomatism and muscovitization of wall rocks adjacent to veins. In several subsequent stages, hematite, coffinite, marcasite, and additional gangue minerals formed, most of them on account of the original ore generation. A supergene overprint redistributed part of the uranium.

Petroš et al. (1986) postulate a metasedimentary uranium origin with subsequent enrichment during magma differentiation and final hydrothermal redistribution into dilational structures, possibly with some contribution of uranium from residual magmatic fluids for perigranitic (Bohemian type) veins (class 3.1.2.1) in the Příbram district, ČSFR.

Metallogenetic hypotheses of Iberian type deposits (3.1.2.3) are contentious (perhaps due to limited exploration in depth) and include concepts such as supergene, lateral secretory and hypogene origins.

Metallogenetic considerations for subtype 3.2, *not granite-related veins*, face in many cases the problem of an adequate uranium source and a mechanism for propelling the mineralizing fluids. Wallace (1986) suggests for the metamorphite hosted Schwartzwalder veins (class 3.2.1) that the source of uranium and all other vein components was the metamorphic terrane surrounding the deposit. Leaching of the elements occurred by evolved connate hydrothermal fluids. The fluids probably derived originally from meteoric waters and resided in deep cataclastic zones. Mobilization of the fluids was generated during the incipient uplift of the crystalline block of the Front Range in the course of the Laramide Orogeny. Migration occurred along permeable fault zones created by repeated deformation of brittle rocks. The connate hydrothermal solutions were carbonate-rich and produced successive wall rock alterations around fractures and several generations of vein mineralization during repeated major movement along faults. Mineral deposition resulted during episodic brecciation that reduced the confining pressure which simultaneously increased the pH and decreased $f(\text{CO}_2)$ and $f(\text{O}_2)$. Reduced sulfur species in solution reduced the uranium carried in solution.

Similar processes may have formed the sediment hosted Shinkolobwe deposit (class 3.2.2). In this case sediments with anomalous contents of uranium and other metals (Série de Mine) probably provided the vein forming elements.

Remarks

Vein deposits are often composed of small lodes and almost always occur in groups which cumulatively yield small to large resources. Grades are highly variable and many known deposits contain sections of very high grade ore.

4.3.1 Subtype 3.1: Granite-related

Class 3.1.1: Intragranitic (Limousin type)

3.1.1.1: veins in granite

Type Example: Fanay, Limousin, France

3.1.1.2: disseminations in episyenite pipes

Type Example: Pierres Plantées, Margeride, France

References: Cariou 1964; Cathelineau 1985; Friedrich et al. 1987; Leroy 1978a, 1978b; Leroy and Cathelineau 1982;

Host Rocks/Structures

Ziegler and Dardel (1984) define ore-hosting fertile granite as a highly differentiated two-mica leucogranite with an average composition of ca. 36% quartz, 27% orthoclase, 27% albite, 10% muscovite and biotite, enriched in Be, Li, F, Sn, W, Th and U. The main facies is medium to coarse-grained and has intercalations of a fine-grained facies. The granite is of peraluminous composition derived from crustal material (Friedrich et al. 1987). Lamprophyre, pegmatite, aplite and micro-granite dikes transect the complex.

Mineralized structures are dominantly controlled by a dilational system of a distinct direction (NW-SE in Limousin). Major faults are rarely or not mineralized. The most favorable host structures are those of secondary order, forming \pm parallel fractures or complicated interwoven stockwork systems.

Alteration

Pre-mineralization alteration consists of albitization and episyenitization. Episyenitization is reflected by dissolution of quartz with destruction and neoformation of minerals leading to feldspar-episyenite (commonly barren of U) and mica-episyenite (Leroy and Cathelineau 1982).

Ore-related alteration extends usually for less than 0.5 m into wall rocks adjacent to veins and includes \pm total muscovitization (phengitization) of K-feldspar, chloritization of mafic minerals and pyritization accompanying pitchblende emplacement. A second phase of alteration associated with coffinite formation after pitchblende consists of hematitization, montmorillonitization, adularia formation, and silicification partly by replacement of first stage alteration products.

Ore and Associated Minerals

Pitchblende, coffinite and the alteration products thereof are usually associated with pyrite, marcasite, melnicovite, quartz, chalcedony, fluorite, baryte, and calcite. Gangue minerals occur in minor amounts and locally are absent. Other sulfides (galena, bismuthinite, a.o.) are scarce, but occur in some deposits in significant amounts (e.g., Bois Noirs, Forez, France).

Mode of Mineralization/Dimensions

Veins in Granite. Veins, veinlets or stringers of pitchblende and associated minerals occur in simple linear configuration but more commonly occupy a complex network or stockwork of fractures or breccias particularly in proximity to lamprophyre dikes, roof pendants, and other inhomogeneities in the host granite. Individual veinlets/veins vary in thickness from a few mm to rarely more than 5 m. Lateral and vertical continuity is variable, averaging from less than 1 m to some 10 m, but may be as long as 1000 m and more. Depth extension is generally less than 300 m. Mineral distribution also varies considerably. Reserves range between less than 1 mt to some 100 mt U_3O_8 and grades between less than 0.1% and up to 40% U_3O_8 in some ore shoots (the Henriette deposit, France, yielded 120 mt U_3O_8 at an average mining grade of 37% U_3O_8 from a vein averaging 5 m long, 0.4 m thick and 250 m deep).

Disseminations in Episyenite. Mineralization is hosted in irregularly pipe- or lense-shaped bodies of mica episyenite developed at intersections of two structure systems. Vertical extensions range between 30 and 200 m, and diameters between few meters and several 10 m. Grades are generally high, up to 1% U_3O_8 and more. Where mineralized veins intersect episyenite pipes grades may increase to between 1 and 10% U_3O_8 . Reserves vary between a few tonnes and several 100 mt U_3O_8 , rarely 1000 mt U_3O_8 or more. The type example Pierres Plantées in the Margeride district, France, is an episyenite pipe measuring 35 to 50 m in diameter, 175 m deep and yielded 1300 mt U_3O_8 with an average mining grade of 0.3 to 0.5% U_3O_8 . Mining districts may cover an area a few km to some 10 km long and wide (Limousin district France: ca. 15 km long, 5 km wide).

Resources

Individual vein systems contain reserves that range from some 10 mt to several 100 mt U_3O_8 but may be as large as 4000 mt U_3O_8 (La Commanderie, Vendée, France), at mining grades ranging from 0.15% U_3O_8 (La Commanderie) to 37% U_3O_8 (Henriette). Episyenite-hosted ore bodies have reserves of a few tonnes to 1300 mt U_3O_8 (Pierre Plantées) averaging 0.3 to 1% U_3O_8 . Districts have resources in the order of 5000 mt U_3O_8 (Morvan, France, average grade

0.16% U_3O_8) to at least 35 000 mt U_3O_8 (Limousin, average grade 0.2% U_3O_8).

Remarks

For more details see Chapter 5.3.1.

Examples of Vein, Class 3.1.1 Intragranitic Deposits/Occurrences

Brazil: ? Itataia/Ceará
 Canada: Millet Brook/Nova Scotia, ? Gunnar/Saskatchewan
 China: Xiazhuang/Guidong Massif, Ruijin/Jiangxi, SE China, Xian/Central China
 France: Limousin, Marche, Margeride, Millevaches, Morvan districts/Massif Central, Vendée district/Armorican Massif
 Germany: Menzenschwand/Black Forest, Grosschloppen/Fichtelgebirge
 Portugal: Alto Alentejo, Beiras districts
 Spain: Los Ratonos/Caceres

Class 3.1.2: Perigranitic

3.1.2.1: Veins in (meta)sediments, monometallic (Bohemian type)

Type Example: Příbram, Central Bohemian Pluton, ČSFR

Reference: Petroš et al. 1986

Host Rocks/Structures

Geology (at Příbram) consists of weakly metamorphosed Upper Proterozoic schists and Cambrian conglomerates and sandstones folded into a large NE-SW trending anticline. The SE limb of the anticline is occupied by granitic rocks of the differentiated Central Bohemian Pluton. Three dominant fault systems transect the region. Regional faults subparalleling the intrusive contact and anticlinal axis partition the anticline into longitudinal segments. The segment closest to the pluton hosts the mineralized veins. These veins mostly occupy second or third order faults trending preferentially perpendicular to oblique to both the anticlinal axis and intrusive contact. A wide variety of magmatic dikes occurs, including aplitic granite, granite-porphyry, aplite, pegmatite and lamprophyre.

Alteration

Pre-uranium host rock alteration includes silicification, sericitization, and carbonatization. Uranium mineralization related alteration commonly extend from 0.1 to 3 m, locally to several tens of meters (in zones of closely spaced or bifurcating veins) into the wall rocks and include sericitization, chloritization, and hydrohematitization.

Ore and Associated Minerals

Principal uranium minerals are pitchblende, coffinite, uranium-anthraxolite (high polymeric bitumen containing pitchblende, coffinite, calcite and other minerals), and the alteration products thereof. Associated metallic minerals include sulfides of Fe, Pb, Zn, Cu, a.o., which are present in minor to trace amounts. Gangue is abundant, and includes carbonates (dominantly calcite), quartz, and chlorite. Certain ore and gangue minerals form a characteristic paragenesis developed during consecutive stages.

Mode of Mineralization/Dimensions

Prominent types of mineralization are pitchblende-calcite veins, emplaced both inside and immediately outside of the intrusive contact and mixed uranium-anthraxolite-pitchblende veins occurring at some distance from the contact. Uranium and gangue minerals form stringers, veinlets, coatings, reniform accretions and pods, that range from mm to several 100 cm wide. This assemblage aggregates to irregularly shaped tabular or lense-like ore shoots that range from 1 to several tens of m long and deep, and a few cm to 5 m wide, interrupted by barren, gangue, or gouge-filled intervals within mineralized structures. Ore shoots commonly develop at inhomogeneities in the veins (change in strike or dip, thinning or widening, change of wall rock lithologies, splaying of structures). Ore-bearing structures may persist to as much as 2000 m deep containing irregularly distributed ore shoots at variable depth. Ore shoots usually occupy between 1 and 50% (average about 10 to 15%) of a structure with the remainder being barren. Mining districts may cover areas a few to some 10 km long and wide and may contain up to several tens of mineable veins (Příbram 1 to 2 km wide, 25 km long, about 30 shafts).

Resources

Individual vein systems contain from a few tonnes to a few 1000 mt U_3O_8 at grades varying between ca. 0.1% to some 10% U_3O_8 . Districts may account for a few 100 mt to several 10 000 mt U_3O_8 (Příbram presumably yielded in the order of 50 000 to 60 000 mt U_3O_8 , at grades of about 1 to 2% U_3O_8).

Remarks

For more details see Chapter 5.3.2.

Examples of Vein, Class 3.1.2.1, Perigranitic Monometallic Deposits/Occurrences

China: see class 3.1.1

ČSFR: Daměťice/Central Bohemian Pluton, Brezinka/Zelezne Hory

France: ? Bois Noirs/Forez, Les Bondons/Lozère, Massif Central, La Dorgissière, Le Rousset/Vendée, Pennaran, Materie Neuve/Guérande Peninsula, Armorican Massif

Greenland: ? Puissagtaq/Igaliko Fjord, SE Greenland

USA: ? Midnite/Washington [may belong to strata-structure type (16)]

Class 3.1.2: Perigranitic**3.1.2.2: In metasediments, polymetallic (Erzgebirge type)**

Type Example: St. Joachimsthal/Jáchymov, Karlovy Vary/Eibenstock Massif, ČSFR

Reference: Komínek and Veselý 1986

Host Rocks/Structures

Geology at Joachimsthal consists of intensely folded Upper Proterozoic to Lower Paleozoic, partly pyritic or graphitic mica schists, phyllites and calc-silicate units, folded into an asymmetric anticline. The metasediments are intruded by the highly differentiated Eibenstock Massif which includes a younger deuterically (?) altered leucocratic granite facies characterized by high U/Th ratios. This facies underlies and partly surrounds the mineralized district in a form akin to a half-bowl at a depth of as much as 1000 m deep. A contact-metamorphic aureole (hornfels, more massive texture) up to 60 m wide surrounds the

granite. Three dominant fault sets transect the district. Mineralized veins preferentially follow minor faults oriented perpendicular and oblique to the anticlinal axis.

A wide variety of magmatic dikes occurs, including aplitic granite, granitic porphyry, pegmatite, and lamprophyre.

Alteration

Pre-uranium host rock alteration is reflected by chloritization, phlogopitization, pyritization, and calcitization associated with destruction of mafic minerals. These alterations are overprinted by intense silicification with replacement of earlier formed minerals. Uranium mineralization related alteration rarely extends more than 10 cm into the wall rocks and is reflected by hematitization of pyrite, dolomitization of calcite and recrystallization of albite and adularia in calcite veins.

Ore and Associated Minerals

Principal uranium minerals are pitchblende, coffinite and alteration products thereof. Associated metallic minerals present in minable quantity are primarily sulfides and sulfarsenides of Ag, Co, Ni and Bi. Sulfides of other metals and hematite also occur. Gangue is abundant and includes carbonates (dominantly dolomite), quartz, albite, adularia, fluorite, and baryte. Certain ore and gangue minerals form characteristic parageneses developed during successive stages. Mineral phases occur in several generations.

Mode of Mineralization/Dimensions

Two principal varieties of vein forming mineral assemblages are distinguished. “*Simple veins*” are composed of pitchblende, carbonate, and gouge with mylonitized rocks, often selvaged by quartz, adularia, albite, and fluorite. These veins occupy structures of second or third order. Length commonly is 150 to 400 m and width 3 to 25 cm, rarely 50 cm. “*Complex veins*” are composed of several generations of pitchblende, carbonate, and younger carbonate-arsenide and quartz-sulfide assemblages, intermixed with breccias and gouge. These veins occupy higher order structures. Length of the veins may exceed 1000 m (max. 2200 m). Width is from 10 to 60 cm.

Mineralization occurs as erratically distributed ore shoots (a few m^2 to rarely $1000 m^2$ in size) separated by barren intervals down to a depth

of about 700 m below surface. Cumulative occupancy of a structure by ore, although highly variable, averages less than 10%.

A vertical mineral zonation is reflected by predominance of arsenides and native Ag in the upper levels (down to 400 m), arsenides and native Bi in the medium to lower levels down to about 700 m below surface. The bulk of uranium occurs in the lower level. Near and within the contact-metamorphosed zone enveloping the granite, at distances of ca. 20 to 120 m from the contact ore structures tend to lose uranium mineralization except for a very few cases where wide veins contain some uranium down to the granite.

Structural ore control and distribution corresponds to that described under class 3.1.2.1.

Resources

Individual vein systems contain from a few tonnes to several hundred tonnes U_3O_8 . Grades range from <0.1% to several percent U_3O_8 . In addition, high grades of Ag, Co, and Ni may occur. Known districts account for a few 100 mt to 10 000 mt U_3O_8 and more (St. Joachimsthal presumably yielded 12 000 mt U_3O_8 , ranging in grade from 0.1 to 1% U_3O_8).

Remarks

For more details see Chapter 5.3.3.

Examples of Vein, Class 3.1.2.2, Perigranitic Polymetallic Deposits/Occurrences

Canada: ? Port Radium, Echo Bay/Great Bear Lake, NWT

ČSFR: Javornik, Bila Voda, Rychlebske Hory (Glatzer Schneeberg)

Germany: Alberode-Niederschlema, Pöhla-Tellerhäuser, Schneeberg, Johanngeorgenstadt, Erzgebirge, Wittichen/Black Forest

Great Britain: Cornwall region

Poland: Kowary-Schmiedeberg/Riesengebirge, Kletno/Snieznik Klodzki (Glatzer Schneeberg)

USA: Black Hawk/New Mexico

Class 3.1.2: Perigranitic

3.1.2.3: In contact-metamorphics (Iberian type)

Type Example: Alto Alentejo, Portugal

Reference: Basham and Matos Dias (1986)

Host Rocks/Structures

Hosts rocks are pelitic-psammitic sediments that exhibit little or no effect of regional metamorphism (schist-greywacke complex of Proterozoic to Lower Paleozoic age on the Iberian Peninsula) but is contact-metamorphosed into hornfels, speckled andalusite-cordierite schist etc. up to approximately 2 km, from the granite intrusion. Granites and vein composition are similar to those in Limousin (see class 3.1.1). Zones of intense fracturing, brecciation and shearing disrupt the metasediments. Faults displace the granite contact. Dikes of microgranite and lamprophyre occur.

Alteration

Cordierite megacrysts may be completely altered to aggregates of sericite and muscovite. Chlorite-rich bands crystallized. Considerable hematitization occurs around mineralized zones.

Ore and Associated Minerals

Principal uranium minerals are hexavalent U species. Rare pitchblende and coffinite associated with quartz, pyrite, and chalcopyrite occur at depth.

Mode of Mineralization/Dimensions

Uranium minerals occur as disseminations mainly in the weathered or oxidized zone from 0 to 40 m deep, within intensely fractured slivers. The minerals impregnate and coat fracture and schistosity surfaces. Slivers extend laterally for tens to hundreds of meters. Mineralized zones composed of slivers with discontinuous mineralization have widths up to 2 km and may extend for a length up to several km along the granite contact (Nisa deposit Portugal: 5 km long, 1 to 1.5 km wide).

Resources

Individual deposits contain some 10 mt to about 2500 mt U_3O_8 (Nisa). Districts have a few 1000 mt to some 10 000 mt U_3O_8 . Average grade is commonly low, about 0.1% U_3O_8 or less.

Remarks

For more details see Chapter 5.3.4.

Examples of Vein, Class 3.1.2.3, Perigranitic Deposits/Occurrences in Contact-metamorphics

Italy: Alm Bos/Adamello Massif
 Poland: Kowary-Schmiedeberg/Sudetes
 Portugal: Beiras district
 Spain: Don Benito/Badajóz, Ciudad Rodrigo district/Salamanca
 USA: Little Man Mine/Wyoming

4.3.2 Subtype 3.2: Not granite-related**Class 3.2.1: In metamorphic rocks**

Type Example: Schwartzwald, Colorado, USA
 Reference: Wallace 1986

Host Rocks/Structure

Host rocks include a variety of mafic metasediments often, but not necessarily, metamorphosed to amphibolite grade facies. Schwartzwald ore is associated with large tensional structures (Illinois and Rogers faults) and their branching horsetail fractures that discordantly transect strata. They contain ore almost exclusively where they cut horizons of garnet-biotite-gneiss (protolith: iron and sulfur-rich pelitic sediment) and quartzite adjacent to hornblende gneiss (mafic volcanite). Regionally, the Schwartzwald deposit is situated within the mobile belt of the Laramide Orogen a few tens of km away from the Colorado Mineral Belt.

Alteration

Several types of alteration may affect the host rocks. These are commonly restricted to a zone of less than 2m into the walls from veins. Schwartzwald veins are selvaged by early carbonatization and sericitization of the mafic wall rock constituents and later hematitization and K-feldspathization (adularia) replacing the earlier alteration products immediately proximal to a vein.

Ore and Associated Minerals

Principal uranium minerals are uraninite, pitchblende, coffinite, and in oxidized zones hexavalent U minerals. Associated minerals can include a variety of sulfides, arsenides, selenides

mostly of Fe, Cu, Pb, Zn, Mo and trace amounts of Ag, Co, Ni, Hg, Sb, and others. Gangue minerals may be carbonates (calcite, dolomite, ankerite, rhodochrosite), quartz, chalcedony, adularia, albite, fluorite, baryte and chlorite. All minerals may be present in one or several generations.

Mode of Mineralization

Uranium and gangue minerals form stringers, veinlets, and veins within larger tensional structures and particularly in horsetail fractures which branch away from the main lodes. Mineralization is relatively continuous although grades are highly variable. Abrupt changes in strike and dip of host structures are associated with differences in width of veins and ore quality. Commonly wider structures correspond with lower grades. Sites of branching veins are often marked by high grade ore accumulation.

Age Constraints

There are no age constraints except the restriction to orogenic belts.

Dimensions/Resources

Individual veins (deposits in brackets) may be a few meters to 150 m (<200 m) long, several mm (50 m) to more than 15 m (150 m) wide and m to 150 m (in excess of 1000 m) deep, containing up to >10 000 mt U₃O₈ at (average) grades ranging from 0.2 to 0.4% U₃O₈ occasionally to several % U₃O₈. Districts may contain several 10 000 mt U₃O₈.

Remarks

Class 3.2.1 of vein deposits resembles very much perigranitic vein deposits (3.1.2.1) except for the noticeable absence of a granitic intrusion, and relative continuity of mineralization. Whether the continuity of mineralization is fortuitous and typical only for the Schwartzwald deposit or whether it is a general rule has not been established.

For more details see Chapter 5.3.5.

Examples of Vein, Class 3.2.1 Not Granite-Related (Monometallic) Deposits/Occurrences in Metamorphic Rocks

Algeria: ? Hoggar region
 ČSFR: Rožná, Olší/Moravia, Okrouhlá Radouň,
 S. Bohemia, Zadní Chodov, Dyleň/ W. Bohemia
 France: Retail/Vendée
 Mozambique: ?Tete district
 Romania: Apuseni Mts., East Carpathians
 Sweden: Arjeplog-Arvidsjaur districts
 USA: Ascension, Mena/Front Range, Colorado,
 Coles Hill/Virginia
 Russia: ?Vikhorevka/Lake Baykal region

Class 3.2.2: In sediments (polymetallic)

Type Example: Shinkolobwe, Shaba, Zaïre
 Reference: Derriks and Vaes 1956

Host Rocks/Structures/Alteration

Host rocks may consist of various sedimentary lithologies. At Shinkolobwe host rocks are dominantly siliceous dolomite and dolomitic and carbonaceous shales, partly affected by Mg-metasomatism with magnesite replacing dolomite. Regionally, Shinkolobwe is located within a fold belt close to the hinge where the fold axis changes direction and the style of folding changes from open to tight overturned folds associated with thrusting. No granites or other intrusives are exposed in the area. At the deposit, host rocks are heavily fractured within a tectonic zone bound by two major faults about 200 m apart at the surface. Due to complex tectonics, flat-lying wedges of impermeable strata formed. They are underlain by more incompetent rocks in which numerous fissures, shears and joints opened, hosting the bulk of the mineralization.

Ore and Associated Minerals

Principal uranium minerals are uraninite (at Shinkolobwe) or pitchblende and alteration products thereof. Associated minerals may include Co-Ni sulfides and selenides, sulfides of Fe, Cu, Mo, Pb, Zn, a.o. and trace amounts of precious metals, phosphates (monazite) etc. Gangue minerals are carbonates (magnesite, dolomite), quartz, chlorite etc.

Mode of Mineralization

Uranium and gangue minerals occur in veins, stockworks, along bedding planes, as breccia

matrix, replacement masses, nodules and as disseminated particles and aggregates in the host rocks. Major faults are barren. Mineralization is highly variable in grade and distribution but in general fairly continuous. At Shinkolobwe and other deposits in the Katanga copper belt of Zaïre and Zambia, uranium veins always occur in beds underlying the cupriferous strata, which locally contain anomalously U tenors, at the base of a thick pile of sediments of shallow marine origin.

Age Constraints

No age constraints appear to be valid except a very likely time correlation with regional tectonism associated with an orogeny (in the case of the Shaba copper district the core zone of the Lufilian Orogeny, reflected by granite intrusions and up to amphibolite grade metamorphism runs about 150 km S of Shinkolobwe).

Dimensions / Resources

Individual veins (deposits in brackets) may be m to 10 m (>200 m) long, mm to 1 m (more than 100 m) wide and m to several 10 m (>450 m) deep. Reserves are up to ca. 25 000 mt U₃O₈ at (average) grades ranging from 0.1 to >1% U₃O₈. Districts may contain up to several 10 000 mt U₃O₈.

Remarks

Shinkolobwe and other vein deposits of class 3.2.2 display a vein to stockwork type ore distribution discordant to strata, resembling in many aspects, notably in its ore and gangue mineral association and structural control granite-related vein deposits of class 3.1.2.2. Major differences include absence of granitic intrusions, a relative continuity of mineralization, and in the case of the Katanga copper belt, anomalously uraniumiferous sediments which may have provided the source for uranium and the associated elements.

For more details see Chapter 5.3.6.

Examples of Vein, Class 3.2.2 Not Granite-Related (Polymetallic) Deposits/Occurrences in Sediments

USA: ? Pitch Mine/Marshall Pass, Colorado
 Zaïre: Kalongwe, Swambo/Shaba

4.4 Type 4: Sandstone (Fig. 4.4)

Definition

Sandstone uranium deposits occur in reduced continental fluvial and less commonly in mixed fluvial-marine (arkosic) sandstones that contain, are interbedded with and bounded by less permeable horizons. Primary uranium phases are generally of tetravalent state uranium and consist dominantly of pitchblende and coffinite.

Associated organic material in Phanerozoic (post-Devonian) deposits (type 4a) is of terrestrial plant origin as distinct to marine, algae (?) derived material in Proterozoic deposits (type 4b).

Based on configuration, spatial relation to the depositional and structural environment and/or elemental associations, sandstone uranium deposits may be divided into three overall subtypes and further into classes that can be gradational into each other:

Subtype 4.1: tabular/peneconcordant ((a) Phanerozoic, (b) Proterozoic)

Class 4.1.1: extrinsic carbon (a)
(Westwater Canyon type)
Type Example: Grants Uranium Region, USA

Class 4.1.2: vanadium-uranium (a, b)
Type Example: a) Uravan Mineral Belt, USA,
(Salt Wash type)
b) Mounana, Gabon
(Franceville type)

Class 4.1.3: basal channel (a)
(Chinle type)
Type Example: Monument Valley, USA

Subtype 4.2: rollfront (or roll-type) (Phanerozoic)

Class 4.2.1: continental basin assoc. with detrital carbon
(Wyoming type)
Type Example: Wyoming Basins, USA

Class 4.2.2: mixed fluvial marine assoc. with extrinsic sulfide (South Texas type)
Type Example: South Texas Coastal Plains, USA

Subtype 4.3: tectonic-lithologic

Type Example: a) Grants Uranium Region, USA
b) Mikouloungou, Gabon

[Description of subtype 4.3 is included in sections 4.1.1 and 4.1.2(b)]

References: (a) Adams and Saucier 1981; Adams and Smith 1981; Boyle 1986; Chenoweth and Malan 1973; Crew 1981; Crawley 1983; Grutt 1972; Galloway 1985; Granger and Finch 1988; Grutt 1972; Harshman and Adams 1981; Rackley 1976; Thamm et al. 1981; IAEA/Finch (ed.) 1985; Turner-Peterson et al. (eds) 1986 (b) Diouly-Osso and Chauvet 1979; Gauthier-Lafaye 1986

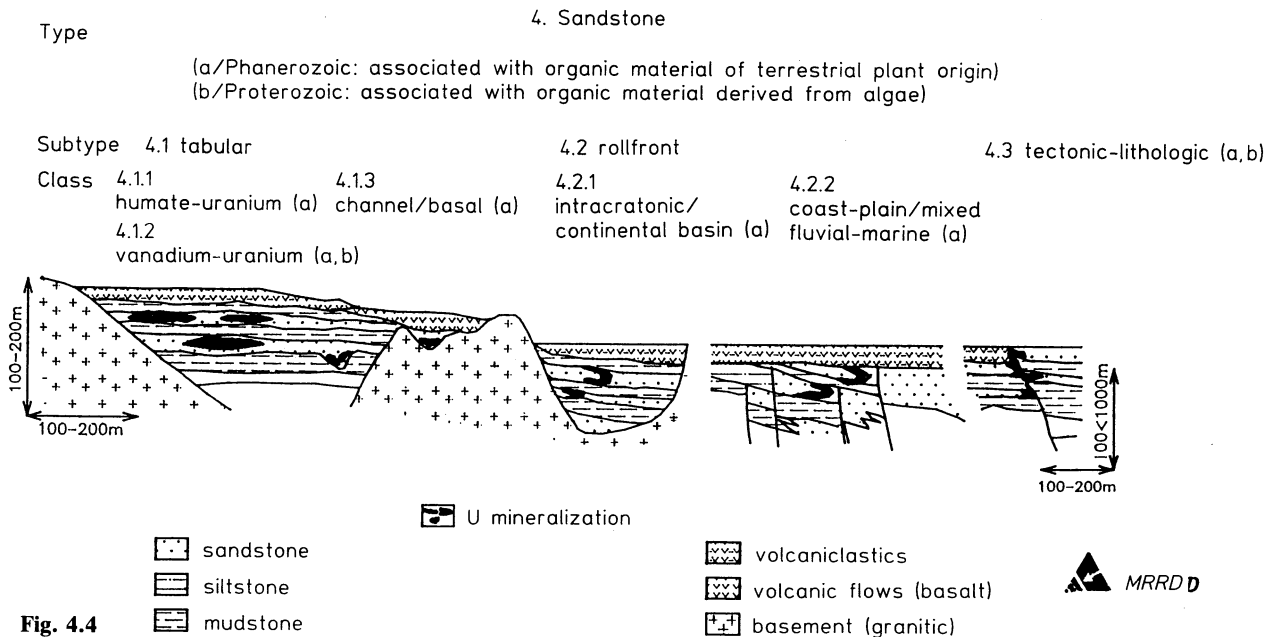


Fig. 4.4

Tabular deposits also referred to as peneconcordant deposits consist of uranium matrix impregnations that form irregularly shaped frequently elongated lenticular masses within selectively reduced sediments. The mineralized zones are, on a large scale, oriented parallel to the depositional trend but, on a small scale, they cross-cut sedimentary features of the host fluvial sandstone.

Further subdivision into classes is based on uranium fixing agents such as amorphous organic material of extrinsic origin (e.g., humate), or detrital plant debris of intrinsic origin, or metallic associations (vanadium) that occur in fluvial systems. Deposits in sandstone channels incised into unconformably underlying sediments or crystalline rocks are referred to as basal channel deposits.

The primary mineralization may be redistributed into secondary uranium “stack” deposits in the host sandstone.

Rollfront deposits consist of arcuate zones of uranium matrix impregnations that crosscut sandstone bedding extending from overlying to underlying less-permeable horizons. The zones are convex down the hydrologic gradient. They display diffuse boundaries with reduced sandstone on the down-gradient side and sharp contacts with oxidized sandstone on the up-gradient side. The normally oxidized up-gradient sandstone can also be in a reduced state if it has been re-reduced through the influx or re-introduction of reductants as found in some deposits of class 4.2.2. The mineralized zones are elongate and sinuous approximately parallel to the strike, and perpendicular to the direction of deposition and groundwater flow.

Further subdivision of rollfront deposits is based on emplacement either in intracratonic basins filled with continental fluvial sediments and containing detrital carbon as a potential reductant, or in mixed fluvial-marine sediments of coastal plains containing pyrite and marcasite as potential reductant that originated from influx of H₂S into the host sands.

Tectonic-lithologic deposits are discordant to strata. They occur along permeable fault zones with linguiform impregnation of the adjacent clastic sediments where uranium may form rather thick ore bodies which are also referred to as stack deposits when derived from redistribution of uranium.

Principal Recognition Criteria

Host Environment

- Immature permeable sandstone, feldspathic or arkosic, more rarely quartzose and cherty sandstone, pebble conglomerates or marginal marine or eolian siltstone and sandstone
- Dominantly medium to coarse grain size, rarely fine or very coarse (pebble)-grained
- Mostly cross-stratified and with lenticular bedding
- Coefficient of permeability 75 to 3501/m²/day (Austin and D’Andrea 1978)
- Abundance of U precipitants/reductants, particularly carbonaceous material (fragments of woody material ± coalified, humic components, amorphous humate), hydrocarbons (petroleum, “dead oil”) and/or sulfides (H₂S, pyrite)
- Tuffaceous material may be present as volcanic debris within host sands, interbedded tuff-rich layers or overlying bentonitic mudstone derived from tuffs
- Often interbedded with impermeable horizons (mudstone)

Mineralization

- Multiple mineralized horizons may exist
- Rollfront deposits are crescent-shaped in cross-section, transgressive to stratification of host sands, in planview they resemble an irregularly laid pipe; roll fronts can occur in multiple superjacent horizons
- Boundaries of mineralized bodies are in some deposits sharp and continuous whereas in other deposits they are highly irregular and diffuse
- Tectonic-lithologic ore bodies of stack type are multi-shaped, sometimes Christmas-tree like, depending on structural distribution and impregnation of permeable horizons adjacent to host structure
- Configuration, size and composition of subtypes seemingly are a function of (a) type and permissivity of aquifer/host sandstone, (b) stratigraphic interbedding of permeable with impermeable beds, (c) kind, mode, and distribution of reductants and/or complexing agents, (d) derivation, hydro-chemistry and flow rate of groundwater system

Age Constraints

- Principal distribution in sediments of middle Paleozoic to Tertiary age, i.e., after development of lush terrestrial vegetation
- Minor in Precambrian sandstones, particularly in those containing carbonaceous material supposedly of algae origin (e.g., Franceville Basin, Gabon)

Metallogenetic Aspects

Generally it is accepted that sandstone uranium deposits are of diagenetic-epigenetic low-temperature origin. Groundwater chemistry and migration are instrumental in uranium leaching from source rocks and its transportation to a chemical interface commonly provided by reducing or complexing agents where uranium is deposited. Essential parameters controlling these processes and localization of uranium mineralization are depositional environment, host rock lithology, permeability, adsorptive/reducing agents, adequate solutions, a uranium source, and apparently an arid to semi-arid climate.

Fluvial, first cycle feldspathic or arkosic sandstones of limited thickness (<10 m) interbedded with layers of fine-clastic sediments deposited in intracratonic basins provide the most favorable host for large and relatively high-grade uranium deposits. A marginal marine environment is also prospective, but to a lesser degree. The presence of uraniferous tuffaceous material either as a constituent of the host sandstone or in the overlying strata may enhance the favorability, due to its potential as a uranium source rock. The feldspar component of the host rock is probably of no direct importance in the mineralizing process, but indicates a granitic source from which the uranium may have originated and an environment of rapid erosion and sedimentation providing the required hydro-physical conditions, particularly permeability for adequate groundwater migration. Impermeable or less permeable strata or other barriers may be instrumental in channeling vertically and laterally uraniferous fluids to favorable sites of uranium deposition, at the same time prohibiting widespread flushing and dilution of fluids.

Uranium is soluble in large quantities only in its hexavalent state. Therefore, uranium-transporting fluids have to be sufficiently oxygen-

ated to keep uranium in solution for transport, and limited to the point that reduction can take place in order to precipitate uranium in ore grade quality and quantity. Complexing agents such as carbonate ions are highly capable of enhancing the solubility and mobility of the uranyl ion in the form of carbonate or other complexes in groundwater that is neutral or alkaline and that may be oxidizing or reducing (Hostetler and Garrels 1962).

For precipitation, the hexavalent uranium in solution must be reduced to the tetravalent state to form pitchblende or coffinite, the principal uranium minerals in most reduced sandstone deposits. Under certain conditions uranium minerals may also crystallize in an oxidizing environment when complexing agents are present, for example vanadium compounds, to fix the uranyl-ion in form of uranyl vanadates which are fairly stable in oxidized rocks. To reduce the hexavalent uranium a reductant is required. Many substances have been invoked as uranyl reductants including \pm coalified vegetal, woody fragments (coalification not higher than subbituminous), structureless organic matter (humate), petroleum, "dead" oil, "sour" natural gas, hydrogen sulfide, and pyrite or other sulfides. Bacterial activity is considered by some authors an important factor in producing a reducing environment.

The formation of either tabular or rollfront type deposits occurred in response to specific processes.

Tabular deposits presumably formed stationary in locally reduced zones within oxidized sandstones. Transport of uranium supposedly occurred by weakly alkaline, mildly reducing to oxidizing groundwater capable of keeping uranium in solution as uranyl-carbonate until it was locally precipitated by concentrated reductants, such as humate, plant remains or H_2S , and for chelation or complexing by which organic matter accreted uranium from the groundwater (Schmidt-Collerus 1979). Granger (1976) proposes that peneconcordant deposits remained stationary and accumulated their uranium from waters flowing mainly outside and not through the ore zones as in rollfront deposits. To permit such a mechanism, the author suggests diffusion of uranium ions in the groundwater to the site of deposition along a concentration gradient. The gradient develops by the extraction of uranium from the groundwater flowing marginal to the deposit.

Unlike tabular deposits, rollfront deposits are of dynamic nature. They form at the down-dip migration boundary of an active but short-lived oxidation interface ahead of a pervasive alteration tongue within originally reduced, pyrite-bearing sandstone. The spatial distribution of the altered tongue and unaltered sandstone suggests an oxidizing uraniferous groundwater of neutral to slightly alkaline nature that moved downdip in a confined aquifer in response to a hydraulic gradient. As the oxygenated solution moved downdip in the permeable horizon it penetrates the reduced facies. Organic material and sulfides, mainly pyrite, were destroyed, and ferric iron was produced until the water lost its potential for oxidation. In zones of abundant reductants, such as detrital carbon (commonly plant debris, class 4.2.1) or extrinsic sulfides (H_2S , pyrite, marcasite, class 4.2.2) a distinct geochemical front developed with an abrupt redox interface. At this site and for a short distance ahead of the ferrous/ferric iron interface, the uranium transported in the oxygenated solution is reduced and deposited as pitchblende.

Since the geochemical alteration system was of dynamic nature, the influx of oxidizing groundwater continued. The alteration front "rolled" downflow and spread laterally towards the boundaries of the transmissive host bed. Previously crystallized pitchblende became decomposed and the uranium redistributed across the front for renewed deposition as long as the system was operative. The crescent shape of a rollfront ore body (in cross-section) is considered evidence for the dynamic movement of the front which migrated more rapidly in the more permeable units mostly in the middle part of the sandstone layer.

Most of the rollfront deposits are considered the result of a single major cycle of uplift, erosion, sedimentation, and mineralization by fluids moving in response to the same hydraulic gradients which have been responsible for the sedimentation of the host sandstone. Another variety of rollfront deposits, although very similar to the type described above, are related only to the physical and chemical nature of the host sediments but not to the hydrologic system responsible for the host rock deposition. Instead they originated long after deposition of the host rocks by a second cycle of uplift, erosion, and deposition (Harshman and Adams 1981).

Tectonic-lithologic stack type deposits are in part considered the product of redistribution of primary uranium into permissive hosts such as structures by younger processes as typically found in the Grants Uranium Region, but likewise they may have originated by the introduction of primary uranium as interpreted for some deposits in Gabon (Mikoulougou).

The source of uranium and associated metals in sandstone deposits is considered to be either of uraniferous granitic provenance, or clastic granitic material or felsic volcanoclastics in the host sandstone, or felsic volcanoclastics (e.g., rhyolitic tuff) in overlying and/or underlying beds.

Remarks

Sandstone uranium deposits are commonly of low to medium grade (0.05–0.4% U_3O_8) and of small to large size, up to 50 000 mt U_3O_8 rarely more, but districts may have substantial resources of several 100 000 mt U_3O_8 .

Examples of Sandstone, Subtype 4.1, Tabular Deposits/Occurrences (Not Differentiated)

(C = Cenozoic, M = Mesozoic, P = Paleozoic, PC = Precambrian)

Argentina: Tonco-Amblayo (M)/Jujuy-Bolivian Basin, Los Colorados (M)/Paganzo Basin, Sierra Pintada (P)/San Rafael Basin, Malargue (M)/Neuquén Basin, Pichiñan/Chubut (M)

Australia: Angela (P)/Amadeus Basin, Malbooma (P)/Drummond Basin, Mulga Rock (P)/Officer Basin, Westmoreland (PC)/Queensland, Manyin-gee W.A.

Brazil: Figueira (P)/Paraná Basin

Bulgaria: Orranovo-Simitli Basin (C), Eleshnitsa district (C), W. Balkan Mts. (P)

China: Mengqiguer, Daladi, Kashi (M)/Zhungel-Tianshan U prov., Jianchang, Quinlong, Langshan areas (M)/Yinshan-Liaohe U prov., Wudang-Huaiyong Massif (M)/Qilian-Qinling U prov., South Lancang River, Gaoligong (C)/W. Yunnan U prov., Tunling (M)/Jingan Basin

ČSFR: Hamr-Stráz (M)/North Bohemian Basin

Germany: Königstein (M)/Elbsandsteingeb., Müllenbach (P)/Black Forest

Gabon: Oklo (PC)/Franceville Basin

France: Coutras (C)/Aquitaine Basin, Lombre (P)/Cerilly Basin
 Hungary: Pecs (P)/Mecsek Mountains
 Madagascar: Antsirabe Basin (C)
 Niger: Akouta, Arlit, Ebala, Madaouela, (P), Azelik, Imouraren, Takardait, (M)/Agades Basin
 Pakistan: Dera Ghazi Khan area (C)
 Romania: Apuseni Mts (P), Banat (P)
 South Africa: Beaufort West (P)/Karoo Basin
 Spain: Mazarete (M)
 USA: Colorado Plateau (P + M), Sherwood (C)/Washington, Tallahassee Creek (C)/Colorado, Anderson (C)/Date Creek Basin, Arizona
 Slovenia: Zirovski vrh (P)
 Russia: Stavropolsky, Pyatigorsk, Kislovodsky, Lermontovsky (P)/Caucasus

Examples of Sandstone, Subtype 4.2 Rollfront Deposits/Occurrences (Not Differentiated)

Australia: Beverley (C)/Lake Frome Basin, Manyingee (M)/Carnarvon Basin
 Bulgaria: Tracien Basin (C)
 Mexico: La Sierrita (C)/Burgos Basin
 Niger: Akouta (P)/Agades Basin
 USA: Wyoming Basins (C), Black Hills (C + M)/South Dakota, Crow Butte (M)/Nebraska, Weld County (M)/Colorado, Texas Coastal Plain (C)
 Uzbekistan: Uchkuduk (M), Sugrally (M), Lyavlyakan (C), Beshkak (C), Bukinay (M), Kanimekh (M)/Navoi region, Kyzylkumsky

Examples of Sandstone, Subtype 4.3 Tectonic-Lithologic Deposits/Occurrences

Australia: Red Tree (PC)/Westmoreland
 France: Mas Lavayre (P)/Lodève Basin
 Gabon: Mikouloungou, Mounana (PC)/Franceville Basin
 USA: Ambrosia Lake district (M)/Grants region

4.4.1 Subtype 4.1: Tabular/peneconcordant

Class 4.1.1: Extrinsic carbon (Westwater Canyon type) (Phanerozoic)

Type Example: Grants Uranium Region, San Juan Basin, USA

References: Adams and Saucier 1981; Granger and Finch 1988; Turner-Peterson et al. (eds) 1986

The subsequent summary also addresses class 4.3.1, tectonic-lithologic stack deposits, as found in the Grants Uranium Region spatially associated with class 4.1.1 deposits.

Host Rocks/Structures

Type example is uranium mineralization in the Westwater Canyon Member of the Late Jurassic Morrison Formation, Grants Uranium Region, New Mexico, USA.

Host rock is fine- to coarse-grained, poorly sorted, cross-bedded mostly light yellow-brown to gray arkosic sandstone, containing small pebbles and cobbles and thin seams or beds of gray mudstone and siltstone. Sandstone consists of 50 to 90% quartz, 5 to 35% feldspar, up to 30% chert and less than 0.5% heavy minerals. White clusters of kaolinite are common. Other matrix materials are calcite, iron oxides, and clay. Amorphous carbonaceous material in the form of humate fills interstices and coats sand grains. Permeability ranges from low to high. Thickness of the host unit ranges from one to several tens of meters. The Westwater Canyon Member is overlain by a greenish-gray bentonitic (tuffaceous) silt-mudstone of the Brushy Basin Member. Sand to mud/shale ratios are 1:1 to 2:1 for the Morrison Formation within the mineral belt. Depositional environment of the host sequences is an extensive coalescing alluvial fan system developed by aggrading braided streams within a continental basin (San Juan Basin). Source area of the host rocks is granitic terrane and volcanic air-fall ash and tuffaceous material.

Regional tilting associated with major N-S faulting developed during the Laramide Orogeny and caused redistribution of primary uranium mineralization into roll-type and, near structures, into class 4.3.1 "stack" deposits.

Alteration

Both oxidation and either a single or multiple episodes of reduction have altered the host rocks. Hematitization and weak limonitization characterize oxidized facies. Reduced facies display destruction of detrital feldspar, volcanic ash, magnetite and ilmenite associated with sulfidation (mainly pyrite), kaolinitization, chloritization, albitization, montmorillonitization, and

carbon (humate) formation. Calcitization and minor silicification cemented the units. The carbon with which the uranium is associated was introduced into the sandstone from adjacent silt-mudstones during compaction.

Ore and Associated Minerals

Principal ore minerals are pitchblende, coffinite and uraniferous humate present in reduced ore. Locally hexavalent U minerals occur in oxidized ore. Associated minerals of As, Ba, Fe, Mo, Sb, V, and others are commonly present in trace amounts. Pyrite is more abundant.

Mode of Mineralization

Class 4.1.1 mineralization is characterized by the association of uranium with humate in isolated and stacked peneconcordant lenses. Uranium minerals occur as disseminations coating sand grains, filling small interstices and partly replacing feldspar in the host sandstone. Primary mineralization occurs in multiple horizons commonly concomitant with humate. Mineralized zones are lenticular or tabular, peneconcordant elongated parallel with the paleochannel systems which are termed blanked or trend ore. Boundaries between mineralization and host rocks are irregularly shaped. Redistributed mineralization is within structures and also displays features of rollfront character developed proximal to fault and fracture zones that cut primary peneconcordant bodies. Redistributed uranium forms much thicker ore bodies than those of primary tabular mineralization and is therefore referred to as a stack deposit.

Dimensions/Resources (Grants Uranium Region)

Individual tabular deposits ("stack" deposits in brackets) may be several tens of meters to 2000 m (<100 m) long, several meters to several 100 m (a few m to 40 m) wide, a few centimeters to 5 m (few m to 50 m) and in excess of 1500 m deep, containing several tens and up to 50 000 mt U_3O_8 at (average) grades ranging from 0.1 to 0.4% U_3O_8 occasionally to >1% U_3O_8 . Districts may contain up to 300 000 mt U_3O_8 .

Remarks

The Grants Uranium Region is 175 km long and up to 80 km wide and includes five mining districts

and other prospective districts. It constitutes the largest single known sandstone uranium region in the western world.

For more details see Chapter 5.4.1.

Examples of Sandstone, Class 4.1.1 Tabular, Extrinsic Carbon Deposits/Occurrences

France: Lodève Basin (P) ?, Aquitaine Basin (C) ?

South Africa: Beaufort West (P)/Karoo Basin

Class 4.1.2: (a) Vanadium-uranium (Salt Wash type) (Phanerozoic)

Type Example: Uravan Mineral Belt, Colorado Plateau, USA

Reference: Thamm et al. 1981

Host Rocks/Structures

Type example is V-U mineralization in the Salt Wash Member of the Late Jurassic Morrison Formation as present in the Uravan Mineral Belt, Utah-Colorado, USA.

Host rock is a fluvial fine- to medium- and coarse-grained feldspathic to quartzose sandstone. This unit ranges from 50 to 120 m thick, is red, brown or gray in color, and contains 5 to 25% tuffaceous material and abundant organic debris in the form of logs and fragments of vegetal trash. These materials accumulated particularly at sites where paleochannels change direction, in mud bars or changes in stream load carrying ability. Sandstone layers are interbedded with reddish and gray siltstones and bentonitic mudstones. The Salt Wash Member is part of a coalescing alluvial fan formed by a system of aggrading braided streams. The Uravan Mineral Belt occupies a transversal zone where grain size of the sandstone is transitional from medium to fine. Source area for Salt Wash sediments was the granitic Mogollon Highland.

Positive areas formed by salt diapirs and associated anticlines within the basement controlled river orientation and facies pinchouts during Salt Wash time.

Alteration

Reduction alteration is recognized chiefly by color changes and is most obvious in mudstones

turning from purplish or reddish to gray-green at contacts with mineralized sandstones which are stained light yellow-brown. Common authigenic transformations include pyritization, calcitization, and argillitization. Detrital ilmenite and magnetite are corroded.

Ore and Associated Minerals

Principal ore minerals in reduced zones are pitchblende, coffinite, and vanadium minerals. Oxidized zones are dominated by uranyl vanadates, commonly carnotite and tyuyamunite. Associated minerals are pyrite and marcasite. Mo, Cu and Se minerals occur in trace amounts. Vanadium-uranium ratio is 5:1 to 10:1 in the Uravan Mineral Belt and in other Salt Wash districts 1:1 to 15:1.

Mode of Mineralization

Class 4.1.2 mineralization is characterized by vanadium-uranium associated with plant debris. Mineralization occurs as disseminations filling pore spaces, coating sand grains and replacing interstitial clay, organic substances, and cementing material. U-V minerals have accumulated in commonly small pods which locally are highly mineralized tree trunks. The pods may display shapes ranging from tabular, concordant to bedding to roll-type. Deposits consist of clusters of pod-like bodies aligned parallel to the paleochannel, where they may occur in several superjacent sand horizons. Distribution of deposits is rather erratic.

Dimensions/Resources (Uravan Mineral Belt)

Individual deposits (ore trends in brackets) may be up to 200 m (up to a few km) long, <1 m to 100 m (several 100 to 1000 m) wide, several centimeters to 10 m thick, containing <1 to 2500 mt U_3O_8 at (average) grades ranging from 0.1 to 0.5% U_3O_8 occasionally to >1% U_3O_8 . Districts may contain up to 50 000 mt U_3O_8 . Vanadium grades may range from <0.5 to >3% V_2O_5 .

Remarks

The Uravan Mineral Belt is the largest known V-U district in the USA. Most other districts with similar mineralization associated with Salt Wash

sandstone had resources of a few hundred to several thousand tonnes uranium.

For more details see Chapter 5.4.2.

Examples of Sandstone, Class 4.1.2(a), Tabular, Vanadium-Uranium Deposits/Occurrences

Argentina: Rodolfo (C)/Cosqin district

Australia: Bigrlyi (P)/Ngalia Basin

USA: La Sal-La Sal Creek (M), Lukachukai-Carrizo (M), Henry Mountains (M)/Colorado Plateau

Class 4.1.2: (b) Vanadium-uranium (Franceville type) (Proterozoic)

Type Examples: Franceville Basin, Gabon

4.1.2.1 tabular: Oklo, Gabon

4.1.2.2 tectonic-lithologic: Mounana and Mikouloungou, Gabon

References: Diouly-Osso and Chauvet 1979; Gauthier-Lafaye et al. 1980

Both type examples occur in the same stratigraphic horizon and show a number of similar features except for the structural component of mineralization and respective configuration of ore bodies. The subsequent synopsis addresses both subtypes together.

Host Rocks/Alteration/Structures

Continental sandstone and arkose containing redistributed marine carbonaceous matter. The uranium hosting unit is overlain by carbonaceous shales and rests on early Proterozoic granite and gneiss. Folding and faulting distorted the sediments. No apparent alteration except some silicification.

Ore and Associated Minerals

Pitchblende and coffinite in reduced zones, and uranyl vanadates and phosphates in oxidized zones. Associated minerals include in reduced mineralization karelianite, montroseite, roscoelite, and minor amounts of pyrite, marcasite, melnicovite, galena, sphalerite, chalcocopyrite, baryte, and calcite as fissure fillings.

Mode of Mineralization

Uranium is in tabular deposits (Oklo) concentrated predominantly in fluvial sands in the form

of microcrystalline pitchblende within the organic matrix and occurs preferentially on the flanks or rims of paleochannels or where an intermediate thickness of sandstone is combined with high concentrations of organics. Mineralization of the tectonic-lithologic subtype occurs in the same organic-rich sedimentological environment but displays a strong affinity to cataclastic zones adjacent to uplifted crystalline basement (Mounana) or to an overthrust of carbonaceous shales (Mikouloungou).

Age Constraints

A certain age constraint is imposed by the required development of organic creatures (algae) in a continental environment.

Dimensions/Resources

Tabular deposits are up to 900 m long, 600 m wide, and several meters thick and contain as much as 13 000 mt U_3O_8 at a grade of ca. 0.4% U_3O_8 . Tectonic-lithologic deposits range up to 100 m long, 40 m wide and 120 m deep, containing up to 6000 mt U_3O_8 at a grade of 0.2 to 0.6% U_3O_8 . The Franceville district, Gabon, accounts for approximately 25 000 mt U_3O_8 .

Remarks

Although uranium occurrences are not uncommon in Proterozoic sandstone displaying the above-listed features, the Franceville Basin is the only one known to contain minable U deposits.

For more details see Chapter 5.4.8.

Examples of Sandstone, Class 4.1.2(b), Proterozoic Deposits/Occurrences

Australia: Westmoreland/Queensland, Pandanus Creek/Northern Territory

Class 4.1.3: Basal-channel (Chinle type)

Type Example: Monument Valley, Colorado Plateau, USA

Reference: Chenoweth and Malan 1973

Host Rocks/Structures

Type example is uranium mineralization in the Shinarump Member of the Late Triassic Chinle

Formation, as exposed in the Monument Valley, Utah, USA. Host rock is a fluvial medium- to coarse-grained conglomeratic, crossbedded, poorly sorted, lenticular arkosic sandstone. This unit ranges from 3 to 75 m thick, is gray-yellowish and red to brown in color and contains interbedded greenish-gray mudstone and siltstone. Carbonaceous material, logs, and fragments of vegetal trash are locally abundant, especially at bends, meanders of the paleochannels, in mud bars or where changes in stream load carrying ability occurred. The sediments deposited by degrading anastomosing streams incising distinct, relatively narrow channels into flood plains consisting of red siltstone of the Moenkopi Formation in the Monument Valley.

In other regions, deposits may occur in extensive blanket sands formed in braided fluvial systems that either unconformably overlie or are eroded into underlying sedimentary or crystalline rocks. Local areas of moderate relief controlled river flow and pinchouts during deposition of the Shinarump Member.

Alteration

Reduction reflected by bleaching of the originally red and brown sandstone to light gray, cream to yellowish and greenish colors is the most obvious alteration. Calcitization caused cementing of sandstone (up to 15% $CaCO_3$).

Ore and Associated Minerals

Principal ore minerals in reduced zones are pitchblende, coffinite and locally vanadium minerals (montroseite, corvusite). Oxidized zones are dominated by hexavalent U minerals and uranyl vanadates. Associated minerals can include sulfides of Cu, Fe, Mo, Pb, Zn, and minerals containing Ag, Cd, Cr, Co, Ni, Se, Sr. In several districts V_2O_5 contents exceed U_3O_8 contents (V:U ratio 1:2 to 7:1).

Mode of Mineralization

Class 4.1.3 mineralization is characterized by uranium associated with plant debris deposited in distinct channels preferentially in their basal parts or scours cut into underlying formations. This situation is in principle also valid for mineralization in all other members of the Chinle Formation. Uranium minerals impregnate sandstone

voids, coat sand grains, replace quartz grains, clay particles and particularly fossil plant debris, and fill vertical fissures beneath the scour base. Most deposits are of small size. They consist of closely spaced lenticular pods which are generally concordant with the bedding. Localization of deposits within channels is controlled by the abundance of carbonaceous trash which otherwise accumulated at inhomogeneities of paleochannels.

Dimensions/Resources

Individual deposits (ore trends in brackets) may be a few meters to 300 m (a few kilometers) long, <1 m to more than 100 m (several 100 m) wide and <0.2 to 3 m (<15 m) thick, containing 1 to several 100 mt U_3O_8 at (average) grades ranging from 0.1 to 0.35% U_3O_8 occasionally to 0.5% U_3O_8 . Districts may contain up to 5000 mt U_3O_8 .

Remarks

Class 4.1.3 deposits resemble those of class 4.1.2 except that the vanadium content is commonly lower and that the deposits are restricted to distinctly developed paleochannels and generally to only one horizon.

For more details see Chapter 5.4.3.

In some countries, e.g. Okanagan region (Blizzard deposit), British Columbia, Canada, and Central Honshu (Tono, Ninyo-Toge), Japan, U mineralization occurs in sand filled channels incised into a basement which includes uraniferous granites. U is thought to have been leached from the granites and redeposited in the channel sands. (For details see Boyle 1982b, 1985, 1986, Katayama et al. 1974, Katayama and Kamiyama 1977)

Examples of Sandstone, Class 4.1.3 Tabular, Basal Channel Deposits/Occurrences

Australia: ? Mulga Rock (P)/Officer Basin, Yarramba (C)/Lake Frome Basin, Manyingee (C)/Carnarvon Basin

Canada: Blizzard, Tyee (C)/Okanagan Highlands

France: St. Pierre du Cantal (C)/Massif Central

Japan: Ninyo-Toge (C), Tono (C)

USA: White Canyon, Lisbon Valley (M)/Colorado Plateau

4.4.2 Subtype 4.2: Rollfront

Class 4.2.1: Continental basin, associated with detrital carbon (Wyoming type)

Type Example: Wyoming Basins, USA

References: Crew 1981; Harshman and Adams 1981

Host Rocks/Structures

Host rocks are Upper Cretaceous and Tertiary poorly consolidated medium- to coarse-grained, poorly sorted arkoses to feldspathic sandstones that range from a fraction of 1 m to 100 m thick (av. less than 30 m). Thin discontinuous beds of mudstone, some pebbles of crystalline rocks or mudstone, and tuffaceous debris may be interstratified. Pyrite and carbonaceous matter in the form of woody remains and masses of humic components are abundant. In some basins natural gas and methane are present. The host sands are regionally transmissive, providing conduits for groundwater migration downdip. Mineralized sands are part of a stratigraphic sequence of alternating sandstone, siltstone and bentonitic mudstone deposited predominantly by braided streams in wedge-shaped coalescing alluvial fans with overbank flood plains. Sand/shale ratios range from 1:1 to 4:1 in the host formations. Provenance of the host sediments are granitic highlands surrounding the basins, and reworked pre-existing sediments. Volcanic air-fall ash and tuff contributed to the sedimentary pile and occurs either as constituent of the mineralized sands, interbedded tuffaceous rich layers or in superjacent bentonitic mudstone.

The attitude of the mineralized beds is commonly very shallow, usually dipping less than 5°. Steeper dips up to 25° exist locally. Minor faults dissect the mineralized horizons. Tilting of some basins subsequent to ore formation (Shirley Basin and Gas Hills) caused a reversal in the groundwater flow resulting in incipient destruction of mineralized zones. Regional controls for the mineralized paleodrainage system included regional tectonic movements which were instrumental in intracratonic downfaulting of basins of restricted dimensions in the foreland of fold belts. Graben structures have controlled paleodrainage systems. Intraformational unconformities appear to be influential on groundwater migration.

Alteration

Alteration effects vary to some degree from basin to basin depending on mineral constituents in host sands. The most conspicuous is hematitization and limonitization associated with decomposition of pyrite in some basins. In other basins pyrite corrosion, argillitization of feldspars and montmorillonitization of tuffaceous components may be more dominant. Normally, gray, tan, or pink sandstones are bleached by mineral forming solutions to cream or light gray hues. Formation of Fe-rich montmorillonite imparts greenish-yellowish colors to the rock.

Ore and Associated Minerals

Principal ore minerals are pitchblende and coffinite with associated pyrite, marcasite, hematite, ferroselite, native selenium and calcite. Minerals of Cu, As, P, and others may be present.

Mode of Mineralization

Uranium mineralization follows the redox front separating nonoxidized from oxidized sandstone. The mineralization transects the stratification of the host beds and is thus discordant with the strata. In cross-section, the form of a deposit resembles a crescent. In plan view, a deposit appears like a sinuous, irregularly laid pipe following the geochemical front of invading oxidation. The uranium minerals impregnate interstices of the sandstone and coat sand grains. Pitchblende and coffinite are concentrated in the front part of the redox zone, ferroselite has formed on the concave side, whereas native selenium, jordisite, and calcite typically occur on the convex side of the rollfront.

Dimensions/Resources

In the apex segment of the rollfront the thickness or height of mineralization ranges from a few tens of cm to 10 m and rarely 15 m, decreasing in the tails to zero. The width normal to strike (parallel to cross-section) varies between a few centimeters and several 100's m. The length along the strike may extend up to several kilometers.

Resources range from a few tonnes to several 1000's of mt U_3O_8 in individual deposits at grades averaging between 0.05 and 0.25% U_3O_8 , rarely

up to 0.5% U_3O_8 or more. Districts contain several 10 000 mt U_3O_8 (65 000 mt U_3O_8 in Gas Hills, Windriver Basin).

Remarks

For more details see Chapter 5.4.4.

Examples of Sandstone, Class 4.2.1 Rollfront, Continental Basin Associated with Detrital Carbon Deposits/Occurrences

Australia: Honeymoon, Beverley (C)/Lake Frome Basin, Manyingee (M)/Carnarvon Basin
USA: Gas Hills (C), Powder River Basin (C), Shirley basin (C), Red Desert (C)/Wyoming, Black Hills (M)/South Dakota, Weld County (M)/Denver-Julesburg Basin

Class 4.2.2: Mixed fluvial-marine, associated with extrinsic sulfide (South Texas type)

Type Example: South Texas Coastal Plain, USA
a) Fluvial-marine: Panna-Maria; b) Fluvial: Benavides

References: Adams and Smith 1981; Galloway 1985

Host Rocks/Structures

Host rocks consist of a variety of fluvial to marginal marine, poorly consolidated sandstones that range from 5 to 20 m thick. These units are interbedded with or overlain by volcanic ash or tuffaceous beds of several formations. Host rocks include

a) *fluvial-marine* fine-grained carbonaceous, tuffaceous, quartzose sandstone and greywacke interbedded with blackish shale and lignite deposited as lagoonal, deltaic and barrier bar sediments under shallow water, nearshore marine or brackish water conditions;

b) *fluvial* fine- to coarse-grained sands interbedded with bentonitic mudstone of an aggrading stream system and fine-grained feldspathic sands containing only minor vegetal debris, deposited in a fluvial-alluvial fan, stream and interchannel floodplain environment.

The sandbeds are locally along faults, invaded by hydrocarbons, methane and H_2S . Distribution of mineral trends is controlled by broad scale sedimentary features such as megachannel systems.

Faulting is extensive in the South Texas Coastal Plain. A series of growth faults trending parallel to the coast line permitted influx of hydrocarbons, H₂S and methane into the host sands. Likewise active salt domes, while creating favorable environments for petroleum reservoirs, also permitted migration of gases.

On a regional tectonic scale, all known uranium occurrences are confined to the Rio Grande Embayment.

Alteration

Several stages of reduction, oxidation, and re-reduction affected the host rocks, in part similar to the alterations in the Wyoming Basins (class 4.2.1). Processes include pyritization, marcasitization, hematitization, corrosion, and argillitization of feldspars, silicification, calcification, destruction of heavy minerals and montmorillonitization of pyroclastics. H₂S introduced along faults before ore formation reduced the host sands and prepared the hosts for rollfront development.

Ore and Associated Minerals

Principal ore minerals are pitchblende and coffinite commonly present as poorly crystalline, minute particles. Associated elements include Mo, Se, V, and P. In oxidized zones a variety of hexavalent U minerals have formed.

Mode of Mineralization

Uranium has accumulated in both peneconcordant blanket type, and rollfront deposits along paleochannels. Roll-type deposits greatly resemble those in the Wyoming Basins.

Dimensions/Resources

Rollfront deposits vary from 0.5 to 7.5 m in thickness, 10 to 100 m in width and are up to 10 km long. Individual deposits contain several 100 to 5000 mt U₃O₈, rarely up to 10 000 mt, at grades between 0.05 and 0.2% U₃O₈. Total resources of the South Texas Coastal Plain district are estimated at up to 80 000 mt U₃O₈ at an average grade of about 0.1 to 0.2% U₃O₈.

Remarks

For more details see Chapter 5.4.5.

Examples of Sandstone, Class 4.2.2 Rollfront, Mixed Fluvial-marine Associated with Extrinsic Sulfide Deposits/Occurrences

Karnes, Live Oak, Duval and Webb Counties districts (C)/Texas Coastal Plains, (?) Crow Butte (M)/Great Plains, Nebraska

4.5 Type 5: Collapse Breccia Pipe

(Fig. 4.5)

Definition

Collapse Breccia Pipe deposits occur in more or less circular (10–300 m in diameter) and vertical (up to 1000 m deep) collapse structures filled with down-dropped coarse fragments and fine matrix of the penetrated sediments. Uranium mineralization is predominantly confined to particular intervals of permeable (\pm sandy) matrix material and to arcuate bounding fractures (annular ring). Principal uranium phase is pitchblende, which is commonly accompanied by a variety of ore (Cu, Ag, etc.) and gangue minerals.

Type Example: Orphan Lode and Hack Canyon, Arizona Strip area, USA

References: GSA/Wenrich and Billingsley (eds.) 1986; Wenrich and Sutphin 1989

Principal Recognition Criteria

Host Environment

- Mineralized structures are roughly circular and vertical, extending from karst caverns in a basal limestone upward through flat-lying beds of alternating shales, siltstones, sandstones, and impure limestones occasionally as high as into uraniumiferous sandstones
- Pipes are filled with highly brecciated material composed of fragments and matrix material of the various penetrated lithologies
- Uranium mineralized pipes appear to be restricted to an area covered or formerly covered by sandstones that locally contain uranium deposits (Chinle Formation)
- Pipes are bounded by a set of concentric, circular fractures termed annular ring

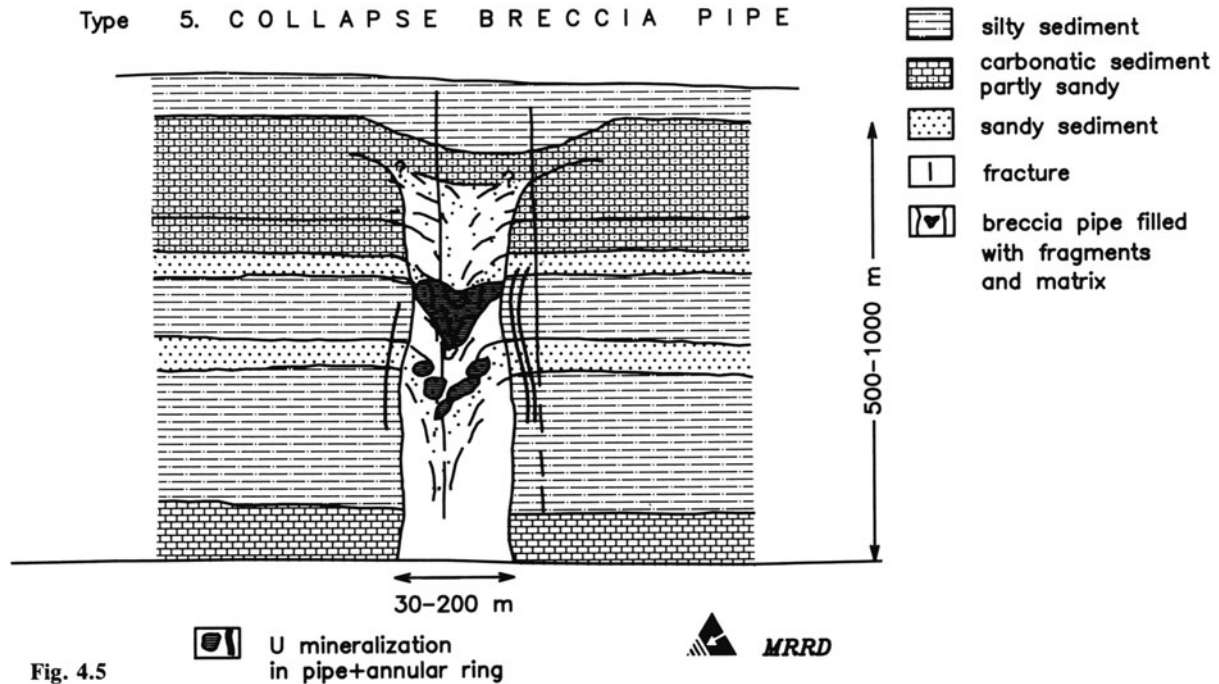


Fig. 4.5

Alteration

- Bleaching of red sediments, carbonatization, silicification, and some sulfidization of pipe infill and immediately adjacent wall rocks
- Alteration is commonly of weak intensity and little extension from pipe into wall rocks

Mineralization

- Principal U phases are pitchblende and coffinite and alteration products thereof
- Associated minerals include sulfides, arsenides, and locally oxides, carbonates and sulfates of Fe, Cu, Ni, Co, Mo, Pb, Zn, As and trace amounts of Ag, Au, Hg, Sb and V
- Gangue minerals include calcite, dolomite, siderite, baryte, collophane, chalcedony, quartz, gypsum, and anhydrite
- Uranium minerals occur (a) as veinlets and stringers in fractures within and surrounding the pipe, (b) as stratiform disseminations in porous sandstone blocks and irregular impregnations of the matrix within the pipe interior
- U mineralization is particularly associated with sand dominated pipe segments
- Sulfides are disseminated through most of the pipe
- Pyrite is enriched up to 15% in mineralized zones and often forms together with marcasite

a sulfide cap (3-15 m thick, up to 80% sulfide) above the uppermost U mineralization

Age Constraints

No principal time constraint except that the type of sedimentation, hydraulic groundwater systems (karst development) and provision and transport of sufficient uranium require a coincidence of certain climatic conditions that prevail only during restricted periods in earth history.

Metallogenetic Aspects

The metallogenesis of uranium mineralization in collapse breccia pipes of the Arizona Strip type is still enigmatic. Uranium is thought to have entered a pipe either through sandstone aquifers interbedded with the sedimentary sequence or through structures extending upwards into overlying uraniumiferous sandstone horizons or perhaps through both. The pipe structure formed by stoping from a karst cavern upwards through the flat-lying sediments possibly along joint or fracture systems. Sulfur, organic material, and other elements may have derived from surrounding sediments or may have been introduced from basal lithologies by upward migration.

Dimensions/Resources

Pipe diameters range from 10 m to more than 300 m, averaging less than 100 m. Within the pipe, mineralization is restricted to variably wide sandy sections, and fissures. Vertical extension of mineralized intervals (commonly one rarely two) ranges from few meters to more than 100 m. Resources of individual pipes are few tonnes to about 2500 mt U₃O₈ at grades between 0.3 and 1% U₃O₈. Known reserves of the Arizona Strip area are about 15 000 mt U₃O₈. Au, Ag, and/or Cu have been recovered from some pipes.

Remarks

Although of small size, collapse breccia pipe deposits represent low cost uranium resources due to their high grades.

For more details see Chapter 5.5.

Examples of Type 5: Collapse Breccia Pipe Deposits/Occurrences

USA: Canyon, Easy 1, Kanab North, Mohawk, Pigeon, Pine Nut/Arizona Strip area

4.6 Type 6: Surficial (Fig. 4.6)

Definition

Surficial uranium mineralization may be defined as young near-surface uranium concentrations either stratabound in predominantly unconsolidated surficial formations/sediments proximal or superjacent to uraniferous source rocks or structure-bound within source rocks. Uranium occurs in mineral form almost exclusively as uranyl species or otherwise adsorbed on host constituents. Thorium is absent.

Based on host environment, four principal subtypes and some classes are recognized:

Subtype 6.1: duricrusted sediments

Class 6.1.1: fluvial/valley-fill
Type Example: Yeelirrie, Australia

Class 6.1.2: lacustrine/playa
Type Example: Lake Maitland, Australia

Subtype 6.2: peat-bog

Type Example: Stevens Co., Washington state, USA

Subtype 6.3: karst-cavern

Type Example: Pryor Mts, USA

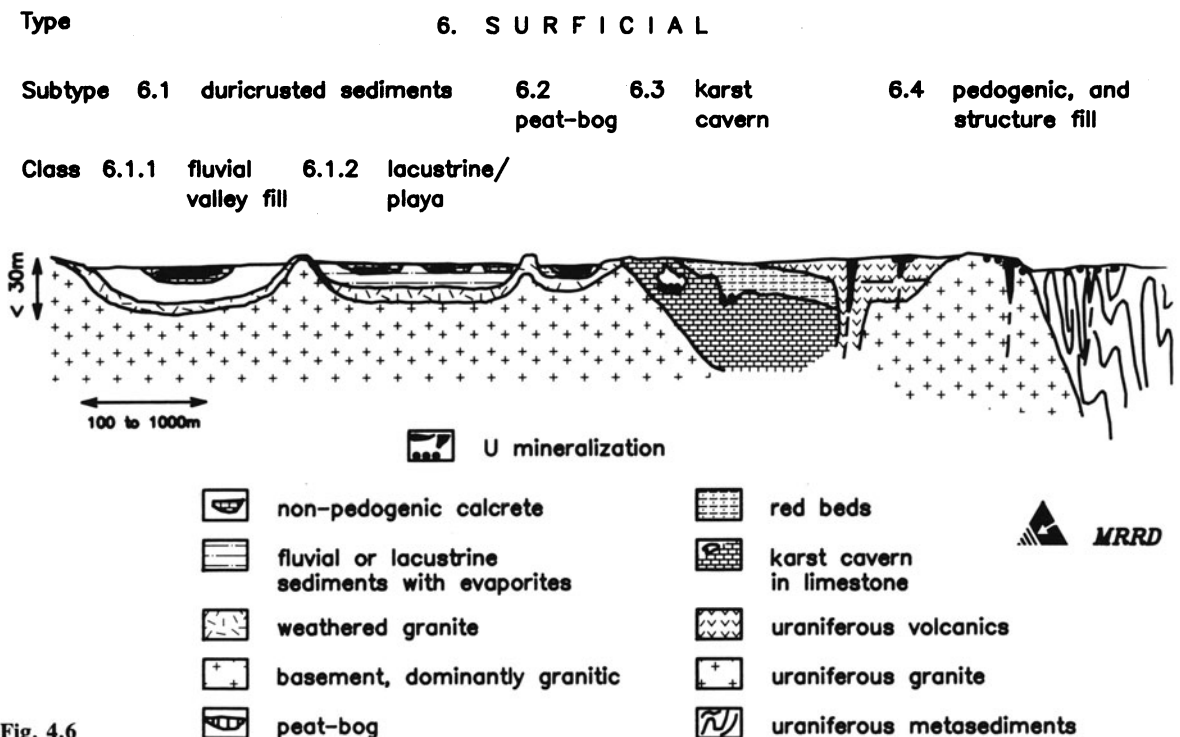


Fig. 4.6

Subtype 6.4: surficial pedogenic and structure fill

Type Example: Daybreak, USA; Cotaje, Bolivia

References: Bell 1963; Butt et al. 1984; Cameron 1984; Cavaney 1984; Carlisle 1983; Hambleton-Jones 1984; IAEA/Toens (ed) 1984; Johnson et al. 1987; Mann and Deutscher 1978; Pardo-Leyton 1985; U.S.-AEC 1959

The four subtypes are characterized by

1. *Duricrusted shallow sediments* in arid to semi-arid climates consisting of fluvial, alluvial and eolian channel fills and associated playamarginal deltas, evaporative lacustrine basins, or alkaline and saline playas, cemented or replaced along the groundwater table by carbonates, silica and sulfates in form of nonpedogenic calcrete, dolocrete, silcrete, gypcrete. Organic matter is absent or occurs in insignificant amounts (subtype 6.1).
2. Highly *vegetal organic and clay-rich* shallow depressions in humid climates (6.2).
3. *Karst caverns* in limestone having a floor cover of fallen blocks, chert fragments and other insoluble residues of limestone embedded in a matrix of reddish-brown sand, silt and clay that may be loosely consolidated or cemented by silica (6.3).
4. *Surface-bound mineralization* (a) in pedogenic formations including soils and crustations such as pedogenic calcrete, silcrete, gypcrete, laterite/ferricrete etc. and (b) as joint and fracture filling (6.4).

Principal Recognition Criteria*Host Environment*

- Variety of surface-bound settings (see above), capable of precipitating uranium and associated elements by reduction, complexing, adsorption, etc. from ground- or surface waters
- Hydrogeochemistry of ground- or surface waters enriched in U and other elements
- Zones of fluctuating groundwater table, and/or lateral groundwater migration within the host rocks
- Internal drainage, i.e., \pm closed basins for subtype 6.1
- Absence of cover rocks
- Adequate nearby source for uranium and other

elements (often but not necessarily uraniferous granitic complexes)

- Adequate humid climatic conditions for chemical weathering and liberation of ore-forming elements and arid enough to deposit the elements in intermontane or intracratonic environments and militating against flushing out of the newly formed minerals and as such preserving the mineralization (particularly important for subtype 6.1)

Mineralization

- Almost exclusively uranyl minerals, dominantly uranyl vanadates in subtypes 6.1 and 6.3; uranyl phosphates in subtype 6.4
- Much of the uranium adsorbed on host soil constituents (organic substances, clay minerals, etc. particularly in subtype 6.2)

Remarks

For details on mineralogy and petrography of surficial uranium occurrences see Pagel (1984).

Age Constraints

Restricted to recent times (estimated at less than 1 m.y. old).

Metallogenetic Aspects

Surficial uranium concentrations can generate in a wide range of geological and climatic environments provided

- an adequate source of ore forming elements is present,
- the climate promotes uranium mobilization and redeposition,
- adequate hydrologic and geomorphologic regimes exist for mobilization and transport of the ore-forming elements and their trapping in potential sites for ore formation such as ancient and recent valleys, basins, and structure zones,
- the lithology of potential hosts warrants precipitation and accumulation of uranium.

The source of uranium and other elements is only empirically deduced. Since essentially all surficial uranium deposits occur in regions containing uraniferous intermediate to felsic intrusive or extrusive rocks or uraniferous (meta) sediments it

is thought that these rocks provided the commodities required. For example, all duricrust type occurrences in the Yilgarn Block, Australia, occur in terrane dominated by late Archean granite containing partly 8–10 ppm U with maxima of 80 ppm U (Gamble 1984). A similar situation is given for the deposits in the Namib Desert that occur in regions with outcrops of Proterozoic granites, pegmatites, migmatites, many appreciably anomalous in uranium. Structure-controlled mineralizations on the Altiplano, Bolivia, are hosted by Tertiary rhyolitic ignimbrites containing up to 95 ppm U (Leroy et al. 1985). It is for this spatial relationship of surficial uranium occurrences to uraniferous complexes and the general high U content in groundwaters of the catchment area within these complexes that most authors consider them as the source of uranium and most other calcrete related elements. Vanadium poses a problem. No conclusive evidence for a source has been established as yet. Mafic minerals of greenstone belts or granitic rocks such as pyroxene, hornblende, and biotite have been suggested as a vanadium source for the Western Australian deposits by Mann and Deutscher (1978). Hambleton-Jones (1976) reports certain schists of the Damara Belt to be enriched in vanadium and a possible source for the Namib Desert surficial deposits.

Climate influence on the generation of the various types of surficial uranium deposits is reflected by the localization of (a) duricrust-related uranium deposits such as calcrete, dolocrete, silcrete, gypcrete in channels and playas, and of uranium accumulations in closed alkaline and saline basins as well in hot arid to semi-arid desert zones, and (b) organic matter-hosted deposits such as bogs and swamps in cold to moderate climates. Between these two extreme climatic cases there are a large number of organic and inorganic environments favorable for accumulation of uranium but, as mentioned earlier, almost all of them are of subordinate magnitude and of no economic importance. Boyle (1984) points out that the economic potential for surficial uranium deposits, relative to climatic zones, decreases from hot arid to semi-arid, cold-temperate, temperate and to tropical. This sequence also correlates with increasing dilution and precipitation of uranium in the hydrosphere.

Geomorphologic environments and hydrologic regimes required for ore formation include

- areas of lateral groundwater migration or discharge such as linear depressions in form of fluvial drainage systems;
- regions of internal drainage, i.e., closed or partially closed basins such as alkaline lakes, playas, deltas, swamps, bogs etc. supplied by surface or groundwaters which have traversed a source area;
- zones within source rock terrane characterized by faulting and fracturing and vertical groundwater movement and water table fluctuations.

Within the first two given areas localization of mineralization is often governed by local morphological features. (a) In linear depressions uranium precipitation may occur at constrictions laterally by narrowing of the channel or vertically by a basement rise. Throughflowing waters will stagnate or will suffer reduced flow rates at these barriers providing time for increased uranium precipitation as will be discussed later. (b) At internal drainage regimes, absence of outflow exits is a salient criteria for uranium accumulation in semi-arid and arid climates. In contrast, organic-rich depressions in humid environments require for concentrating uranium a relatively continuous percolation of groundwater through the organic material.

Lithology may exert a physico-chemical control on ore localization in various ways. Argillaceous layers commonly act as aquiclude. As such they may constitute both a barrier for groundwater flow, thereby enhancing the conditions for increased precipitation of uranium or, if present in multiple horizons, they may channel the waters into areas optimal for ore accumulation, for example in deltas, at bog-sediment interfaces, or in marl/clay-silt/sand-carbonaceous suites. Porosity and permeability are an additional lithologic prerequisite for mineral formation providing both, an aquifer for the mineralizing fluids and an ore mineral host such as the valley and delta calcretes-dolocretes in arid regions.

Mobilization, transport and redeposition of uranium and associated elements, particularly V for carnotite crystallization, and Mg, Ca, Ba, Sr, CO₂, SO₄ etc. for associated minerals in duricrust and karst deposits (subtype 6.1 and 6.3) and PO₄ for structure fill mineralizations (subtype 6.4), demand a coincidence of specific conditions, additionally to the above-discussed criteria. They are

- access to the required elements;
- adequate weathering conditions;
- hydrochemistry and complexing transport agents;
- physico-chemical precipitation mechanisms.

Access to elements and adequate weathering conditions is required to liberate, at least partially, the ore-forming elements from the source rocks. To achieve this purpose, the source terrane must be sufficiently exposed to and undergo intense chemical weathering under oxidizing conditions in a pre-mineralization period. Such weathering effects are reflected, in the Yilgarn Block for example, by deep-reaching regolithic profiles. For the formation of duricrust-type deposits, subsequent to the chemical weathering period a change into a hot, semi-arid or arid climate is mandatory to retain the uranium in an internal drainage system or, alternatively, to prohibit its flushing by streams and rivers into the seas, which is typical for humid moderate to tropical climates. Further on, under hot, arid conditions, the sporadic and mostly minor rain fall causes retardment of the groundwater flow, so that migration of the groundwaters transporting the ore-forming elements from the source to the site of deposition is slow. This situation, combined with a high rate of evaporation, provides also the hydrodynamic conditions favorable for the precipitation of the uraniferous nonpedogenic calcrete minerals such as calcite, dolomite, carnotite, etc. Another prerequisite for the availability of uranium in hot climates is the absence of certain saprolites such as pedogenic calcrete, ferricrete, ferrallitic laterite, Fe-Mn oxides, and clays in the source areas. These surface constituents may seriously hamper the transport of uranium by its fixation in the regolith.

Hydrochemistry and complexing agents govern the mode of transport of the ore-forming elements. Uranium is commonly dissolved in natural waters as the uranyl ion which may complex as bi- or tri-carbonate, phosphate, sulfate, fluoride, chloride, or hydroxide. The nature of the complex is a function of the pH domain. Therefore, certain uranyl complexes are specific for certain environments of acidity.

Boyle (1984) lists the following pH ranges for the formation of various types of surficial deposits.

- In waters with pH > 7 uranyl bi-carbonate and tri-carbonate complexes are dominant and

most important for the generation of subtype 6.1 (duricrust type) deposits such as Yeelirrie, Australia, and Langer Heinrich, Namibia.

- Waters with pH 4.5 to 7.5 provide stability for uranyl-phosphate complexes that may have been instrumental in the formation of subtype 6.4 deposits such as Daybreak, USA, and Cotaje, Bolivia.
- Waters with pH < 5 support uranyl sulfate and fluoride complexes which are important during the weathering of sulfide deposits such as Bondon, France, where pre-Liassic paleo-weathering processes contributed to mineral formation as reported by Eulry and Vargas (1980).

Physico-chemical mechanisms leading to precipitation of the ore-forming minerals from the transporting surface or groundwater include particularly destabilization of uranyl-complexes and sorption of uranium and, in some cases, reduction of uranium. Processes involved, individually or combined, are

- decrease in hydrostatic partial pressure due to loss of CO₂, for example by evaporation in near surface environment leading to dissociation of uranyl-carbonate complexes;
- change in pH either by loss of CO₂, oxidation of sulfides, interaction with soluble humic or fulvic particles or mixing of different solutions, affecting the solubility and stability of uranyl-complexes;
- change in redox conditions by carbonaceous matter, gases such as hydrocarbons and H₂S, anaerobic bacterial activity and oxidation of sulfides reducing hexavalent to tetravalent uranium;
- sorption processes resulting in adsorption of both uranous and uranyl-ions on carbonaceous particles, clays, phosphates, zeolites and hydrous oxides of Fe, Mn, Al, Ti and Si.

Other processes that also may have influenced directly or indirectly precipitation of U and/or U-V minerals include

- evaporation of surface and groundwaters, for example in arid climates by upwelling of groundwater in calcrete-dolomite drainage channels that results in both increase of U, V, and K contents and release of CO₂ or, in alkaline and saline playas, leads to accumulation of U in final residues; evaporation of

soil moisture associated with capillary rise of groundwater may be the mechanism for U enrichments in pedogenic calcretes or ferricretes in hot climates and perhaps of the structurally controlled mineralizations in moderate climates such as the autunite deposits of Daybreak, USA;

- interaction of two or more groundwaters, for example mixing of separate uraniferous and vanadiferous groundwaters resulting in deposition of carnotite (Mann and Deutscher 1978).

For extensive discussions of the above summarized mineralization processes, the reader is referred, among others, to Arakel (1988), Boyle (1982, 1984), Briot (1978), Carlisle et al. (1978), Hambleton-Jones (1976), Mann and Deutscher (1978), Samama (1984).

For more details on the *metallogenesis of subtype 6.1* deposits see Chapter 5.6.

Additional details on the formation of subtype 6.2, 6.3, and 6.4 mineralizations are given below.

Subtype 6.2, peat – bog, metallogenetic aspects: Noteworthy mineralization has formed in glaciated terrane of cold to cool temperate climates of the northern hemisphere, and in recent times as indicated by strong radioactive disequilibrium. Prerequisite for optimal U accumulation are organic-rich channels or basins through which a relatively constant filtering of uraniferous surface or groundwaters occurs. The waters collect the uranium by weathering and leaching from uraniferous granites, volcanics, or other lithologies. For example, in the Flodelle Creek area, probable source rocks are provided by the Cretaceous Phillips Lake Granodiorite containing 4 to 80 ppm U (av. 16 ppm U), part of which must be present in leachable form as reflected by shear-controlled near-surface mineralizations grading as much as 500 ppm U. Uranium-transporting waters appear to be neutral to slightly acid and may carry several hundred ppm U. Otton and Zielinski (1985) report for the Flodelle Creek head waters a pH-range from 5.85 to 7.55, and contents of 17 to 318 ppm U associated with high covariation of Ca^{2+} , Na^+ , Mg^+ , and HCO_3^- ions.

A mechanism that is essential for the fixation of uranium is not so much reduction but ion exchange and adsorption on organic material as reflected by the high correlation coefficient of up to 0.8 for U to organic matter.

Subtype 6.3, karst-cavern, metallogenetic aspects: The most likely source of uranium is tuffaceous sediments formerly overlying the Madison Limestone. Uranium is thought to have been leached from the pyroclastics during the present erosion cycle by groundwaters which transported it downwards to be redeposited in the karst openings as uranyl vanadates.

Subtype 6.4, surficial pedogenic and structure fill, metallogenetic aspects: The most appealing hypothesis on mineral formation at Daybreak, USA is supergene leaching of uranium from a uraniferous quartz-monzonite during a period of deep weathering since Tertiary times and subsequent redeposition of the uranium as open space fillings along a fluctuating water table. The actual cause for precipitation of the relative high grade uranium remains open for speculation. A similar type of near-surface structure-controlled deposit, with uranium derived from uraniferous rhyolitic volcanics and supposedly precipitated by H_2S or hydrocarbons, occurs at Mina Cotaje, Bolivia (ca. 100 mt U_3O_8 , 0.1% U_3O_8).

Remarks

Surficial uranium deposits are commonly relatively small and of low grade except those deposits used as type examples. From the latter only Yeelirrie, Australia, is of large and potentially economic size. Mining of the small deposits mentioned was possible under exceptional favorable conditions (nearby mill, amenability to heap leaching, etc.).

4.6.1 Subtype 6.1: Duricrusted sediments

References: Butt et al. (1984); Hambleton-Jones (1984); Mann and Deutscher (1978)

Class 6.1.1: Fluvial valley-fill

(also referred to as calcrete, groundwater-calcrete or valley-calcrete type)

Type Example: Yeelirrie, Yilgarn Block, Australia

Reference: Cameron 1984

Host Rocks/Alteration/Structures

Mineralization is hosted by nonpedogenic earthy or porcellaneous, porous calcrete or highly carbonatized fluvial and alluvial sediments composed of dolomite, calcite, clays, feldspar and locally gypsum and celestite. The calcrete grades laterally and downward into clay-quartz and argillaceous grit sediments from which it has been derived by groundwater-related alteration. Calcretized sediments occupy the axial portion of shallow valleys up to a few km wide and up to 200 km long. Basement topography under valleys has locally strong relief with abrupt drops of up to some tens of meters. For example, at Yeelirrie a basement high chokes the channel section. Calcrete forms near-surface, semi-continuous highly elongated, tabular lenses which may be 20 to 150 km long, 0.5 to 4 km wide and 2 to 15 m thick. Longitudinal topographic gradient of channels is rather gentle, between 0.05 and 0.1%. Channel-filling alluvium and calcrete commonly broaden into wide flood plains and deltas in their lower course prior to terminating in playas.

In other regions (e.g., Namibia) instead of, or in addition to calcrete, channel sediments may have been transformed into silcrete or gypcrete providing the host for mineralization.

Ore and Associated Minerals/Mode of Mineralization

Principal ore mineral is carnotite and rarely other uranyl-minerals. Carnotite occurs as stringers, seams and disseminations in earthy calcrete, as fracture coating and vug lining in porcellaneous calcrete, and as grain coating in clay-quartz sediments immediately below the calcrete. Mineral distribution, although highly irregular in detail, displays a general continuity in form of flat-lying shallow elongated lenses up to a few meters thick. Most of the mineralization is emplaced immediately beneath the present water table and is best developed in the transition zone below the calcrete.

Pagel (1984) notes that in valley-fill and lacustrine/playa deposits in various countries, the uranium minerals are commonly associated with a variety of other minerals. Celestite is known from a number of deposits but is largely erratically distributed and confined to specific parts of a deposit. Its presence is reflected by Sr contents of as much as 6%. Fluorite and baryte are reported

from a few deposits. Sepiolite occurs often and attapulgite is occasionally present. Barbier et al. (1980) estimate that in the Mudugh occurrence, Somalia, between 5 and 20% of mineralized samples contain attapulgite and sepiolite. This is also the case in the Hammadas, Ain Ben Tili area, Mauritania, from where Braun (1974) reports a clay mineral associations change within the sedimentary profile from bottom to top as follows: the basal conglomerate contains montmorillonite and illite, the mid section, montmorillonite and attapulgite; and in the top calcareous cap, montmorillonite decreases and sepiolite appears. Smectite is present in several deposits. Briot (1978) found in Yilgarn Block deposits an inter-layered illite/smectite clay and suggests that smectite derived by alteration of illite. Smectite and illite are also present in the Tumas River occurrence, Namibia. Kaolinite and illite exist often in surficial uranium occurrences, but their relationships to mineralization is unclear in some cases whereas in others they are the only clay minerals present. At a short distance away from deposits other clay mineral assemblages may occur. Briot (1978) noticed chlorites with traces of illite and talc along the margins of the Yeelirrie deposit.

Dimensions/Resources

Nonpedogenic valley calcrete U deposits may extent several km long, a few tens of meters to ca. 2 km wide and <1 to 15 m thick, commonly containing from some <10 to about 5000 mt U_3O_8 at grades of 0.03 to 0.08% U_3O_8 .

Yeelirrie, Australia, is an exception. It measures 9 km long, 0.5 to 1.5 km wide and 1 to 15 m, average 3 m thick, containing 52 500 mt U_3O_8 at an ore grade averaging 0.15% U_3O_8 . Total resources of a district such as the northern Yilgarn Block may be in the order of 60,000 to 70 000 mt U_3O_8 .

Examples of Surficial, Class 6.1.1 Valley Fill Duricrust Deposits/Occurrences

Australia: Lake Way, Lake Raeside, Hinkler-Centipede/Yilgarn Block
 Namibia: Langer Heinrich, Aussinanis, Tumas/Namib Desert
 Somalia: Dusa Mareb-El Bur region/Mudugh
 South Africa: Brulkolk/Bushmanland Plateau, Cape Province

Class 6.1.2: Lacustrine/Playa

Type Example: Lake Maitland, Yilgarn Block, Australia

Reference: Cavaney 1984

Host Rocks/Alteration/Structures

Playa sediments are dominantly fine-grained clays and silts containing gypsum, halite, and carbonates, and are associated with hypersaline waters. Dolomite and calcite, together with clay minerals and quartz, form a discontinuous horizon, some dm to m thick, of calcrete/dolocrete. Intervening material consists of carbonated clays. The calcrete is a major aquifer and the principal uranium host. It lies a few meters below the surface under a sequence of almost impermeable dolomitized clays and silt-clay sediments. Silts and sands underlie the calcrete and may be interbedded with more calcrete horizons.

Ore and Associated Minerals/Mode of Mineralization

Principal ore mineral is carnotite, present as disseminations, coating cracks and filling vugs within the harder calcrete beneath the dolomitized clay horizon. Most of the mineralization occurs in calcrete but extends into underlying silts and sands. Distribution of the mineralization is irregular although in overall continuity.

Dimensions/Resources

Individual deposits may be <1 km to 8 km long, <100 m to 1.5 km wide and 0.1 to 3 m thick containing <10 to ca. 4000 mt U_3O_8 at (average) grades ranging from 0.03 to 0.09% U_3O_8 occasionally to 0.15% U_3O_8 . Districts may contain up to some 10000 mt U_3O_8 .

Remarks

For more details on subtype 6.1 deposits see Chapter 5.6.

Examples of Surficial, Class 6.1.2 Lacustrine or Playa Duricrust Deposits/Occurrences

Australia: Lake Maitland, Lake Austin/Yilgarn Block

South Africa: Abikwaskolk, Dirkskop/Bushmanland Plateau, Cape Province

4.6.2 Subtype 6.2: Peat-bog

Type Example: Flodelle Creek, Washington state, USA

Reference: Johnson et al. 1987

Host Rocks/Alteration/Structures

Swamps, bogs, muskegs, swampy meadows at the edge of lakes or ponds in flood plains or cutoff meanders composed of vegetal organic matter (up to 65% of rock), often peat mixed with and embedded in alluvial clay, marl, silt, and sand constitute the most favorable host environment. The organic sediments have accumulated in blanket-like lenses, 1 to 10 m thick, elongated along the axis of valleys tens to 100 m wide. Mineralized bogs or swamps commonly occur in clusters controlled by topography along drainages underlain by anomalously uraniumiferous granitic rocks (at Flodelle Creek, Cretaceous Phillips Lake Granodiorite containing 4 to 80 ppm, average ca. 16 ppm U).

Ore Minerals/Mode of Mineralization

No discrete U minerals occur. U is probably present as urano-organic complexes and/or adsorpt on organic material (correlation coefficient U-organic matter often 0.6 to 0.8), but also on clay, marl and gray to black silty sand particles. U distribution and tenors are highly variable apparently depending on mode of waters (surface, ground, upwelling waters), direction of water flow, and transmissivity of the peat and interbedded sediments. The highest concentrations (up to some 1000 ppm U, locally 1% over as much as 1 m) may occur in either the upper or lower part, at the upstream section of a peat lense but also as spotty mineralization throughout the unit.

Some uranium occurrences of this subtype contain molybdenum and selenium and/or other elements. Boyle (1982) reports local concentrations of, and positive correlations between Mo, Se, Cu, V, As, REE, and U in recent bogs and marshes.

Age Constrains

Mineralization is of Holocene age. All uranium is in disequilibrium. Daughter products are often almost absent, reflecting a recent age of uranium precipitation.

Dimensions/Resources

Individual deposits may be tens of meters to some 100 m long, few meters to more than 100 m wide and <1 m to few meters thick containing <1 to ca. 50 mt U₃O₈ at (average) grades of some 100 ppm U, rarely up to 0.2% U₃O₈. Districts may contain up to some 100 mt U₃O₈.

Examples of Surficial, Subtype 6.2 Peat and Bog Deposits/Occurrences

Canada: Prairie Flats/Okanagan Valley region
South Africa: Henkries, Kannikwa/northern Cape Province
USA: Flodell Creek/NE Washington

4.6.3 Subtype 6.3: Karst-cavern

Type Example: Pryor-Little Mountains, USA
Reference: Bell 1963

Host Rocks/Alteration/Structures

Karst caverns in limestone (Mississippian Madison Limestone) having a floor cover of fallen blocks, chert fragments and other insoluble residues of limestone embedded in a matrix of reddish-brown sand, silt and clay, that may be loosely consolidated or cemented by silica, constitute the host for this type of U deposit. The caverns developed in limestone units mainly in Tertiary time after uplift during the Laramide Orogeny.

Ore and Associated Minerals

Principal uranium minerals include tyuyamunite and metatyuyamunite associated with calcite, hematite, baryte, gypsum, opal, and locally fluorite and celestite.

Mode of Mineralization

Uranium minerals occur as fine-powdery coatings of fractures and solution voids, crusts on

limestone blocks, calcite crystals, chert nodules, as fissure and vug fillings, and as disseminations in the matrix of the cavern fill. Distribution is restricted to major drainage routes cutting through the uplifted limestone unit.

Age Constraints

Radiometric disequilibrium indicates a relatively recent ore formation.

Dimensions/Resources

Uranium-hosting caverns vary widely in size and configuration between small cavities, a few meters or less across to openings up to 10 m high, 25 m wide and 50 m long. Mineralized floor fill ranges from a few centimeters to almost 3 m thick. The magnitude of ore bodies mined was highly variable containing mostly a few tonnes U₃O₈ with exceptions as large as 80 mt U₃O₈. Ore grade mined averaged 0.5 to 0.8% U₃O₈ and 0.6 to 1% V₂O₅. Some lodes were as rich as 1.27% U₃O₈ (Old Glory Mine). Resources of the district are estimated at several hundred tonnes U₃O₈.

Examples of Surficial, Subtype 6.3 Karst Cavern Deposits/Occurrences

Central African Republic: ? Bakouma
Uzbekistan: Tyuya-Myuyun/Ferghana Basin

4.6.4 Subtype 6.4: Surficial pedogenic and structure fill

Type Example: Daybreak mine, Washington state, USA
Reference: US-AEC 1959

This category comprises surface-bound mineralizations occurring widespread in pedogenic formations, including soils, pedogenic crustations such as laterite/ferricrete, calcrete, silcrete, gypcrete, etc., and structure-bound mineralizations. All occurrences are associated with uraniferous source rocks comparable to those associated with the other types of surficial deposits. All occurrences are of minute to small size and commonly of low grade. Only a very few have been mined. The Daybreak mine, Washington state,

USA, will be described as the type example of this style of minable mineralization.

Host Rocks/Alteration/Structures

At the Daybreak mine, quartz monzonite is the host rock for a shallow dipping mineralized shear zone. The shear is surrounded by intense bleaching and alteration including kaolinitization of feldspars, sericitization, and decomposition of biotite.

Ore Minerals/Mode of Mineralization

The only uranium mineral at the Daybreak mine is meta-autunite without any sulfides or gangue minerals. Uranium minerals, mainly uranyl phosphates and silicates, locally sooty pitchblende and/or coffinite, are reported from other occurrences.

At the Daybreak mine, meta-autunite lines open fractures and voids within a shear zone proximal to the water table, aggregating to pods and vuggy masses as much as 10 cm thick and 1 m long. The best mineralization occurs at intersections of the main shear with cross-fractures where lodes up to 1.5 m long, 1 m wide and 0.3 m thick may accumulate. Comparable mineralizations are known in rhyolitic environments, e.g., in

the Peña Blanca district, Mexico, and at Cotaje, Bolivia.

Dimensions/Resources

At the Daybreak mine, mineralization is hosted in a shear zone in which it extends discontinuously for 600 m long, up to 25 m wide and 30 to 40 m deep with mineable ore limited to a section slightly below the water table. Total production was 25 mt U₃O₈ at an ore grade of 0.3% U₃O₈.

Examples of Surficial, Subtype 6.4 Pedogenic and Structure Fill Deposits/Occurrences

- Argentina: Schlagintweit/Achala batholith, Sierras Pampeanas
- Canada: Summerland area/British Columbia
- Greece: Archontovouni/Paranesti
- USA: Copper Mountain/Wyoming

4.7 Type 7: Quartz-pebble Conglomerate (Lower Proterozoic) (Fig. 4.7)

(also referred to as oligomictic conglomerate or Lower Proterozoic conglomerate or paleoconglomerate type)

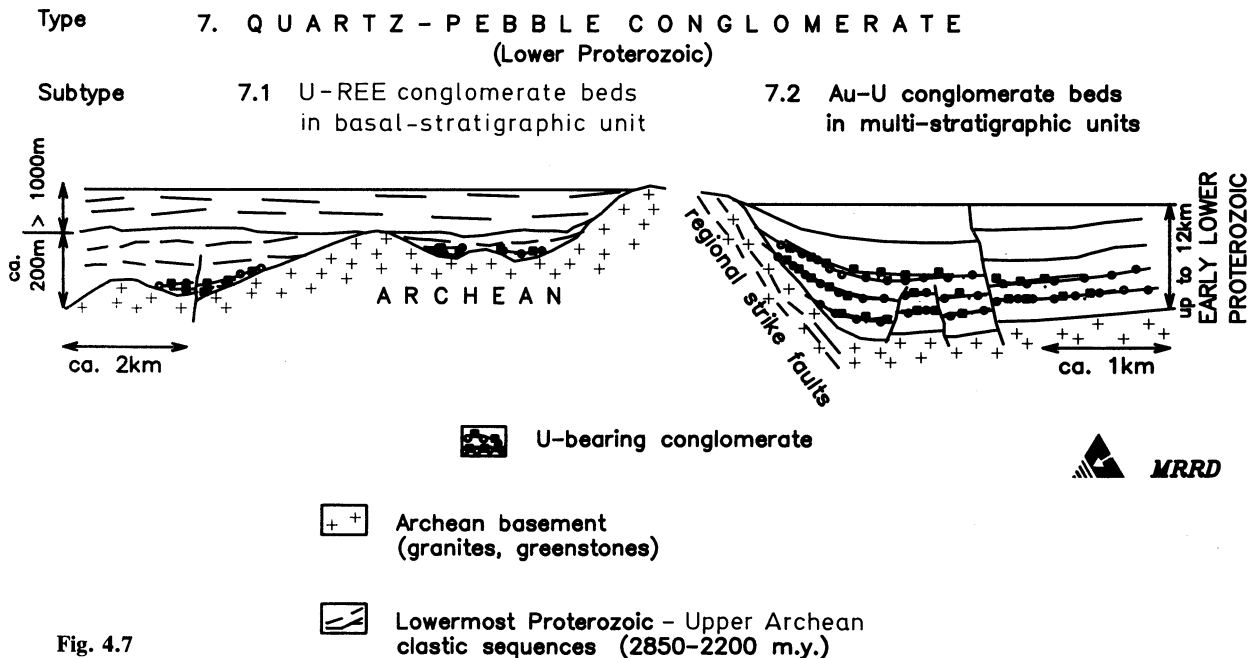


Fig. 4.7

Definition

Quartz-pebble conglomerate deposits consist of uranium and/or other metallic elements of syn-sedimentary detrital origin, modified by diagenetic processes (modified placers). The principal primary uranium phase is detrital uraninite. The conglomerates are interbedded with silicic clastic sequences containing layers of quartzite and argillite. Quartz-pebble conglomerate deposits are restricted to basal Lower Proterozoic units unconformably overlying Archean rocks which include granites.

Two varieties of mineralization can be in the conglomerates:

Subtype 7.1: U-dominant with REE

Type Example: Blind River-Elliot Lake, Canada

Subtype 7.2: Au > U-dominant

Type Example: Witwatersrand, South Africa

References: Button and Adams 1981; Hallbauer 1986; Pretorius 1976, 1981; IAEA/Pretorius (ed.) 1987; Robertson 1989, Roscoe 1969; Ruzicka 1988

In subtype 7.2 deposits, gold is the main product and uranium is by-product.

The time bracket "Lower Proterozoic" has been added to avoid confusion with younger, post-oxyatmversion oligomictic conglomerates which also contain uranium but of epigenetic origin. Mineralization of both kinds requires different depositional environments, the first that for detrital ore mineral accumulation, the second that with reductants for precipitation of uranium dissolved in solutions; the latter corresponds to sandstone-type deposits.

Principal Recognition Criteria*Host Environment*

- Oligomictic quartz-pebble conglomerate composed of well-rounded and well-sorted pebbles (mean diameter 5 to 7 cm) of predominantly quartz and lesser chert (10 to 20%) in highly pyritiferous siliceous matrix containing minor feldspar, sericite, chlorite, and heavy minerals; either submetamorphic or metamorphosed to lower greenschist facies

- Thin and lenticular conglomerate beds often coalescing into thin sheets of fluvial to deltaic sediments in braided-stream sedimentary regimes
- At or near the base of a clastic sequence within depressions possibly paleochannels incised into Archean basement (subtype 7.1) or in repeating conglomeratic beds (reefs) at or near (intraformational) unconformities, within several overlying stratigraphic units, the beds partly originating by reworking of precursor conglomerates (subtype 7.2)
- Lateral extension of payable conglomerate beds from a few km² to as much as 400 km²
- Interbeds of terrestrial to marginal marine quartzite, arkose, siltstone, argillite, and polymict conglomerate, partly arranged in cyclic sequences of variable, sometimes great thickness (several 1000's of m); iron formations may occur higher up in the sequence
- High K/Na (20 to 100) and K/Ca ratios (>40) of host-related arenites indicating provenance from granitic source
- Basins flanked by Archean granites and greenstone belts
- no ore-related alteration, but physical weathering of Archean basement,
- no structural control except for proximity to major unconformities.

Mineralization

- Primary U minerals: uraninite partly thoriferous, uranothorite, perhaps U-Ti oxide phases, associated with secondary U-Ti oxide phases (brannerite), coffinite, thucholite, a.o.
- Associated minerals: wide variety of detrital heavy minerals, including locally native Au; and diagenetic authigenic minerals, locally carbon
- Associated trace elements possibly present: Au, Ag, REE (1 to 100 ppm); As, Co, Cr, Cu, Ni, Pb, Zn, Zr (10 to a few 100 ppm); TiO₂ (0.1 to 2%); S (>1%), and traces of Pt, Os, Ir, etc.
- Subtype 7.1 is monometallic except for occasionally recovered REE minerals, subtype 7.2 polymetallic, gold being the main product
- U/Th ratio of conglomerate matrix: 1 to 15
- Stratiform, matrix-bound dissemination of U and associated minerals
- Ore localization and concentration correlate with well-sorted and densely packed quartz-pebbles reflecting control by hydrodynamic

processes, abundance of pyrite and its predecessors, presence of internal partings of pyrite-rich arenite and occasionally argillite lenticular in shape and structured by trough or tabular crossbed sets, proximity to unconformities or disconformities.

- Geometry of uraniumiferous conglomerate ore bodies is highly variable, depending on the topography of pre-conglomerate unconformity, commonly by far longer than wide and rather thin

Age Constraints

- Restricted to early Lower Proterozoic time prior to oxyatmversion, (ca. 2200 m.y. ago)

Metallogenetic Aspects

A modified placer metallogenesis is commonly forwarded for U mineralization in Lower Proterozoic quartz-pebble conglomerate deposits. The origin of uranium is generally accepted as syndimentary detrital, uraninite, and other heavy minerals deposited as placers in fluvial or deltaic environments. The source of uranium is thought to be Archean granite. The other heavy minerals are considered to have derived from either granite or greenstones. Liberation of ore minerals occurred essentially by physical weathering and erosion. Prerequisite for such a proposition is an anaerobic atmosphere permitting fluvial transport of uraninite and other minerals which are instable and easily weathered in an oxidizing environment. An anaerobic atmosphere prevailed on earth during the Archean and early Lower Proterozoic until oxyatmversion in the middle Lower Proterozoic (ca. 2200 m.y. ago). Since then, the oxygenated atmosphere prohibits longer transport of uraninite, and hence excludes formation of this type of conglomerate deposit.

The diverse heavy minerals associations in the various districts primarily reflect petrologically different sources.

Post-depositional redistribution and mineral crystallization mainly by diagenetic processes led to the formation of a suite of authigenic ore and associated minerals such as brannerite, rutile and anatase by reaction of U with ilmenite, pyrite by sulfidization of magnetite, the sulfide supposedly derived from volcanism.

Remarks

Lower Proterozoic conglomerate deposits are of very low to low grades (0.01 to 0.15% U₃O₈) but contain large resources. Deposits mined primarily for gold yielding uranium as by-product appear to have a longer term economic perspective compared with strictly uranium producers.

Examples of Type 7 Quartz-Pebble Conglomerate Deposits/Occurrences (Undifferentiated)

Brazil: Serro do Corrego/Jacobina, Bahia, Quadrilatero Ferrifero

Canada: Agnew Lake/Ontario, Sakami Lake/Quebec

India: western Karnataka

USA: Phantom Lake/Medicine Bow – Sierra Madre, Wyoming, Black Hills/South Dakota

Russia: ? Noril'sk/northern Siberia

4.7.1 Subtype 7.1: U-dominant with REE

Type Example: Elliot Lake – Quirke Lake district, Canada

References: Robertson 1989; Ruzicka 1988

Host Rocks/Structures

Pyritic oligomictic quartz-pebble conglomerate (termed “reef”) of fluvial origin, deposited in braided-stream channels, with lateral migration coalescing conglomerates into thin crossbedded sheets, interbedded with quartzite banks, chiefly in paleovalleys scoured into Archean greenstones mainly but also into granite. Three different channel systems (termed “trend”) are recognized in the Elliot Lake-Quirke Lake district.

No structural control, except for concentration in channels and their abutment against basement highs, and post-ore displacements.

Alteration

No ore-related alteration, but deep essentially physical weathering and erosion of the Archean paleosurface. Granites are weathered to a quartz-microcline rock displaying a relic granite texture containing sericite derived from plagioclase destruction, and some chlorite. Ferromagnesian

minerals and ferric iron have been removed whereas ferrous iron minerals (pyrite) and tetravalent uranium (uraninite) are still present, reflecting weathering under anaerobic conditions. The weathering is geochemically expressed by Ca leaching indicated by high K/Ca ratios (>40) due to almost complete decay of plagioclase.

Ore and Associated Minerals

Uraninite, U-Ti oxide phases (brannerite), coffinite, thucholite, uranothorite, uranothorianite, monazite, xenotime, locally gummite.

Pyrite (5 to 20 wt. %), allanite, ilmenite, chromite, cassiterite, magnetite, rutile, zircon, garnet, spinel, tourmaline, titanite, apatite, pyroxene.

Mode of Mineralization

Uranium is the primary commodity produced with occasional recovery of Th and some REE, particularly Y.

Several generations of ore and associated minerals occur as disseminated detrital and redistributed matrix components in at least seven conglomeratic horizons that range from 0.5 to >3.5 m thick. Three of the thicker reefs (1.5 to 3.6 m) have uranium grades of 0.05 to 0.15% U₃O₈. The conglomerate beds separated by quartzite banks (0.5 to 6 m thick) are within a sequence about 50 m thick immediately overlying the Archean unconformity. They cover areas, up to 20 km² in lateral extension, within three NW-SE oriented fluvial systems.

Age Constraints

Restricted to the early Lower Proterozoic (ca. 2200 to 2500 m.y. ago).

Dimensions/Resources

The Nordic Trend is 5700 m long and 1300 to 1800 m wide. The Quirke Trend is 9600 m long and 1800 to 2700 m wide. Movable reefs are 1.5 to 3.5 m thick. Total resources are 400 000 to 500 000 mt U₃O₈. Average grades are 0.07 to 0.1% U₃O₈.

Remarks

For more details see Chapter 5.7.1.

4.7.2 Subtype 7.2: Au over U dominant

Type Example: Witwatersrand, South Africa

References: Anhaeusser and Maske (eds) 1986; Pretorius 1976; Hallbauer 1986

Host Rocks/Alteration/Structures

Pyritic, oligomictic quartz-pebble conglomerate of fluvial origin interbedded with quartzite, arkose, shale and volcanics. Carbonaceous material occurs in several horizons. Deposition of conglomerates in several separate stratigraphic cycles within six large fluvial fans on the north and west side of the Witwatersrand Basin.

Ore and Associated Minerals/Metals

Uraninite (2 to 6% Th), uranothorite, brannerite, thucholite, native gold and platinum (Os, Ir, Ru, Pt) minerals.

Pyrite, arsenopyrite, pyrrhotite, cobaltite, gersdorffite, galena, chromite, zircon in relative abundance and about 60 more minerals in extremely small quantities.

Mode of Mineralization

Gold is the main product (<1 to several 100 ppm Au, average 5 to 12 ppm Au) and uranium by-product (av. 0.015 to 0.03% U₃O₈) except in a few mines (e.g., Africander/Vaal Reefs: 0.15% U₃O₈, 1.1 ppm Au).

Several generations of ore and associated minerals occur as detrital and redistributed matrix components in several conglomerate horizons within large fluvial fans. Mineralized reefs occur in all four stratigraphic systems, but the most productive is the Bird Reef Stage in the Upper Witwatersrand System, which yielded ca. 80% of past production. Important concentrations of ore are restricted to distinct narrow zones occupying ca. 2% of the entire Upper Witwatersrand System within a belt running parallel to the former coastline.

On a more local scale, ore minerals tend to have preferentially concentrated (Von Backström 1975, 1976):

- in conglomerate beds less than 30 cm thick,
- immediately above stratigraphic and intraformational local disconformities or unconformities, particularly where conglomerates fill

- depressions or scours in the footwall rocks, or about a slight rise or swell of underlying strata.
- in shallow depressions with gentle slopes,
 - in peripheral zones of deep depressions with steep slopes (axial center zones are weakly mineralized probably due to poorly developed conglomerate),
 - near the base of conglomerate beds along distinct, partly carbonaceous argillaceous/shaly footwall boundaries,
 - in pay-streaks running generally parallel to each other characterized by densely packed, well-rounded and well-sorted pebbles predominantly of quartz, and larger accumulations of other heavy minerals,
 - rare extensions into adjacent arenaceous sediments except by redistribution.

Age Constraints

Restricted to the late Archean – early Lower Proterozoic (ca. 2300 to 2800 m.y. ago).

Dimensions/Resources

The ore-hosting fluvial fan may be up to 40 km long and 90 km wide, across the distal fan base, and several 1000 m thick. Individual deposits are several 100 m to several 1000 m long, several 10 m to several 100 m wide and 5 to 200 cm thick containing up to several 10 000 mt U_3O_8 at (average) grades ranging from 0.015 to 0.03% U_3O_8 occasionally to 0.15% U_3O_8 . Resources can be >600 000 mt U_3O_8 . Gold values may range from <1 to 25 ppm.

Remarks

For more details see Chapter 5.7.2.

4.8 Type 8: Breccia Complex (Fig. 4.8)

Definition

The breccia complex deposit occurs in coarse breccias comprised largely of polymict granite- and hematite-dominated fragments in a hematitic-chloritic-sericitic-silicic matrix. Finer-grained layered rocks occur within the breccias. The breccias fill a large graben-like structure sur-

rounded by alkaline granite. Mineralization consists of a polymetallic Cu-U-Au assemblage. Geological distribution, sulfide assemblage, rock association, and stratigraphic position permit a distinction between strata-bound and strata-transgressive mineralizations.

Type Example: Olympic Dam, South Australia

References: Roberts 1988; Roberts and Hudson 1984

Principal Recognition Criteria

Host Environment

- Host rocks are a thick pile (ca. 800 m) of matrix-rich polymict breccias (Olympic Dam Formation) with some intercalated finer-grained layers
- Fragments consist of altered granite; felsic, intermediate, mafic volcanics; banded iron formation, hematitic siltstone, carbonate, arenite; fluorite, baryte, sulfides (diameter mostly 1 to 3 cm, but up to 12 m)
- Matrix of several phases of hematite, sericite, chlorite, siderite and arkosic material
- Mineralized polymict breccias overlain and underlain by barren monomict granitic breccias
- Position within a large graben-like structure (>7 km long, <4 km wide)
- Surrounding rock is an anorogenic, A-type, K-feldspar rich biotite granite containing 25 to 40 ppm U, 30–50 ppm Th and locally as much as 500–1000 ppm REE
- Structural arches associated with displacement faults cut the graben
- Deposition of breccias in high energy environment under arid sub-aerial conditions
- Rapid facies changes, disconformable contacts between individual breccia units
- Intruded dolerite dikes

Alteration

Two episodes of alteration reflected by:

- Weak pervasive alteration of all lithologies by hematitization, sericitization, chloritization and locally silicification and carbonatization, replacing particularly feldspars and mafic minerals of granite clasts;
- Intense vertically zoned alteration by hematitization and chloritization, dominant in

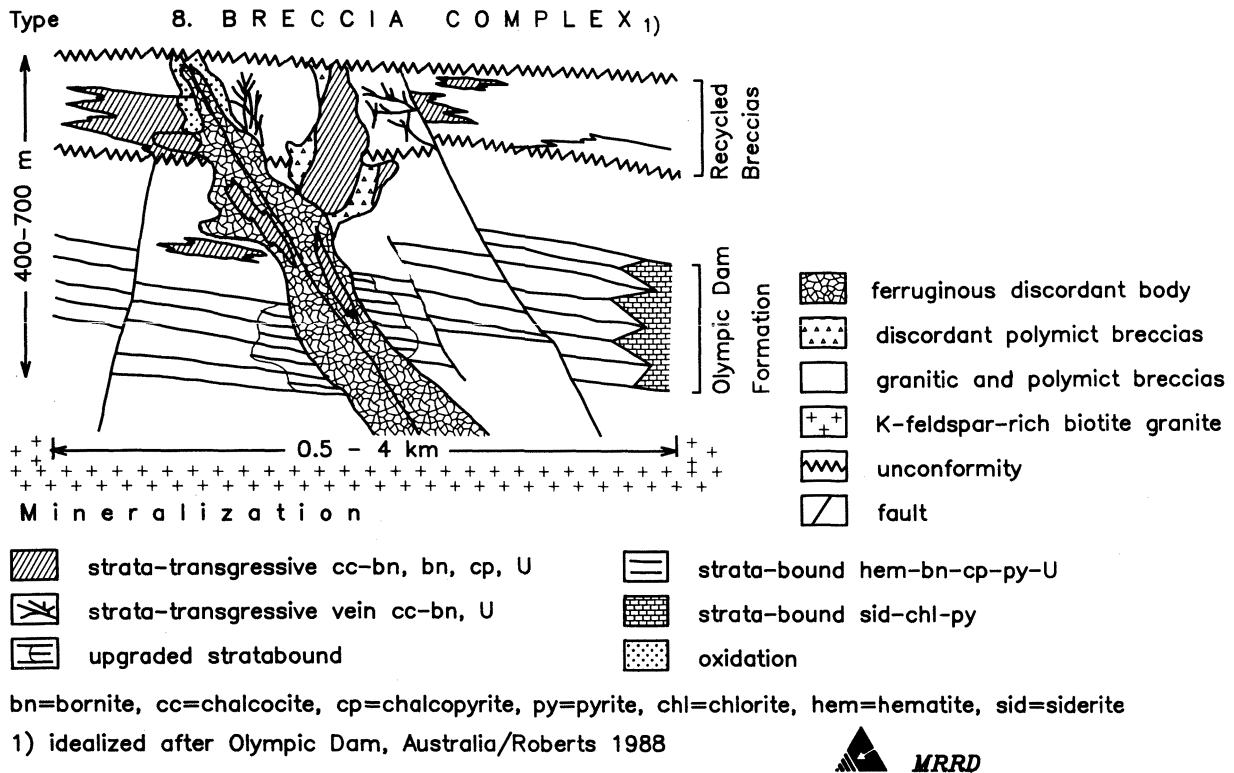


Fig. 4.8

the lower section of the mineralized sequence (Olympic Dam Formation), and silicification and sericitization in the upper section.

Mineralization

- Association of Fe, Cu, U, REE, Au, Ag, with trace amounts of other metals, abundant hematite, and a variety of gangue minerals dominantly quartz and fluorite
- Principal U minerals are pitchblende, subordinate coffinite, locally minor brannerite; Cu occurs mainly as sulfides, in basal part of the deposit associated with abundant pyrite
- Sulfide and associated minerals form two modes of mineralization: older strata-bound assemblages of dominantly Fe- and Cu-sulfides and younger strata-transgressive mineralization of predominantly Cu-sulfides
- Strata-bound mineral assemblage is bornite (chalcocite)-chalcopyrite-pyrite associated with subordinate to trace amounts of minerals of U, Au, Ag, REE, Co, Ni, and abundant hematite. Principal gangue minerals are quartz, sericite, fluorite, and minor siderite and baryte. Verti-

cal zonation is reflected by sulfur-rich, copper-poor assemblage (pyrite-chalcopyrite) at the base grading upwards to a relative Cu-rich, S-poor assemblage (bornite-chalcopyrite). Ore and gangue minerals impregnate the hematite-rich matrix of polymict breccias but also occur in rock fragments. They constitute 5 to 20 vol. % of the matrix in the form of disseminations, replacements, void-fill, and occasionally as thin stratiform layers. The concentration of sulfides displays a consistent relationship to the amount of matrix

- Strata-transgressive mineral assemblage is chalcocite-bornite associated with subordinate U, minor amounts of other sulfides, arsenides/arsenates of Cu, Ni, Co, native Au, Ag, and Cu, and abundant hematite. Principal gangue minerals are fluorite, quartz, and subordinate sericite, chlorite. Ore and gangue minerals form veinlets, veins, irregular lenses restricted to structurally prepared linear zones paralleling the long axis of the graben
- Strata-bound mineralization characteristically displays simultaneous rhythmic precipitation of hematite and sulfides

- Strata-bound mineralization commonly is below strata-transgressive mineralization, but spatial overlapping exists

Age Constraints

Not established (host rocks at Olympic Dam are Middle Proterozoic, not older than ca. 1600 m.y. and sericite alteration is about 1320 m.y. old).

Metallogenetic Aspects

Roberts (1988) suggests for the Olympic Dam deposit that it originated from a large evolving hydrothermal system in an extensional continental environment. During an early, more or less synsedimentary episode, hydrothermal fluids containing ferrous iron are thought to have entered sulfate-rich sedimentary environments forming by rhythmic precipitation of sulfides and hematite strata-bound mineralization in coarse clastic sediments. Continuous modification of the mineralization occurred. In a final stage, extensive high level intrusive activity of probably alkaline nature interacted with and superimposed widespread structure controlled transgressive Cu-U-Au-mineralization on the older strata-bound mineralization.

Dimensions/Resources

Olympic Dam is large in size, extending over an area of up to 7 km long, 4 km wide and 300 m thick. Within this area, structurally controlled mineralization occurs in linear zones greater than 6 km long, up to 0.7 km wide, and more than 300 m thick.

Total resources of the deposit amount to ca. 32 mio. mt Cu, 1.2 mio. mt U_3O_8 and 1200 mt Au. Average grades are 1.6% Cu, 0.06% U_3O_8 and 0.6 g/mt Au. This amount includes higher grade sections with probable reserves of 450 mio. mt containing ca. 11 mio. mt Cu, 360 000 mt U_3O_8 and 270 mt Au, at grades averaging 2.5% Cu, 0.08% U_3O_8 , 0.6 g/mt Au and 6 g/mt Ag (Roberts 1988).

Remarks

Olympic Dam and the nearby Acropolis prospect are the only known deposits of the tentatively

named “Breccia Complex” type. Although of huge size, accessible U amounts are restricted to the quantities recoverable as coproduct to Cu-Au mining.

4.9 Type 9: Intrusive (Fig. 4.9)

Definition

Intrusive deposits consist of disseminated primary, non-refractory uranium minerals, dominantly uraninite, uranothorianite and/or uranothorite in rocks of intrusive magmatic or anatectic origin. Deposits are of low to very low grade (20–500 ppm U) but may contain substantial resources. Further subdivision is based on host rock petrology:

Subtype 9.1: alaskite

Type Example: Rössing, *Namibia*

Subtype 9.2: quartz-monzonite

Type Example: Bingham, USA

Subtype 9.3: carbonatite

Type Example: Phalaborwa, S. Africa

Subtype 9.4: peralkaline syenite

Type Example: Kvanefjeld, Greenland

Subtype 9.5: pegmatite

Type Example: Madawaska, Canada

References: Alexander 1986; Brynard and Andreoli 1988; Berning 1986; Camisani-Calzolari et al. 1985; Maurice (ed) 1982; Sørensen et al. 1974

Subtype 9.1 is in medium- to very coarse-grained alaskite bodies ranging in size from large stocks and domes to tabular dikes and small lenses discordantly to concordantly within isoclinally folded highly metamorphosed and migmatized metasediments. No uranium related alteration is present.

Subtype 9.2 consists of very low grade uranium disseminations in highly differentiated granitic to (cupriferous) quartz-monzonitic (copper porphyries) complexes.

Subtype 9.3 is associated with differentiated (cupriferous) carbonatite complexes.

Type

9. I N T R U S I V E

Subtype	9.1 alaskite	9.3 carbonatite	9.5 pegmatite
	9.2 granite/ monzonite	9.4 peralkaline syenite	

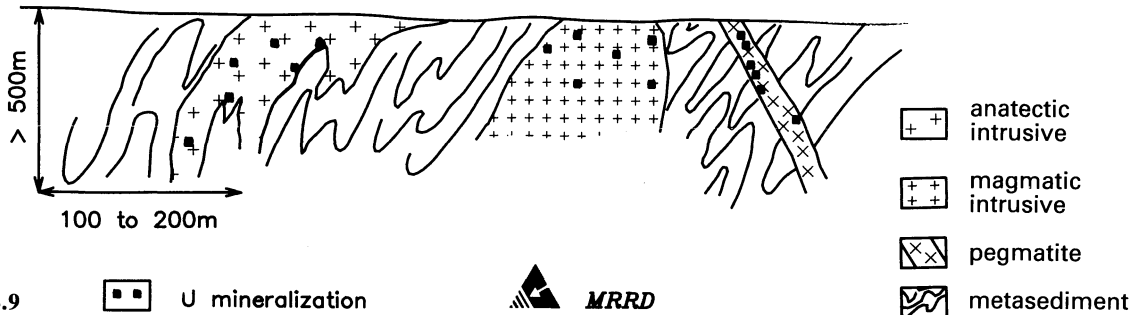


Fig. 4.9

□ □ U mineralization



Subtype 9.4 is in peralkaline syenitic domes or stocks. Uranium phases are commonly of more refractory nature.

Subtype 9.5 is in dikes of granitic, rarely syenitic unzoned pegmatite of silicious and mafic tendency (aegirine-augite).

Principal Recognition Criteria

Host Environment

- Syn- to post-orogenic intrusions within intracratonic mobile belts.
- Commonly sharp contacts and narrow contact metamorphic aureoles around intrusions
- Subtypes 9.1 and 9.2 are late leucocratic peraluminous Si, Al and alkali rich facies in highly differentiated granitic or granitoid complexes, subtypes 9.3 and 9.4 are of basic and peralkaline tendency and occur in distinct stocks and domes
- Abundance of pegmatitic, aplitic and lamprophyric dikes
- Abundance of xenoliths and roof pendants
- Enrichment of volatile (F, Li, Be), RE and/or metallic elements (Cu, Mo, etc.)

Alteration

- No primary ore related alteration except hematitization in pegmatite
- Subtype 9.2 (granite) often affected by Na-metasomatism (albitization)

Age Constraints

No age constraints except for restriction to mobile belts.

Mineralization

- Principal U minerals: ± thoriferous uraninite, uranothorianite, uranothorite and/or uraniferous refractory minerals (typical for subtype 9.4), locally in weathered zones hexavalent U minerals
- U-minerals finely dispersed ubiquitously throughout host rock in subtypes 9.1 to 9.4; in pockets and clusters irregularly distributed in subtype 9.5 pegmatite
- Th/U ratio generally <1 to 3

Metallogenetic Aspects

Uranium-rich alaskite, quartz-monzonite, granite and associated pegmatites are supposedly the product of granitization of uraniferous crustal material as indicated by Sr isotopes. *Subtype 9.1* deposits, such as Rössing, are attributed more to ultrametamorphic-anatectic processes whereas for *subtype 9.2* magmatic differentiation with uranium retained in late-stage phases is favored. The content of U, Th, REE, and other metals in the various granitic facies presumably is a function of their original abundance in the precursor (meta)sediments. Prerequisite for the elemental retainment is a dry granitization process in a closed system.

The origin of both carbonatite *subtype 9.3* and peralkaline syenite *subtype 9.4* related deposits is interpreted as of orthomagmatic differentiation.

Remarks

Intrusive subtype 9.1 to 9.4 deposits are all of very low grade (ca. 20 to 400 ppm U) but may contain large resources. Subtype 9.5 pegmatite deposits may average up to 0.1% U_3O_8 but resources are generally low (a few tonnes to a few hundred tonnes U_3O_8). Uraniferous intrusive deposits in most cases provide good uranium source rocks rather than viable deposits. The only exceptions are the Rössing alaskite deposit and pegmatite deposits of the Bancroft district (Madawaska deposit). Uranium is extracted as by-product from subtype 9.2, e.g., from the Bingham porphyry copper deposit associated with quartz-monzonite, and from subtype 9.3, e.g., from the Phalaborwa carbonatite.

4.9.1 Subtype 9.1: Alaskite

Type Example: Rössing, Namibia

Reference: Berning 1986; Berning et al. 1976; Brynard and Andreoli 1988

Host Rocks/Alteration/Structures

Syntectonic medium- to very coarse-grained alaskite emplaced as bodies ranging from large stocks and domes to tabular dikes and small lenses discordantly to concordantly within isoclinally folded highly metamorphosed and migmatized metasediments. No uranium-related alteration.

Ore and Associated Minerals

Uraninite (U/Th ratio = 9), betafite and alteration products thereof, predominantly β -uranophane in near-surface zone.

Monazite, zircon, apatite, titanite, pyrite, chalcopyrite, bornite, molybdenite, arsenopyrite, magnetite, hematite, ilmenite, fluorite as accessory rock constituents.

Mode of Mineralization

Uranium minerals of minute size occur as inclusions in quartz, feldspar, and biotite disseminated

throughout the alaskite, in interstices and in microfractures. U in mineralized alaskite has particularly concentrated in zones rich in biotite, at constrictions of wide alaskite bodies passing into dikes or apophyses, in alaskites intruded along axial planes into metasediments and in alaskites replacing amphibolite.

Age Constraints

Although Rössing formed during the Damara Orogeny/Pan African Orogeny, 500 to 600 m.y. ago, similar deposits may have formed during any orogenic event of equivalent thermodynamic conditions provided adequate source lithologies were available.

Dimensions/Resources

Individual deposits (in brackets Rössing deposit) may be several tens of meters to several hundred meters (ca. 700 m) long, several tens to more than 500 m (ca. 600 m) wide and in excess of 700 m deep, containing up to ca. 125 000 mt U_3O_8 (Rössing) at (average) grades ranging from 0.002 to 0.04% U_3O_8 , occasionally to 0.1% U_3O_8 .

Remarks

For more details see Chapter 5.9.

Examples of Intrusive, Subtype 9.1 Alaskite Deposits/Occurrences

Canada: Johan Beetz/Quebec, ? Charlebois Lake/Saskatchewan

Namibia: Goanikontes, Ida Dome, Valencia-Trekkopje, SJ Claims/Damara Orogenic Belt

4.9.2 Subtype 9.2: Quartz monzonite (Cu-porphyry)

Type Example: Bingham, Utah, USA

References: John 1978; Lanier et al. 1978

Host Rocks/Alteration/Structures

Epizonal intrusion of several igneous phases ranging in composition from monzonitic to quartz monzonitic. In the Bingham stock six major igneous phases are recognized, from oldest to

youngest: Quartz-poor (<10 vol. % quartz) equigranular to porphyritic monzonite, porphyritic quartz monzonite and recrystallized monzonite; quartz-rich (>20 vol. % quartz), porphyritic latite, quartz monzonite porphyry and hybrid quartz monzonite porphyry; latite porphyry dikes and quartz latite porphyry dikes.

Hydrothermal alteration in and around the ore controlling quartz monzonite porphyry is reflected by Mg and K metasomatism forming an inner zone of quartz-orthoclase-phlogopite, an outer zone of actinolite-chlorite-epidote, and a late sericitic and argillic (montmorillonite mainly) overprint.

Ore and Associated Minerals/Mode of Mineralization

The ore minerals form overlapping sulfide mineral zones containing from the interior low grade core outward: molybdenite, bornite-chalcopyrite, chalcopyrite-pyrite, pyrite, and galena-sphalerite. Gold and silver is present in significant amounts. Pt, Pd, Re, Se, Bi, and U occur in recoverable traces. No uranium mineral is listed, but U may be present as uraninite or uranothorianite. Molybdenite and Cu-sulfides occur as disseminations, and galena-sphalerite with part of the pyrite as veins. The mineralization is concentrated on and drapes around and through the quartz monzonite porphyry facies. Distribution and zoning of mineralization and alteration is controlled by the location relative to the quartz monzonite porphyry facies within the intrusive complex, rock type, degree of fracturing, and permeability.

Age Constraints

Although the Bingham stock is of Eocene age, there should be no principal age constraint other than to periods of magmatic activity.

Dimensions/Resources

Cu- and Mo-mineralization at Bingham with which the recoverable U is associated extends over an area of about 1200 m by 2100 m around and through the quartz monzonite porphyry phase which measures laterally 420 m by 1000 m. Persistence of mineralization into depths is at least 1500 m. Uranium content in the Cu-Mo ore is 20 to 50 ppm. Uranium is extracted from

leach containing 8 to 12 ppm U. Uranium resources recoverable as by-product to the year 2010 amount to ca. 1500 mt U₃O₈ (OECD/IAEA 1986).

Examples of Intrusive, Subtype 9.2, Granite/Monzonite Deposits/Occurrences

Australia: ? Crockers Well/Olary Province (REE + U)

Chile: Chuquicamata Norte (Cu + U)

USA: Twin Buttes/Arizona, Yerington/Nevada (Cu + U)

CIS: ? Akbabay, Aksuyek, Kiyakhty, Koktas/S of Lake Balkash (Cu + U)

4.9.3 Subtype 9.3: Carbonatite

Type Example: Phalaborwa, South Africa

References: Camisani-Calzolari et al. 1986; IAEA 1986a; Phalaborwa Mining Co, 1976

Host Rocks/Alteration/Structures

Carbonatite emplaced into the core of a differentiated alkaline intrusive complex. The carbonatite consists of a younger transgressive carbonatite core intruded into banded carbonatite. Fault systems apparently control the position of the transgressive carbonatite. Both facies are petrographically almost identical and consist of a magnetite-rich soevite. A rim facies of phoscorite has developed. It consists of serpentinized olivine, magnetite (ca. 30%), apatite (ca. 15%), phlogopite and calcite.

Ore and Associated Minerals

Recoverable ore minerals are chalcopyrite, bornite, titaniferous magnetite, baddeleyite, and uranothorianite. Other minerals and elements present in minor to trace amounts are pyrrhotite, pyrite, marcasite, pentlandite, millerite, bravoite, violarite, linnaeite, tetrahedrite, sphalerite, galena, covellite, chalcocite, cubanite, valleriite, as well as gold, silver, platinum, and palladium.

Mode of Mineralization

The transgressive carbonatite contains a high content of copper sulfides, mainly chalcopyrite

and less bornite, and accessory minerals, often in veinlets, up to 2 cm wide and less than 1 m long, horizontally and vertically. The banded carbonatite contains copper sulfides, mainly bornite as discreet grains widely disseminated throughout the rock. All ore minerals extend from the carbonatite into the phoscorite with bornite also prevailing in the phoscorite. Uranothorianite and baddeleyite are equivalent in all facies.

Age Constraints

No age constraints except to periods of magmatic activity.

Dimensions/Resources

Mineralized carbonatite and phoscorite at Phalaborwa form an elliptical, almost vertical dipping pipe. Diameters are 800 m and 1400 m. Drilled depth exceeds 1000 m. Average grade is ca. 0.004% U₃O₈ (0.51% Cu). Recoverable resources amount to several thousand tonnes uranium.

Examples of Intrusive, Subtype 9.3 Carbonatite Deposits/Occurrences

Brazil: Araxa
Finland: Sokli
India: Sevathur

4.9.4 Subtype 9.4: Peralkaline syenite

Type Example: Kvanefjeld, Illimaussaq, Greenland

References: Bohse et al. 1974; Sørensen et al. 1974

Host Rocks/Alteration/Structures

A differentiated agpaitic-peralkaline nepheline syenite complex includes as latest member lujavritic facies. The syenites have intruded into altered volcanic rocks and continental sediments.

Ore and Associated Minerals/Elements

Principal U-Th-bearing minerals are of refractory nature and include steenstrupine, eudialyte, and monazite. Associated elements include F, Li, Be, Zn, Zr, Y, Nb, and other REE.

Mode of Mineralization

U-Th minerals are disseminated in lujavrite. Highest but heterogeneously distributed U-Th concentrations occur at or near the contact of intrusive apophyses and sheet-like bodies of medium- to coarse-grained lujavrite in strongly deformed and metasomatically altered lavas. Analcime veinlets are often abundant in the contact zone. Mineralized zones containing in excess of 400 ppm U are rather small.

Age Constraints

The Illimaussaq syenite suite is about 1150 m.y. old but similar types of uranium occurrences may exist in comparable lithologic facies of any age from late Archean to Recent.

Dimensions/Resources

The Kvanefjeld deposit covers an area of about 700 m by 1500 m and extends for more than 100 m deep (investigated depth). Average grade is 0.03 to 0.04% U₃O₈. Resources amount to more than 30 000 mt U₃O₈.

Examples of Intrusive, Subtype 9.4 Peralkaline Syenite Deposits/Occurrences

Brazil: Catalão
Cameroun: Lolodorf
China: Saima Massif/NE China
Greenland: Motzfeldt Center/SE Greenland
South Africa: Pilanesberg/Bophuthatswana
Russia: Vishnevogorsk, Novogorny/Ural Mountains

4.9.5 Subtype 9.5: Pegmatite

Type Example: Madawaska/Bancroft, Canada

Reference: Alexander 1986

Host Rocks/Alteration/Structures

Granitic, rarely syenitic unzoned pegmatite of SiO₂ and mafic tendency (aegirine-augite), stained pink to brick-red by hematite, fine- to extremely coarse-grained emplaced as en-echelon dikes of tabular to flat lenticular shape with swells, offshoots, and apophyses transgressive or

paralleling metasediments and igneous rocks metamorphosed to amphibolite facies. Post-metamorphic deformation and metasomatism are common. Hematite is a characteristic alteration product.

Ore and Associated Minerals

Uraninite, uranothorite, and alteration products thereof mainly uranophane. Average U/Th ratio is 2.

Thorite, allanite, euxenite, davidite, spencite, magnetite, pyrite, marcasite, pyrrhotite, chalcocopyrite, molybdenite, zircon, sphene, fluorite in accessory amounts, and abundant hematite.

Mode of Mineralization

U is concentrated in discontinuous pods, shoots and bands, commonly controlled by mafic minerals and particularly by hematite and magnetite. Some mineralization is associated with late fractures. Although mineralization occurs randomly in the pegmatite in larger bodies, it is frequently proximal to the footwall and hanging wall side. Depth continuation is often more persistent than lateral continuity. U-tenors range from traces to 0.06% and rarely to 4% U_3O_8 over limited extent, changing within fractions of 1 m.

Age Constraints

The Bancroft pegmatites occur within the Grenville orogenic belt (950–970 m.y. old) but similar deposits may occur in any orogenic belt.

Dimensions/Resources

Individual deposits may be less than 1 m to several 100 m long, several centimeters to several 10 m wide and in excess of 400 m deep, containing up to 200 mt U_3O_8 at (average) grades ranging from 0.05 to 0.15% U_3O_8 . Districts may contain up to 2000 mt U_3O_8 .

Examples of Intrusive, Subtype 9.5 Pegmatite Deposits/Occurrences

Canada: Campbell Island/Ontario
Finland: Palmottu/Nummi-Pusula
Russia: ? Kem, Chupa area/Onezhsky

4.10 Type 10: Phosphorite (Fig. 4.10)

Definition

Phosphorite-related uranium mineralization consists of marine phosphorites of continental-shelf origin containing synsedimentary stratiform, disseminated uranium. The dominant uranium mineral is cryptocrystalline fluor-carbonate-apatite containing syngenetic uranium substituting for calcium. Two subtypes are recognized:

Subtype 10.1: phosphoria (Idaho Phosphoria type)

Type Example: Montpelier, Idaho, USA

Subtype 10.2: land pebble (Florida type)

Type Example: Land Pebble district, central Florida, USA

References: Altschuler et al. 1958; Heinrich 1958; McKelvey et al. 1956

Principal Recognition Criteria

Host Environment

- Phosphorites of marine origin deposited on continental shelf
- Subtype 10.1: bedded phosphorite with oolitic, pisolitic, pelletal and laminated textures associated with fine-grained miogeosynclinal facies (black shale, mudstone, chert, lesser carbonate beds) but noticeable absence of carbonates within uraniumiferous phosphorites
- Subtype 10.2: nodular phosphorite locally reworked to apatite pebbles interbedded with fine- to medium-grained shallow marine facies (sand, clay) and carbonate beds
- Widespread extension of phosphorite horizons, up to several 1000's of km^2
- Bedded phosphorites contain a higher uranium content and are formed distal to shore-line (subtype 10.1) as compared to nodular phosphorites which are proximal to shore line formation, except for the land pebble subtype (10.2) (partly due to reworking and secondary U enrichment)

Mineralization

- Either none or only rare discrete primary uranium minerals

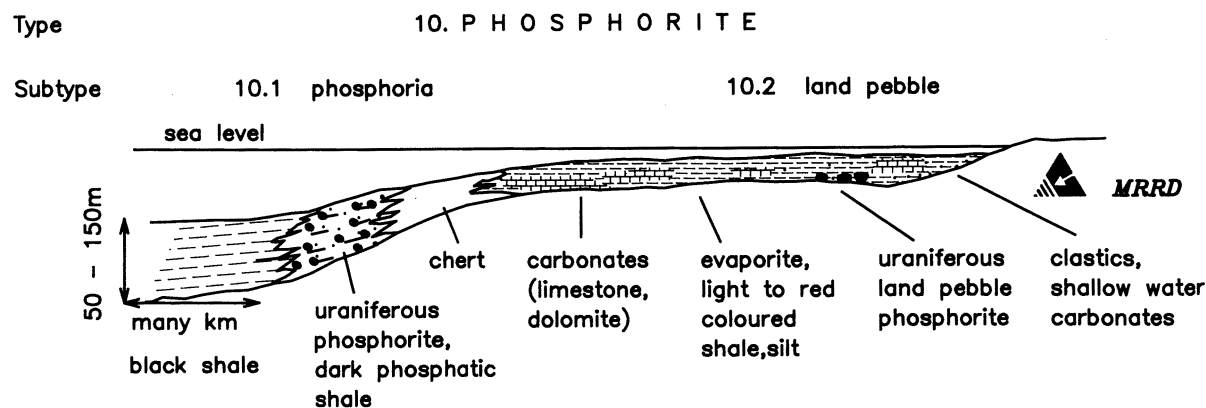


Fig. 4.10

- Principal uranium bearing mineral is cryptocrystalline fluor-carbonate apatite
- Unfavorable minerals for uranium accumulation are Al and Ca-Al phosphates (or other non-Ca phosphates)
- Positive correlation of U and P when concentration of both elements is relatively high
- Negative correlation of U and carbonate contents
- U exhibits a rather uniform distribution throughout a given bed
- No ore-related alteration except weathering
- No age constraints

Metallogenetic Aspects

Only phosphates of shallow marine origin contain appreciable amounts of uranium. Uranium accumulation is thought to be due to syngenic sedimentary extraction of U from seawater and incorporation into phosphate minerals.

Two favorable environments of sedimentation are recognized.

The first, represented by the *Phosphoria Formation*, Idaho (subtype 10.1) has formed at the outer or distal shelf margin where thick layers of bedded phosphorite developed within a pile of very fine-grained miogeosynclinal sediments including black shale, more or less carbonaceous mudstone, chert beds, and only minor carbonates. Principal U-P mineral is cryptocrystalline fluor-carbonate apatite. Uranium is considered to have been syngenetically incorporated into the apatite lattice by replacing the Ca ion. The higher P (25 to 35% P_2O_5 over 1 to 3 m) and correlated

higher U enrichment (up to 6500 ppm, average 60 to 200 ppm U) is attributed to the sedimentary environment of bedded phosphorite formation at the margin of a continental shelf, where (a) upwelling of P saturated deep marine waters provided a renewable P source, (b) slow rate of sedimentation caused longer exposure of apatite grains permitting extraction of U from the seawater to replace Ca in apatite, (c) absence of CO_2^{2+} ions in the waters which allows U to remain in solution. Variations in U content relative to P are interpreted to have resulted from either one or a combination of items (a) to (c) cited above.

The second environment is a shallow marine near-shore platform represented by lower grade phosphatic and uraniferous nodular phosphorites (average 10 to 20% P_2O_5 , 20 to 80 ppm U) except for the land pebble mineralization. In this environment, fine- to medium-grained clastics (clay, sand, glauconite) and shallow-water carbonates precipitated contemporaneously with phosphate.

The *land pebble phosphorite* (subtype 10.2) as found in the Pliocene Bone Valley Formation, Land Pebble district, central Florida, contains pebbles and sand size grains of fluor-carbonate apatite enriched with up to 35% P_2O_5 and 500 ppm U and locally more. The enrichment is attributed to reworking and corresponding re-exposure of the apatite particles to uranium bearing seawater during repeated marine transgressions. Associated with this evolution is an irregular, up to a few meters thick, leached horizon developed within the Bone Valley Formation by weathering. Its upper section,

composed of Al-phosphates (wavellite), and its middle section, dominated by Ca-Al-phosphates (millisite, crandallite, referred to as aluminum phosphate zone), have released uranium supposedly by acid solution leaching. Altschuler et al. (1958) suggest U reconcentration at or near the base of the leached zone composed of incipiently leached residual apatite formed in response to neutralization of the acid fluids by the Ca-phosphate. Fixing of uranium resulted by adsorption on the porous, partially leached, residual apatite leading locally to concentrations of as much as several thousand ppm U. Principal U collectors are Ca-phosphates (apatite) and, to a lesser extent, Ca-Al-phosphates (crandallite), whereas Al-phosphates (wavellite) are unfavorable U collectors. Distribution of these minerals also reflect the U-grade zonation within the leached profile.

Remarks

Although uraniumiferous marine phosphorites constitute large U resources, their commonly very low average grade (<20 to 300 ppm U) and difficult metallurgical U extraction excludes them from being a primary U source. U is recovered, however, as a byproduct of phosphate production.

In contrast to marine phosphorites, all other phosphatic rocks contain lower concentrations of uranium. They include residual phosphorites derived by weathering of marine phosphatic limestone, phosphatized rocks resulting from solutioning of phosphates from rocks higher in the sequence and its redeposition as interstitial fillings or replacements in subjacent rocks, guano mainly composed of bird and bat excrements, and detrital weathering products thereof and of marine phosphorites such as fluvial pebble deposits.

Examples of Type 10 Phosphorite Deposits/ Occurrences (not Differentiated)

Central African Republic: ? Bakouma
Israel: Zefa/Negev
Morocco: Ganntour-Bahira/Youssoufia, Oulad Abdoun/Khouribga
USA: Bone Valley/Florida, Green River/Utah-Wyoming

4.10.1 Subtype 10.1: Phosphoria (Idaho type)

Type Example: Montpelier, Idaho, USA; Permian Phosphoria Formation

Reference: McKelvey et al. 1956

Host Rocks/Alteration/Structures

Phosphatic shales composed of bedded fluor-carbonate apatite as fine-grained oolites, pisolites, pellets or laminae and phosphatic fossil fragments (brachiopod shells, fish scales, etc.) mixed with variable amounts of finest-grained detritus, mainly clay particles, carbonaceous matter and locally carbonate. Sedimentary environment is the distal part of a continental shelf, where uranium-bearing deep seawater could ascend and flood the phosphorite and where contribution of detrital clay and silt was minimal and accumulation rate was strongly retarded. Associated sediments include over- or underlying, often pyritic cherts, mudstone, black shale which laterally interfinger with sandy, carbonatic, red bed and evaporitic shallow water sediments.

Ore and Associated Elements/Mode of Mineralization

U occurs in rather uniform dissemination in phosphatic beds in dominantly bedded cryptocrystalline fluor-carbonate apatite of pelletal, oolitic etc. texture. Although present in almost all phosphorite beds U grades vary considerably from 10 to 6500 ppm U and to a large extent, but not necessarily, are correlative to the phosphate content. P₂O₅ enrichment is greatest in the top and/or basal segments of phosphatic layers as exemplified by the Mead Peak Phosphatic Shale Member, the main phosphate member of the Phosphoria Formation. This member is 60 to 150 m thick and averages 11 to 12% P₂O₅, whereas the upper and lowermost 1 to 3 m contain from 25 to 35% P₂O₅ and also contain the highest uranium tenors.

Dimensions/Resources

The Phosphoria Formation stretches over many thousands of km², its phosphatic member ranges from 60 to 150 m thick. The best mineralizations occur over a thickness of 1 to 3 m. Total resources are several million tonnes U₃O₈. Uranium grades average 60 to 200 ppm.

4.10.2 Subtype 10.2: Land Pebble (Florida type)

Type Example: Land Pebble district, central Florida, USA; Pliocene Bone Valley Formation
Reference: Altschuler et al. 1958

Host Rocks/Alteration/Structures

Phosphatic pebbly argillaceous sandstones are crudely graded bedded, reworked and composed of nodules and sandsize grains of fluor-carbonate apatite mixed with clay minerals (smectite, montmorillonite) and quartz grains of shallow marine near-shore continental shelf origin. The phosphorite is interbedded with marine sands and shallow water limestone and dolomite. Black shales and cherts are noticeable absent. Where affected by weathering, apatite is replaced in the top zone by Al-phosphate (wavellite) and in the middle zone by Ca-Al-phosphate (crandallite, millisite). Smectite is transformed to kaolinite. Incipiently or incompletely leached residual apatite of the bottom zone is highly porous and enriched in U, whereas the secondary Al- and Ca-Al-phosphates contain only minor U.

Ore and Associated Minerals/Mode of Mineralization

U occurs in stratiform dissemination bound to Ca-phosphate (principally fluor-carbonate apatite) in the form of sandsize particles and nodules in beds mixed with quartz and clay minerals. Although apatite grains and nodules are often enriched up to 500 ppm U and locally up to several 1000 ppm at bottom of leached zone, the mineralized lower Bone Valley Formation averages ca. 150 ppm U: due to the quartz and clay matrix.

Dimensions/Resources

Lateral extension of the lower Bone Valley Formation is about 2500 km² in which deposits of the Land Pebble district occur. Mineralized beds range in thickness from less than a meter to 10 m averaging 5 to 7 m. Total U resources are in the order of 500 000 mt U₃O₈ or more. Grades of land pebble mineralization average ca. 150 ppm U.

4.11. Type 11 :Volcanic (Fig. 4.11)

(also referred to as volcanogenic type, or U-Mo type in Russian literature)

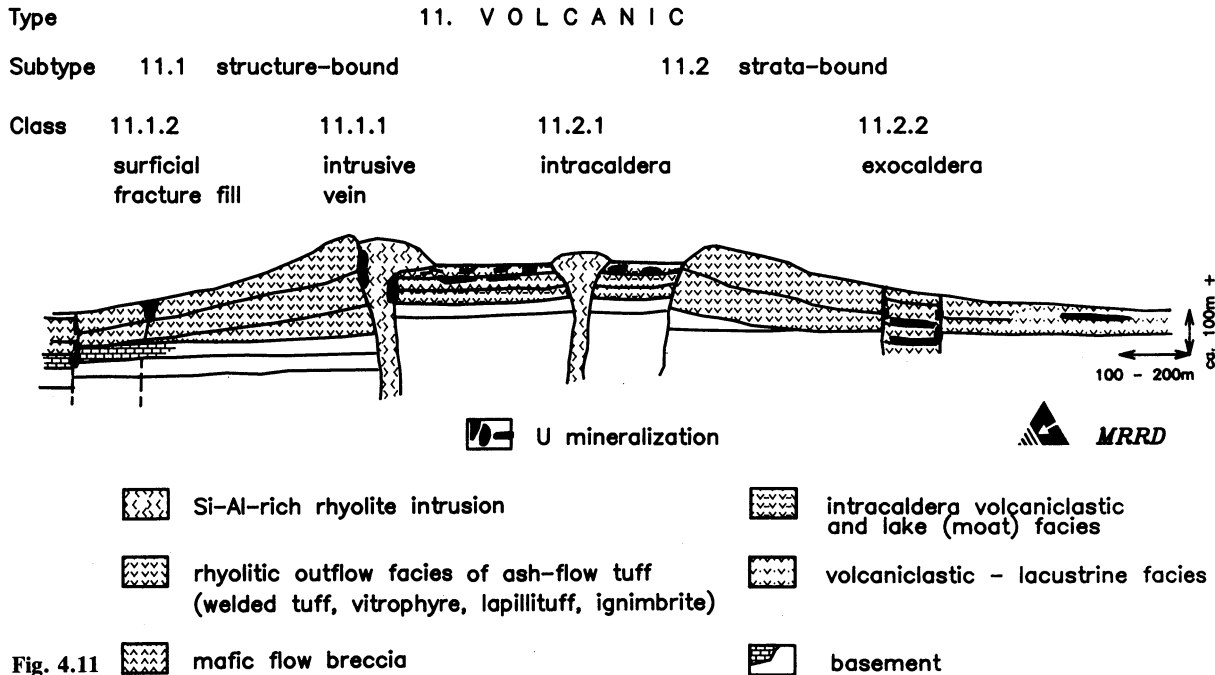


Fig. 4.11

Definition

Volcanic deposits are associated with felsic to intermediate volcanic rocks and their sedimentary derivatives. Uranium occurs as structure-bound or strata-bound concentrations which can be separated into several classes:

Subtype 11.1: structure-bound

Class 11.1.1: intrusive veins
Type Example: Nopal I, Mexico

Class 11.1.2: surficial
Type Example: Cotaje, Bolivia

Subtype 11.2: strata-bound

Class 11.2.1: intracaldera
Type Example: Aurora, USA

Class 11.2.2: exocaldera
Type Example: Margaritas, Mexico

References: Chen Zaobo 1981; Dayvault et al. 1985; George-Aniel et al. 1985; Goodell 1985; Goodell and Waters 1981; IAEA 1985; Leroy et al. 1985, 1987; Pardo-Leyton 1985; Sherborne et al. 1979

Structure-bound mineralization include intrusive veins associated with volcanic intrusions, diatremes, flows or bedded pyroclastic units (class 11.1.1) and surficial fracture fills (class 11.1.2) in similar lithologies. *Strata-bound mineralization* consists of disseminations and impregnations in permeable and/or reactive flows, flow breccias, tuffs and other lithologies. Distinction of strata-bound classes is based on their intracaldera (class 11.2.1) or exocaldera (11.2.2) host environments, the latter is mixed with nonvolcanic clastic sediments.

Principal Recognition Criteria*Host Environment*

- Volcanogenic intrusive and extrusive rocks of felsic to intermediate magmatism
- Preferentially leucocratic, rhyolitic facies high in silica and alumina, low in iron and calcium, rich in volatiles
- Abundance of fluorite, tourmaline, topaz reflecting volatile enrichments of F and B
- Enrichment in trace elements particularly U, Mo, Sn, W, Hg, As, Sb, Li

- Occurrence of volcanic domes, subvolcanic intrusives, ring dike intrusives, outflow facies of ash-flow tuffs, lavas, ignimbrites, pyroclastics, intracaldera volcanoclastic and lacustrine or moat facies
- Facies with major permeability variations due to welding or fracturing (vesicular flow zones, flow breccias, contacts between thick rhyolitic units and mafic lavas or limestones, ring dike faults, fault intersections, grabens, fracture zones proximal to domes, subvolcanic intrusions or major dikes)
- U source and U host rocks are often identical
- Glassy and unwelded volcanics are better sources than crystalline or welded rocks

Alteration

- Feldspathization
- Zeolitization
- Devitrification
- Advanced to complete argillitization
- Strong hematitization
- Intense silicification

Mineralization

- Principal uranium minerals are pitchblende, rarely coffinite, in many deposits uranyl minerals
- U adsorbed on or incorporated in various host minerals (U bearing clay minerals, uraniferous opal etc.)
- Associated metallic minerals include mainly pyrite, minor to traces of Mo, Pb, Sn, W, Li, Hg, Sb, W and other minerals
- Associated gangue minerals: fluorite, quartz, carbonates, baryte, jarosite
- Occurrence of U minerals predominantly as disseminations, very rarely as more massive concentrations (stringers, veinlets, pods)
- Higher grade mineralization always of erratic distribution

Age Constraints

No restrictions except to taphrogenic episodes

Metallogenetic Aspects

Prerequisite for mineralization are volcanic facies containing U in excess of average crustal

abundance and in leachable form. These parameters are provided mainly by rocks of rhyolitic composition that are unwelded and have a glassy groundmass. Matrix-bound uranium is easily liberated by devitrification in reaction to both volcanic hydrothermal (hot springs, fumaroles) and meteoric supergene waters, which then transported the U to sites of deposition either in porous volcanic beds or fractures. In addition, U may be introduced by volcanic hypogene fluids. U-transporting solutions are thought to be oxidized and slightly acidic, containing F, CO₂ or other ions, which facilitate transport of U. Suggested processes for fixing U include reduction and adsorption, associated with neutralization by wall rock interaction and boiling or evaporation of fluids. In near-surface deposits U precipitation often occurs along groundwater tables.

Remarks

Volcanic uranium occurrences have often been overprinted by strong hydrothermal or diagenetic processes, making it difficult to attribute them to a distinct class.

Most of the volcanic uranium occurrences also comply with criteria defining other types of deposits particularly of vein, surficial, fracture fill and tabular sandstone types except for their crucial volcanogenic relationship and subeconomic magnitude. Grades are low to very low (0.02 to 0.1% U₃O₈) and resources are commonly small (<1000 mt U₃O₈). Volcanic occurrences may be more important as potential sources for other types of deposits, particularly for those of sandstone type.

Examples of Type 11 Volcanic Deposits/ Occurrences (not Differentiated)

Australia: Maureen/Queensland
 Brazil: Osamu Utsumi/Poços de Caldas
 Bolivia: Cotaje/Altiplano
 Bulgaria: East Rhodope Mts, East Balkan Mts
 Canada: Michelin/Labrador
 China: Quinlong-Daxing'anling volcanic belt, Langshan area/NE China, Balyanghe/NW China, Gan-Hang and S. Jiangxi-N. Guangdong volcanic belts/SE China
 Kazakhstan: Pribalkhashky region

Romania: Apuseni Mts
 Russia: Streltsovsky region/Transbaikal
 Uzbekistan: Karamazarsky region

4.11.1 Subtype 11.1: Structure-bound

Reference: Leroy et al. (1987)

Class 11.1.1: Intrusive Veins

Type Examples: Nopal I, Peña Blanca, Mexico
 Reference: George-Aniel et al. 1985;

Moonlight, Mc Dermitt, USA
 Reference: Dayvault et al. 1985

Host Rocks/Alteration/Structures

Host lithologies are variable and include rhyolitic ignimbrite, rhyolitic breccias, dacite flows, granodiorite, a. o. Hydrothermal and/or diagenetic alteration is intense and may consist of devitrification, argillitization (kaolinite, montmorillonite), zeolitization and silicification. At Nopal I, host rocks are completely altered. Alteration increases with intensity and density of fracture systems and decreases with distance from the ore body (60 to 200 m away). Deposits occur in intensely fractured and brecciated zones caused either by crosscutting fault sets (Nopal I) or along ring fracture systems (Moonlight).

Ore and Associated Minerals

Principal uranium mineral in an unoxidized environment is pitchblende associated with minor pyrite, molybdenite, and traces of other sulfides. Gangue minerals may be fluorite, quartz, locally minor adularia, carbonate, apatite, jarosite, baryte, and Ti-minerals. Most mineralization is oxidized containing mainly uranyl-phosphates and -silicates and limonite. Mineralization commonly includes concentrations of Pb (<2000 ppm), Mo (<500 ppm) and anomalous amounts of As, Sb, Ag, Cu, Hg, Sn, W, Zr.

Mode of Mineralization/Dimensions/Resources

Uranium minerals occur as disseminations or coatings in a pipe-shaped deposit filled with silicified tectonic breccia at Nopal I (20 × 40 m wide, >100 m deep) or as disseminations, stringers

and veinlets within tectonic breccia and siliceous cement which form veins, 1 to 5 m wide, at least 50 m deep as at the Moonlight mine. Ore distribution is irregular changing from sections with little uranium to grades which locally reach 10% U_3O_8 .

Deposits contain from less than 1 mt to a few 100 mt U_3O_8 at ore grades averaging from <0.1% to 0.5% U_3O_8 (Nopal I ca. 350 mt U_3O_8 ; 0.3% U_3O_8).

Examples of Volcanic, Class 11.1.1 Structure-Bound Intrusive Vein Deposits/Occurrences

Australia: ? Ben Lomond/Queensland
 Canada: Rexspar/British Columbia
 Kazakhstan: Pribalkhashsky region
 Peru: Macusani
 USA: Marysvale/Utah, White King Mine/
 Lakeview, Oregon
 Russia: Streltsovsky/Transbaikal

Class 11.1.2: Surficial veinlike

Type Example: Cotaje, Sevaruyo, Bolivia
 References: Leroy et al. 1985; Pardo-Leyton 1985

Host Rocks/Alteration/Structures

Host lithologies are rhyolitic to rhyodacitic ignimbrite and tuff layers with intercalated volcanic breccias and conglomerates. The tuffs have increased U, Th, Li, Sr, Ba, and REE tenors. Alteration is reflected by marked bleaching, argillitization, dominantly kaolinitization and silicification. Deposits occur near surface in zones of intense fracturing and brecciation.

Ore and Associated Minerals

Principal U minerals are (sooty) pitchblende, coffinite and uranyl phosphates associated with smoky quartz, baryte, siderite, gypsum, and minor Fe, Pb, Zn sulfides. Local enrichment of Mo and V also occur.

Mode of Mineralization

Uranium minerals are irregularly distributed in open fractures forming narrow veins and occur disseminated throughout zones of intense shearing or brecciation which are commonly oxidized.

Dimensions/Resources

Mineralized structures are commonly 10 to 60 m, rarely few 100 m long, 0.1 to 10 m wide and persist from surface to about 30 m deep. (Cotaje: 350 m long, 1 to 10 m wide, 30 m deep).

Deposits contain from less than 1 mt to some 10 mt U_3O_8 . Grades average 0.05 to 0.07% U_3O_8 , but may be as high as 2.5% U_3O_8 . Cotaje accounts for ca. 40 mt U_3O_8 , at an ore grade of 0.07% U_3O_8 . Some districts may contain a few hundred, perhaps a few thousand tonnes U_3O_8 .

Examples of Volcanic, Class 11.1.2 Structure-Bound Surficial Deposits/Occurrences

ČSFR: Novoveska Huta-Muran/Slovakia
 USA: Lucky Lass Mine/Lakeview, Oregon

4.11.2 Subtype 11.2: Strata-bound

Reference: Orajaka (1981)

Class 11.2.1: Intracaldera

Type Example: Aurora-Cottonwood Creek, Mc Dermitt, USA
 Reference: Dayvault et al. 1985

Host Rocks/Alteration/Structures

Host rocks are mafic to intermediate tuffs, flows, and flow breccias associated with domes and overlain by tuffaceous lacustrine (moat) sediments. Individual flows have massive central zones bordered by \pm strongly altered vesicular to scoriaceous flow tops along intraformational unconformities. Alteration and mineralization in lavas is restricted to porous zones along flow tops, brecciated layers and fracture zones. Mineralized facies are almost completely altered to pyritic montmorillonite, chlorite, clinoptilolite, opal, leucoxene rocks with a groundmass of K-feldspar, clay, and quartz. Alteration of lacustrine sediments is reflected by sporadic zeolites, ubiquitous feldspar, and smectite, calcite and quartz crystallization.

Ore and Associated Minerals

Principal uranium minerals are pitchblende, coffinite, and locally hexavalent U minerals asso-

ciated with pyrite. Anomalous concentrations of Hg, Li, As, Sb, Mo, Zn, W, and F are associated with the mineralization.

Mode of Mineralization/Dimensions/Resources

Uranium minerals occur as fine coatings of pyrite and leucoxene mainly concentrated in highly altered porous layers along flow tops and in breccia layers up to a few meters thick. Tuffaceous lacustrine sediments contain minor amounts of U (up to 200 ppm U) predominantly concentrated in intercalated layers 0.5 to 2 m thick, composed of thinly bedded (mm to cm) opal, pyrite, ash, diatoms and minor carbonaceous matter.

Mineralization extends laterally for several 100 m to few 1000 m, and may penetrate upwards and downwards into fracture zones.

Deposits may contain a few tens and up to several 1000 mt U_3O_8 , at grades ranging from 0.02 to rarely 0.1% U_3O_8 . (Aurora: ca. 7500 mt U_3O_8 , 0.05% U_3O_8). Districts, including other types of volcanogenic U deposits, may have potential resources of some 10 000 mt U_3O_8 . (Mc Dermitt ca. 30 000 mt U_3O_8 , 0.03% U_3O_8). No attempts are known to recover U as by-product of Hg, Li, or other metal mining.

Examples of Volcanic, Class 11.2.1 Strata-bound Intracaldera Deposits/Occurrences

Italy: Sabatini, Vulsini/Latium
Russia: Yubileynoye, Novogodneye/Strel'tsovsky, Transbaikal

Class 11.2.2: Exocaldera

Type Example: Margarites, Peña Blanca, Mexico
Reference: Goodell 1985

Host Rocks/Alteration/Structures

Host rocks are facies of ash-flow tuff (vitroclastic alkaline rhyolitic tuffs, etc.). At Margaritas the tuffs fill a graben, 500 m wide, bound on both sides by step faults with displacements of up to 100 m and more. Alteration includes extensive devitrification, partial argillitization, intense silicification and locally abundant hematitization.

If these volcanoclastics are interbedded with lacustrine sediments they form deposits such as those in the Date Creek Basin, Arizona.

Ore and Associated Minerals

Principal uranium minerals are hexavalent U species (uranyl silicates, vanadates, phosphates) associated with molybdenite, powellite, and locally with jarosite, pyrite, calcite and fluorite.

Mode of Mineralization/Dimensions/Resources

Uranium minerals occur as disseminations, encrustations, lamina occupying fractures, joints, and voids. Mineralization distribution is erratic. At Margaritas, higher-grade sections ranging from 0.1 to 0.4% U_3O_8 and 0.1 to 3% Mo are separated by low grade intervals. Mineralization occurs over intervals ranging from 1 to 7 m thick, 100 to 150 m wide and about 300 m long. In most cases, deposits of this type are smaller in dimensions.

Deposits may contain a few tonnes to some 1000 mt U_3O_8 , at grades ranging from 0.02 to rarely 0.2% U_3O_8 . (Margaritas: ca. 2000 mt U_3O_8 , 0.1% U_3O_8). Districts may have resources of several 1000 mt U_3O_8 (Peña Blanca district: ca. 4000 mt U_3O_8).

Examples of Volcanic, Class 11.2.2 Strata-bound Exocaldera Deposits/Occurrences

Australia: ? Maureen/Queensland
Canada: Michelin/Labrador
Italy: Novazza/Val Seriana
Sweden: Duobblon/Sorsele
USA: Date Creek Basin/Arizona

4.12 Type 12: Metasomatite (Fig. 4.12)

Definition

Metasomatite deposits consist of unevenly disseminated uranium in structurally deformed rocks that were affected by alkali metasomatism of dominantly sodium tendency. Metasomatic facies include albitites, aegirinites and alkali-amphibole rocks. Principal uranium phases are uraninite \pm Th rich and U-Th oxides and silicates.

Two subtypes are defined on the basis of the precursor rock facies:

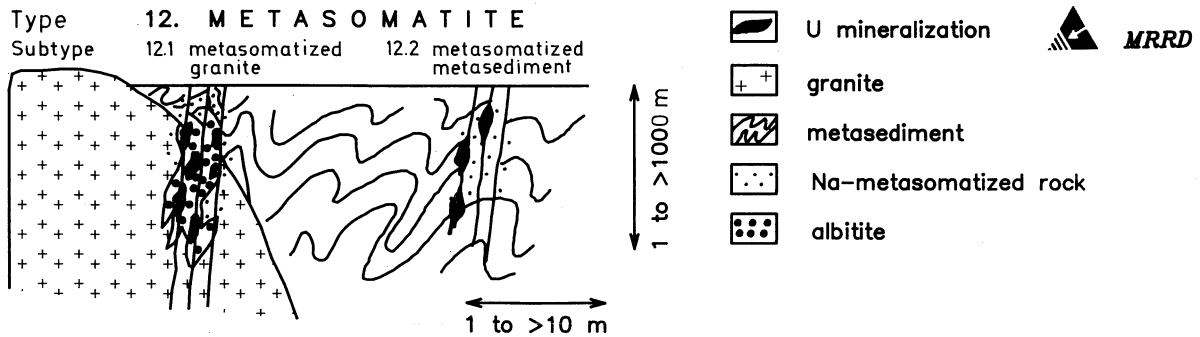


Fig. 4.12

Subtype 12.1: metasomatized granite

Type Example: Ross Adams/Bokan Mountain, USA

Subtype 12.2: metasomatized metasediments

Type Example: Krivorozhsky-Zheltye Vody, Ukraine

References: Avrashov/Bendix (ed.) 1980; Belevtsev et al. 1984; Collot 1981; Fritsche 1986; Fuchs et al. 1981; Kazanzky and Laverov 1977; Mineeva 1984

Principal Recognition Criteria*Host Environment*

- Albitites and granites or metasediments with metasomatic albite-aegirine, albite-arfvedsonite-aegirine or other Na-silicates
- Distribution of metasomatites along cataclastic zones in parent rocks
- Transition margins between metasomatized facies and parent rocks are commonly narrow
- Emplacement of mineralization along micro- and macro-fractures confined to albitized facies
- Parent rocks have often but not necessarily anomalous uranium background values
- Intrusive granites are enriched in alkalis, Al_2O_3 , U, Th, Nb, and REE
- Albitized metasediments are mostly found in middle to high rank, partly dynamothermally, metamorphosed rocks adjacent to leucocratic granite intrusions in mobile belt terranes

Alteration

- Na-metasomatism reflected by enrichment of Na_2O and depletion of SiO_2 and K_2O
- Argillitization (commonly weak)
- Hematitization (locally intense)
- Locally carbonatization

Mineralization

- Principal uranium minerals: uraninite \pm Th rich, uranothorianite, uranothorite, thorite, nenadkevichite, U-Ti oxide phases (branerite), pitchblende and coffinite
- Associated minerals: allanite, bastnaesite, monazite, xenotime, zircon, apatite, galena, pyrite, magnetite, and/or calcite in accessory amounts; locally abundant hematite
- Occurrence of U minerals as disseminated anhedral to euhedral grains and in thin veinlets.

Belevtsev et al. (1984) provide the following additional features for Proterozoic albitite uranium deposits, presumably referring to the Zheltye Vody district, Ukraine:

- U mineralized albitites occur within sediments and volcanogenic rocks that have been metamorphosed to amphibolite grade facies or granitized and which contain elevated U backgrounds
- U hosting albitite occurs along cataclastic and mylonitic zones within metasomatic albitite
- U hosting albitite differs from ordinary U barren albitite by blastoclastic structures, better permeability and presence of hematite, aegirine, alkaline amphibole, chlorite, epidote, and carbonate
- U minerals occur as fine-grained impregnations associated with dark-colored minerals among albitite grains

Kazanzky and Laverov (1977) and Kazanzky et al. (1978) distinguish iron-uranium deposits associated with Na- and CO_3^- -metasomatites (Krivoi Rog) and uranium deposits associated with Na-metasomatites. For both types, a distinct zoning and the association with deep-seated multi-activated fault systems combined with

brecciation and mylonitization are said to be typical.

Age Constraints

No age constraints except restriction to periods of late or post-orogenic magmatic activity.

Metallogenetic Aspects

Metasomatite-bound uranium mineralizations appear to be the final result of a (Na-)metasomatic evolution during the waning stages of an orogeny. In the case of *subtype 12.1* deposits, metasomatism transformed during an early stage previously crystallized leucocratic igneous rocks, essentially granite, into Na-rich facies culminating in albitite in structurally deformed ground perhaps in the apex part of a pluton. Cathelineau (1986) points out that (a) the fluids responsible for albitization and associated desilicification are in composition similar to those of meteoric origin, (b) metasomatic alteration takes place several tens of m.y. after granite crystallization, and (c) there is no relation between late magmatic, pneumatolytic to deuteric processes which also can cause alkali enrichment and albitite-forming metasomatism.

Subsequent to albitization, introduction of U associated with Th and REE occurred on the same reactivated structures along which the albitizing fluids permeated the host granite. This spatial relationship also suggests a metasomatic origin of the U, Th, REE mineralization. Similar processes are assumed for the formation of *subtype 12.2* deposits. But instead of autometasomatism as in granite, metasediments were altered presumably by fluids derived from or mobilized by intruding granites or by late metamorphic events.

Mineeva (1984) comments on the metallogenesis of uranium albitites associated with deep rooted-lineaments which can be attributed to *subtype 12.2* and states that:

- albitization and mineralization evolved through several stages ranging from ultrametasomorphism to post-albitite events;
- polyphase processes imprinted primary and secondary lateral and vertical zoning on host rocks reflected by mineralogy and geochemistry. In contrast, unmineralized albitites are not zoned and REE mineralized albitites

display only primary lateral and vertical zoning;

- post-albitite events superimposed a secondary zoning reflected by a hydrothermal mineral paragenesis of various phases which typically are associated with economic deposits. They include apatite, chlorite, carbonate, baryte, quartz, sulfides and hematite;
- spatial extension of U mineralization in albitites correlates with extension of carbonatization. This reflects the importance of CO₂. CO₂ controls the pH values in the fluid system and influences complexing of U and other elements in solution and their redeposition;
- U redistribution proceeds downwards and affects ubiquitously the host albitites thereby achieving U enrichments.

According to Belevtsev et al. (1984), uranium mineralization resulted from residual metamorphic fluids contained within cataclastic and mylonitic zones of protoactivation. The mineralizing activity progressed through the final stage of metamorphism. Fluid inclusion studies indicate that involved solutions contained carbonate, chloride, and sulfide with concentrations of 10 to 40%. Temperatures ranged during the albitization stage from 350 to 150°C and during the mineralizing stage from 200 to 120°C at pressures of 600 to 900 bar. According to Batashov et al. (1984), the temperature of mineralization was 300 to 200°C.

The source of the uranium for both subtypes remains debatable. Both lateral secretion by the metasomatic solutions leaching U from either uraniferous host granite or host (meta-) sediments or other rocks, or U concentrations in the residual magma are speculated. Size and grade of a deposit may be a function of availability of uranium, ground preparation and the duration of the metasomatic process. Pervasive metasomatism may cause wider distribution associated with dilution of the uranium throughout a large volume of rock. In contrast, narrow zones of metasomatism may have concentrated the uranium to form higher grade mineralization.

Remarks

The processes involved in metasomatism and related mineral formation are to some extent comparable with those leading to vein deposits.

The distinction between the two may be difficult. On the other hand, metasomatic deposits of subtype 12.1 commonly are within anomalously uraniferous granites which may be attributed to the intrusive type of deposits.

Both subtypes generally contain resources of small quantities ($<1000 \text{ mt U}_3\text{O}_8$) and low grade ($<0.2\% \text{ U}_3\text{O}_8$). Known exceptions are the deposits of Ross Adams, USA, Gunnar, Canada and Zhelty Vody (= Yellow Waters), Ukraine.

Note

Uraniferous Na-metasomatized lithologies have drawn much attention in the former USSR for many decades but have been largely neglected in the Western World until recently. The term *albitite deposits* in connection with uranium mineralization was used first by Russian authors. Thorough investigations of this type of uranium deposits were carried out by many of them, e.g., Kazanzky et al. (1968) Smirnov (1977), Kalyaev (1980). Early work in Canada by Robinson (1955) hints to a uranium paragenesis within albitic vein rocks in the Goldfields-region (Beaverlodge district), Saskatchewan. Christie (1953) and Dawson (1951, 1956) describe their veins consisting of microcrystalline aggregates of albite and quartz, stained with hematite associated with calcite and chlorite.

Fritsche (1986) has reviewed pertinent literature and defined types of albitites and related uraniferous albitites (see Chap. 2).

Up to the present, albitites are defined as primary magmatic rock types in most geological nomenclatures, although Goldschmidt (1911) already explained albitite veins as of pneumatolytic contact metasomatic origin. Sørensen (1974) defined albitites as rocks of plutonic character with mainly albite, about 10 vol. % of more calcic plagioclase, 5 vol. % of quartz and with olivine, augite, amphibole, and biotite as minor components. Sørensen (1974) considered the possibility of a secondary metasomatic origin for albitites in addition to a magmatic genesis. Albitization, as defined by Schieferdecker (1959) universally, is "the production, in a rock of albite, as a secondary product". Other definitions restrict albitization to the autometasomatic alteration of plagioclases in magmatic rocks only (e.g., Holmes 1928).

According to Kalyaev (1980), albitization is found in almost every rock type. Mostly it occurs in magmatic rocks but likewise in metamorphic and sedimentary rocks and in porphyry copper deposits. In most cases these autometasomatic, metamorphic or diagenetic albitization processes do not cause a complete alteration of the rock and do not lead to the formation of albitites.

Sarcia (1980) gives a summary concerning uranium in albitites and classifies these deposits as:

- anorogenic deposits associated with deep faults, without direct relation to magmatic rocks. Example: Deposits of the Ukrainian Shield (Smirnov 1977) or Alio Ghelle, Somalia (Cameron 1970);
- deposits in orogenic zones associated with faults accompanied by granitization and magmatism. Examples: Pleutajokk/Sweden (Adamek and Wilson 1977). Espinharas/Brasil (Ballhorn et al. 1981), Kitongo/Cameroon (Fritsche 1986);
- deposits bound to postorogenic fault systems within the basement and the metamorphosed cover. Example: Brousse-Broquiés, Aveyron Rouerque, France (Yerle 1978).

Uranium occurrences associated with alkaline bodies especially in relation to autometasomatically albitized or hydrothermally altered zones or late magmatic fractures where later, post-magmatic hydrothermal processes have been in operation are described by Mackevett (1963) and Thompson et al. (1980, 1982) from the peralkaline intrusion of Bokan Mountain/Alaska and by Sørensen (1970) from Ilimaussaq (Greenland). Similar zones are known from the intrusive bodies of Poços de Caldas/Brazil and Seal Lake/Labrador (Group 1970) or from the CIS (Kozlova and Gurvich 1979), from China and the Mongolian Peoples Republic (Saima Deposit Research Group 1976; Boguslavsky et al. 1966).

4.12.1 Subtype 12.1: Metasomatized granite

Type Example: Ross Adams/Bokan Mountain, USA

References: Collot 1981; Thompson et al. 1980, 1982

Host Rocks

Albitic aegirine granite, albitic arfvedsonite-aegirine granite, albitite derived by epigenetic Na-metasomatism along cataclastic zones in anomalously uraniferous granite. Transitional aureoles between metasomatized facies and parent rocks are commonly narrow. Spatial distribution of metasomatism appears to be restricted to structurally prepared zones in the apical part of a postorogenic or anorogenic pluton.

Pluton-internal shear, fracture and breccia zones confined to albitized facies commonly provide the site for mineralization.

Alteration

Two principal types of alteration can be distinguished:

- Na-metasomatism is characterized by albitization associated with desilicification and in the case of insufficient Al to form albite, by the formation of aegirine and/or arfvedsonite. Geochemical changes are enrichment of Na₂O and depletion of K₂O and SiO₂ (replacement of K-feldspar, Ca-rich feldspar and quartz by albite).
- Weak argillitization of feldspars including secondary albite, and locally intense hematitization. At Ross Adams, hematite imposes a pervasive red staining on microfractured albite and coats uraninite grains indicating a post-albite, post-uranium formation.

Ore and Associated Minerals

Uraninite ± Th rich, uranothorianite, uranothorite, thorite, some brannerite, and coffinite.

Allanite, bastnaesite, monazite, xenotime, galena, pyrite, magnetite, zircon, apatite, fluorite, and calcite in accessory amounts. Locally abundant hematite.

Mode of Mineralization

U minerals occur as disseminated anhedral to euhedral grains and in thin veinlets, with or without accessory pyrite, galena, fluorite, and galena within zones of closely spaced jointing and shearing and some brecciation in a metasomatized albite and aegirine granite. At Ross Adams, the mineralized rocks are related to

portions of the Bokan Mountain granite geochemically enriched, in Na₂O, Al₂O₃, U, Th, Nb and REE.

Age Constraints

No age constraints except restriction to periods of late- or post-orogenic magmatic activity.

Dimensions/Resources

Individual deposits (in brackets Ross Adams deposit) may be several meters to >100 m (ca. 110 m) long, several meters to more than 20 m (7.5–22 m) wide, and in excess of 100 m deep, containing few tens and up to ca. 1000 mt (850 mt) U₃O₈ at (average) grades ranging from <0.1 to >1% U₃O₈ occasionally to 3% U₃O₈. Districts may contain up to few 1000 mt U₃O₈.

*Examples of Metasomatite, Subtype 12.1**Metasomatized Granite Deposits/Occurrences*

Australia: ? Radium Hill/Willyama Block, South Australia

Canada: ? Gunnar/Saskatchewan

Brazil: Lagoa Real/Bahia

Cameroun: Kitongo

4.12.2. Subtype 12.2: Metasomatized metasediments

Type Example: Krivorozhsky-Zheltye Vody district/Krivoy Rog, Ukraine

References: Batashov et al. 1984; Kazansky and Laverov 1977

Host Rocks/Structures

Archean amphibolite and biotite gneiss intruded by quartz diorite and granodiorite form basement to Lower Proterozoic metasediments in the Zheltye Vody district. The Proterozoic suite includes three units, a lower schist-quartzite unit composed of micaceous quartzite, meta-arkose, uraniferous meta-conglomerate, schists and leptites; a middle taconite unit of amphibole-magnetite schist, biotite schist and Fe-rich (magnetite, hematite) quartzite; and an upper dolomite-leptite unit of dolomitic marble, quartzite, graphite-biotite and actinolite schist,

and metasomatic talc-carbonate rocks. Stocks and dikes of microcline granite have intruded along lineaments. Host rocks are folded into large isoclinal folds with steep axes and have repeatedly been strongly fractured.

Alteration

Intense metasomatism has altered metasediments and granites along lineaments. Four main phases of alteration are distinguished: Early Fe-Mg-metasomatism that generated stratiform iron ore bodies, Na-metasomatism, carbonate-metasomatism, and finally silicification that formed secondary quartzites. Products of Na- and carbonate-metasomatism are listed below.

Ore and Associated Minerals

U minerals include uraninite, pitchblende, coffinite, brannerite and nenadkevite. Four principal U-associated mineral assemblages are discerned: (1) apatite-malacon (uraniferous apatite, zircon/malacon, sphene); (2) amphibole-nenadkevite (nenadkevite, brannerite); (3) carbonate-uraninite (uraninite I) and amphibole-aegirine (regenerated uraninite I); and (4) sulfide-pitchblende (pitchblende, coffinite, uraninite II) (Zhukova 1980).

Mode of Mineralization

Economic U mineralization is restricted to Na- and carbonate-metasomatite zones in the middle and upper Proterozoic units. Mineralization occurs in fractured sections at flexures in limbs and in the axial zone of folds in form of lenses, shoots, stratiform bodies in which U minerals are finely disseminated and associated with dark-colored minerals, and as veins. Batashov et al. (1984) distinguish four lithologic mineral settings based on parental heritage,

- a) albitites with alkaline amphibole, aegirine and uraninite, brannerite, and pitchblende derived from biotite, graphite-biotite schists, and granite dikes,
- b) magnetite-riebeckite rocks, aegirinites, martite-carbonate-metasomatites with uraninite derived from iron ores, amphibole-magnetite schists and ferruginous quartzites,
- c) talc-carbonate rocks containing uraniferous apatite-malacon with Th and REE,
- d) pitchblende-coffinite veins.

Age Constraints

Age of U mineralization at Zheltye Vody is about 1770 m.y. but it can be assumed that mineralization can take place at any time of magmatic or metamorphic (?) activity.

Dimensions/Resources

U mineralization at Zheltorechenskoe/Zheltye Vody extends laterally along a large, steeply dipping fold for 1500 m on the W limb, 900 m on the E limb and 700 m in the keel of the fold. It persists to a depth of ca. 2000 m. U hosting metasomatites are tens of meters wide. They decrease at depth below about 1000 m associated with disappearance of uraninite which gives way to uraniferous malacon-apatite.

Examples of Metasomatite, Subtype 12.2 Metasomatized Metasediments Deposits/ Occurrences

Canada: Mosquito Gulch/Nonacho, NWT, parts of Pronto/Blind River-Elliot Lake, Ontario

Brazil: Espinharas/Paraiba

Finland: Kouvervaara/Kuusamo Schist Belt

4.13 Type 13: Synmetamorphic (Fig. 4.13)

Definition

Synmetamorphic uranium mineralization consists of disseminated uranium distributed strata-concordant in more or less continuous lenses or erratically scattered patches within metasediments and metavolcaniclastics. Principal uranium phases are uraninite typical for higher grade metamorphic facies and pitchblende prevailing in low-grade (greenschist) facies.

Type Example: Forstau, Austria

Reference: Dahlkamp and Scivetti 1981

Principal Recognition Criteria

Host Environment

– Metasediments: phyllites, schists, gneisses partly carbonaceous (graphitic), phosphatic or

Type 13. SYN METAMORPHIC

(stratiform U disseminations in unaltered metasediments and metavolcaniclastics)

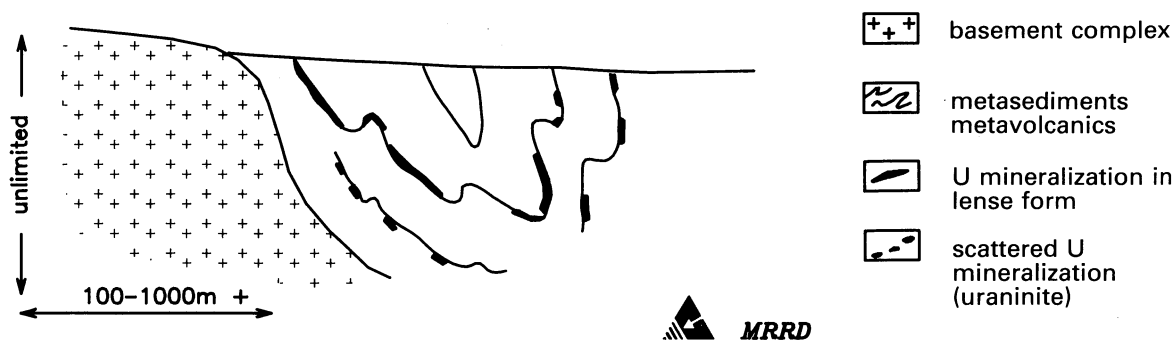


Fig. 4.13

pyroxenitic, derived from pelites, psammites and associated sediments with or without tuffaceous interbeds of eugeosynclinal or lacustrine origin, metamorphosed to from greenschist to amphibolite grade

- Metavolcaniclastics: metamorphosed felsic to intermediate, dominantly rhyolitic volcaniclastic horizons which may be interbedded with clastic sediments

Alteration

- No or only very minor alteration related to mineralization
- No or only minor metasomatism of host rocks

Mineralization

- Principal uranium minerals: uraninite and/or pitchblende
- Some U in lattice or on cleavage planes of various rock constituents such as apatite, biotite, amphibole
- Associated minerals: locally some Mo, Ni, Pb, Zn, a.o. as sulfides, sulfarsenides, etc.; metavolcaniclastics often with Mo enrichments
- U minerals occur disseminated in lenses or in minute to small pockets scattered in favorable lithologies
- Only lithologic, no structural control

Age Constraints

No age constraints other than to orogenies of Lower Proterozoic to recent age.

Metallogenic Aspects

Synmetamorphic uranium occurrences appear to result from regional metamorphism of uraniferous sediments or volcanics within a closed system, remote from intrusions, anatectic centers, or metasomatic fronts. Depending on crystallization conditions, the sedimentary uranium became transformed in situ either to pitchblende, which is prevalent in lower grade metamorphic environments or uraninite prevailing in higher grade metamorphic lithologies.

Dimensions/Resources

Synmetamorphic uranium occurrences are most commonly of low grade (0.001–0.1% U_3O_8) and contain small resources of subeconomic magnitudes (kg to 1000 mt U_3O_8).

The most common occurrences are spotty mineralizations. These mineralizations are discontinuously spread over many km^2 in favorable horizons. They locally achieve high grade. The mineralizations are small in dimensions ranging from mm to m in lateral and vertical extension and exhibit erratic distribution.

Remarks

Synmetamorphic mineralizations make favorable uranium source rocks or protore for other types of deposits rather than feasible exploration targets.

Examples of Type 13 Synmetamorphic Deposits/Occurrences

Australia: ? Mary Kathleen/Queensland
 Canada: Duddridge Lake/Saskatchewan, Amer Lake/NWT, Kitts/Makkovik, Labrador, Mont Laurier/Quebec
 Finland: Nuottijärvi/Paltamo, Lampinsaari/Vihanti (Proterozoic metamorphosed phosphorite)
 Germany: Höhenstein/Bavaria
 Madagascar: Ambindrakemba/Fort Dauphin
 Togo: Lama Kara/Niamtougou
 USA: Kettle Falls Gneiss Dome/Orient, Washington state.

Principal Recognition Criteria

Host Environment

- Lignitic sediments of paludal, limnic or paralic origin
- Generally thin lignitic beds
- Coalification less than bituminous grade
- Pyrite and high ash content
- Intraformational unconformities
- Certain degree of jointing and fracturing
- Lignitic seams interbedded or overlain by acid pyroclastics (rhyolitic tuffs, etc.) containing anomalous contents of U
- Basins surrounded by granites or other rocks with anomalous U contents

4.14. Type 14: Lignite (Fig. 4.14)

Definition

Lignite-related uranium mineralization consists of paludal material composed of a high percentage of land plant debris mixed with detritus coalified to not higher than subbituminous grade and containing either trace to minor amounts of syndimentary, uniformly disseminated uranium or epigenetic, irregularly distributed structurally controlled uranium, the uranium being adsorbed in both cases on carbonaceous matter. Accordingly two subtypes are distinguished:

Mineralization

- No discrete primary U minerals (locally secondary hexavalent U minerals)
- U adsorbed on carbonaceous matter or as uranyl-humate
- Syngenetic U stratiform and persistent but commonly of low values (few 10 ppm)
- Spotty and irregular epigenetic U mineralization of better grade (up to 0.4% U₃O₈) controlled by joints, fracture systems
- U often bound to upper section of the lignite below intraformational unconformities
- Host beds of mixed vegetal carbonaceous and mineral detritus (silt, clay) yielding high ash content
- Thin lignitic host beds (<2 m)
- Often associated with a variety of metallic trace elements

Subtype 14.1: joint-fracture-related

Subtype 14.2: stratiform

Type Example: southwestern Williston Basin, N and S Dakota, USA

Reference: Denson and Gill 1965

Age Constraints

- Time constraint by emergence of land plants, i.e., younger than Devonian

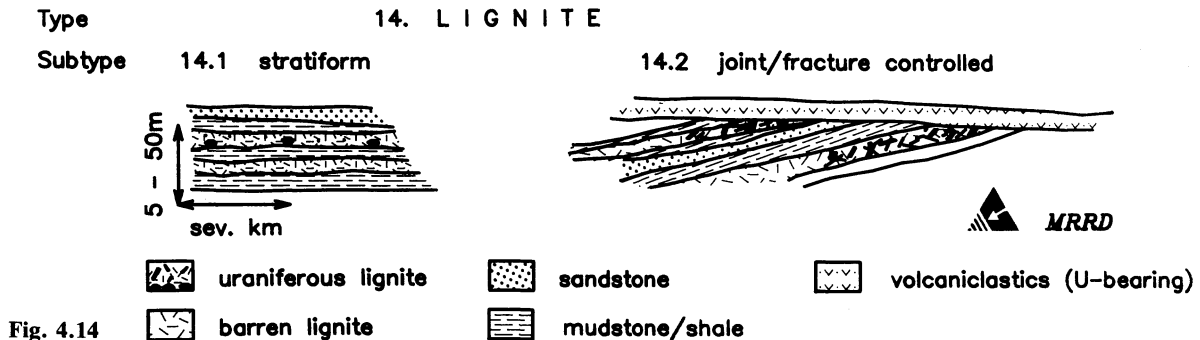


Fig. 4.14

- Lignites, particularly those of Late Cretaceous and younger origin are more favorable; older lignites may have suffered a higher degree of coalification, an apparently negative process hampering epigenetic U mineralization

Metallogenetic Aspects

Lignite, coal, and carbonaceous mud-siltstone are favorable sites for U accumulation when they originated from paludal, low-lying poorly drained shallow depressions with abundant vegetation located either on coastal plains (paralic lignite) or within land-locked basins (limnic lignite). U supposedly originated from either granites, volcanics or other rocks that border the depressions or from interbedded or overlying pyroclastics containing anomalous amounts of U. U is thought to have been leached from these sources. U transport into the basins has been (a) either by surficial waters with precipitation by syndimentary adsorption on organic material (as today found in swamps and bogs in adequate environment, e.g., Stevens County, Washington) to form syngenetic mineralizations, or (b) postsedimentary by groundwater migration into buried basins to form epigenetic mineralization. Infiltration in the latter case occurred along permeable zones, dominantly joint and fracture systems, hence the irregular U distribution. Precipitation of U resulted from adsorption on organic material along dishomogeneities, mainly joints, fractures, more silty intercalations and intraformational unconformities.

Remarks

Uraniferous lignites constitute only potential U resources. Deposits are commonly either too small or of too low grade. The latter is particularly true for stratiform syngenetic deposits (type 10.1) whereas type 10.2 deposits may locally contain noteworthy U tenors.

In addition, uranium extraction is hampered by its binding in organic compounds creating an almost refractory nature for metallurgical extraction.

Examples of Type 14 Lignite Deposits (Not Differentiated)

ČSFR: Sokolov and Trutnov basins/Bohemia
Greece: Serres Basin, Kotili Basin
Germany: Stockheim/Bavaria, Freital/Saxony
South Africa: Springbok Flats-Karoo Subbasin/Transvaal

4.14.1 Subtype 14.1: Joint-fracture-related

Type Example: Slim Buttes, southwestern Williston Basin, S-Dakota, USA
Reference: Denson and Gill 1965

Host Rocks/Alteration/Structures

Pyritic, high-ash lignite, subbituminous coal and nonmarine carbonaceous mud-siltstone. The latter contains abundant plant debris, scattered throughout the rock but preferentially concentrated along bedding planes. Sulfides, dominantly pyrite, are typical, as is a high ash content. The carbonaceous sediments are often interbedded or overlain by uraniferous acid pyroclastic sediments (rhyolitic tuffs etc.) or sandstones. Jointing and fracturing is common. No alteration. Some of the mineralized lignites are in basins bordered by granites or other rocks containing anomalous amounts of U.

Ore and Associated Elements/Mode of Mineralization/Dimensions/Resources

No discrete primary U minerals have formed. Locally secondary hexavalent U minerals occur in joints and fractures. U is adsorbed on carbonaceous matter or bound in organic compounds (e.g., uranyl humate) particularly in cataclastic zones. Other metals present in anomalous amounts but not necessarily correlative with U may include As, Be, Cd, Co, Cu, Ge, Mo, Ni, Pb, Se, Ti, V, Y, Zr and/or REE. Mineralization is spotty and irregularly distributed with strong variations of tenor. Grades are commonly a few hundred ppm U and rarely 0.1% U₃O₈ or more. Thinner seams (cm to less than 1 m) may be mineralized ubiquitously, whereas in thicker seams only parts thereof are mineralized, often restricted to their top. Intraformation unconformities often control U accumulations. Resources vary between <1 mt U₃O₈ to few 100 mt U₃O₈.

4.14.2 Subtype 14.2: Stratiform

Type Example: Slim Buttes, southwestern Williston Basin, S-Dakota, USA
 Reference: Denson and Gill 1965

Host Rocks/Mode of Mineralization

Host rocks and geological setting are more or less identical with those of subtype 14.1 except that interbedded uraniferous volcanoclastics or sandstones may not be present. Uranium is adsorbed on carbonaceous and clayey material and/or bound in organic ionic compounds, e.g., uranyl-humate, and occurs stratiform disseminated throughout the carbonaceous/lignite horizon. Associated elements are similar to those of subtype 14.1. Uranium tenor is generally very low, amounting rarely to more than 50 ppm U.

4.15. Type 15: Black Shale (Fig. 4.15)

Definition

Black shale-related uranium mineralization consists of marine organic-rich shale or humic/coal-rich pyritic shale, containing syndimentary stratiform, uniformly disseminated uranium adsorbed on organic material and clay minerals. Based on the organic substances two subtypes are distinguished:

Subtype 15.1: bituminous/sapropelic black shale

Type Example: Chattanooga, USA

Subtype 15.2: humic/kolm in alum shale

Type Example: Ranstad, Sweden

References: Bell 1978; Carlsson and Nojd 1977; Kim 1988; Mutschler et al. 1976

Principal Recognition Criteria

Host Environment

- Very fine-grained black shales with high contents of organic matter, pyrite and/or marcasite, evenly laminated, dense, may contain thin coalified, phosphatic and/or silty intercalations
- Interbedded with limestone, sand/siltstone and shale beds
- Fairly uniform shale thickness, commonly a few meters and up to some 10 m
- Widespread extension of black shale over several 100's to 10 000's km²
- No ore-related alteration

Mineralization

- No discrete primary U minerals (except locally secondary hexavalent U minerals), instead U is adsorbed on organic and clay particles
- Very low grade mineralization ranging from 50 to 400 ppm U

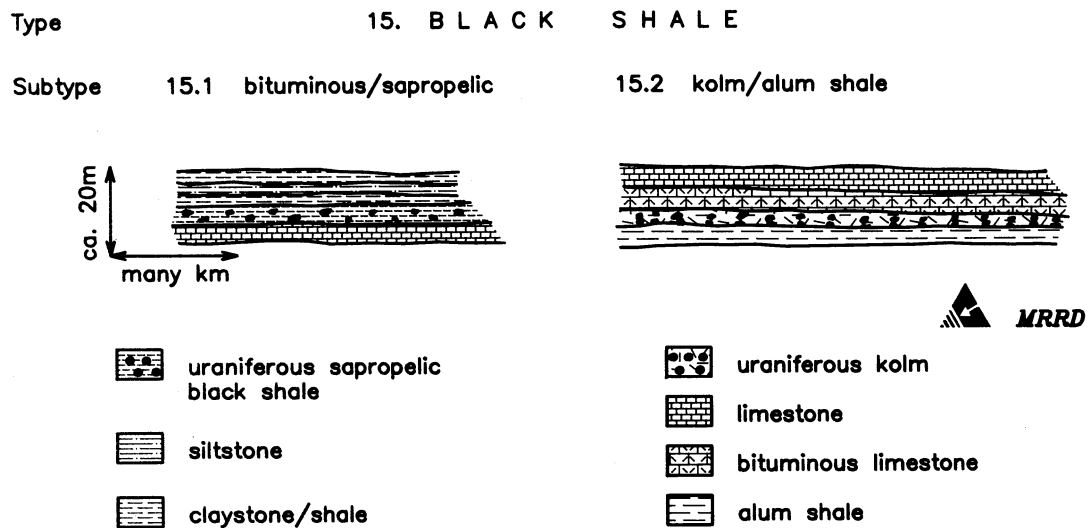


Fig. 4.15

- U disseminated uniformly throughout and coextensive with individual beds over large areas, with different beds commonly having different U tenors
- Better grades in certain beds (dm to m thick) either rich in organics, particularly of vegetal provenance, and/or sediments very fine-grained, or finely laminated or containing phosphatic minerals (e.g., kolm: 380 ppm U)
- Presence of small quantities of other metals (Cu, Cr, Mo, Mn, REE, V and P)

Age Constraints

No age constraints but deposits occur dominantly in Phanerozoic formations particularly of Paleozoic age.

Metallogenetic Aspects

Black shales of marine origin were deposited in shallow, partially closed epicontinental basins within continental terrane tectonically stable for a long period. The depositional environment is characterized by a low rate of sedimentation, brackish to normal marine salinities, anaerobic, strongly reducing conditions, formation of sapropelic-bituminous, and humic, coaly matter from planktonic marine algae and land plant (wood spores) debris.

Synsedimentary deposition of U from seawater by adsorption dominantly on organic matter with particular concentrations in humic-coaly material. If phosphate nodules are present, they normally collected more uranium than the surrounding shale.

Remarks

Black shales, although widespread in the world and hosting enormous quantities of uranium (many million tonnes) constitute only potential U resources. U is perhaps extractable as a by-product of oil, or other metals recovery.

Examples of Type 15 Black Shale Deposits (not differentiated)

China: Jiangnan Block/SE China
South Korea: Ogcheon Group
Russia: Lake Onega region

4.15.1 Subtype 15.1: Bituminous-sapropelic black shale

Type Example: Chattanooga, USA

References: Mutschler et al. 1976; MSR & D 1978

Host Rocks/Alteration/Structures

The Gassaway Member, the upper unit of the Devonian-Mississippian Chattanooga Shale is the main host for uranium. It consists of massive, grayish-black shale with paper-thin partings of silt and films or bands of pyrite and marcasite. About 20 wt. % of the shale is organic material (saprolite, vitrain, bituminous coal) derived mainly from planktonic marine algae and less from land plant debris. The organics fill interstices and coat the minute rock grains of the shale. No structures or alteration are present.

Ore and Associated Elements/Mode of Mineralization/Dimensions/Resources

U distribution is stratiform, adsorbed mainly on organic and to a lesser extent on clay particles. MSR & D (1978) report from a test area in Dekalb County, Tennessee: 55–65 ppm U, 230 ppm Co, 530 ppm Ni, 200 ppm Mo, 1360 ppm V₂O₅, 8600 ppm S and 9 gal/sh.t. of syncrude oil.

Lateral extension of Chattanooga Shale is in the order of 80 000 km², averaging about 10 m thick and a mean grade of 57 ppm U. Estimated resources are at least 4 to 5 million tonnes U (calculated for a restricted area of 12 counties in central Tennessee by Mutschler et al. (1976).

4.15.2 Subtype 15.2: Humic/kolm in alum shale

Type Example: Ranstad, Sweden

Reference: Carlsson and Nojd 1977

Host Rocks/Structures/Alteration

Principal U-host is the kolm horizon within black bituminous alum shale of Cambrian age. The flat-lying black shale unit rests on Cambrian sandstone and is covered by Ordovician Limestone.

Ore and Associated Elements/Mode of Mineralization/Dimensions/Resources

U distribution is stratiform, adsorbed on organic matter and in particular on kolm nodules. The kolm contains about 30% ash. Nodules may contain up to 80% organics and up to 0.4% U. Average values for the kolm horizon are: 300 to 380 ppm U (alum shale ca. 200 ppm U), 22% organic material, 13% pyrite, 6.5% S, 0.065% V, 0.03% Mo, 0.02% Ni, 0.4% Mg, 0.7% P, and high Al and K contents.

Lateral extension of the kolm-bearing alum shale is about 500 km². Thickness of the alum shale is 15 m and the kolm horizon varies from 2.5 to 4 m. Assuming an average grade of 200 to 300 ppm U₃O₈ the Ranstad occurrence is estimated to contain 300 000 mt U₃O₈, including 75 000 mt U₃O₈ averaging about 350 ppm U₃O₈.

4.16 Type 16: Strata-Controlled, Structure-Bound

Type Example: Ronneburg District, Thuringia, Germany

Reference: Lange, Schuster, Weise, Gradowski pers. commun.

Definition

Strata-controlled, structure-bound uranium deposits consist of uranium concentrations in minifractures which form stockworks within or immediately adjacent to carbonaceous, pyritic black shales.

Principal Recognition Criteria

Host environment

- Argillaceous and siliceous black shales with intercalations of dolomitic and phosphorite nodule beds (Graptolitschiefer)
- High organic carbon (up to 9% C), sulfide (up to 3.5% S) and anomalous trace element (U, Mo, Ni, V, As, Sb) contents in the black shale
- Carbonaceous sandy and carbonatic shales (Lederschiefer) underlie, and limestone-

dolomite (Ockerkalk) overlie the main black shale horizon

- Pre-orogenic diabase dikes and sills cut the sedimentary sequence
- Marked tectonic imprint reflected by complex folding, pronounced faulting and thrusting, and high density of minifractures (fissures, joints, cleavages)
- Sediments are not or only weakly metamorphosed

Alteration

- Silicification, chloritization, dolomitization
- Narrow aureoles of bleaching and hematitization (few centimeters wide) around mineralized structures
- Carbonatization and sulfatization in form of narrow fissure fillings
- Post-orogenic (post-Hercynian at Ronneburg) supergene oxygenation (reddening of rocks due to Fe-oxide, Fe-hydroxide formation) associated with partial mobilization of trace elements in subsurface (below Permian paleosurface) and further downwards along major faults
- Formation of cementation zone below the oxidation zone

Mineralization

- Older pitchblende associated with Mg-Fe-carbonates, chlorite, subordinate sulfides, rare coffinite, tennantite
- Younger pitchblende, bravoite, marcasite, Ni-Co-arsenides, hematite, calcite, dolomite
- (Sooty) pitchblende associated with pyrite (no gangue minerals)
- U minerals predominantly fill, coat and impregnate minifractures (joints, cleavages) which are arranged in a stockwork-like pattern within distinct lithologic units
- Porous wall rocks may contain disseminated mineralization for short distances from mineralized fractures
- Distribution and concentration of U in the fractures is highly variable
- Mineralized fractures group to stockwork-type ore bodies, which occur irregularly distributed within weakly mineralized zones
- Position, size and shape of ore bodies are controlled by faults, particularly by intersections of faults

- U mineralization occurs below the lower boundary of the oxidation zone from where mineralization can be found over a vertical interval of about 400 m

Age constraints

- No principal constraints with respect to the age of the host strata but known deposits occur in Eocambrian and Paleozoic sediments
- Geological evidence suggests that the principal ore formation coincided with periods of marked oxidizing climatic conditions (Rotliegend/Permian at Ronneburg, Cretaceous to Tertiary in South China)

Metallogenetic Aspects

Strata-controlled, structure-bound uranium deposits tend to be of polyphase origin involving the following stages:

1. Synsedimentary accumulation of uranium and other metals in favorable sediments such as black shales (at Ronneburg Middle Devonian Tentaculitenschiefer and Silurian Upper and Lower Graptolitenschiefer).
2. Perhaps but not necessarily limited redistribution of uranium by metamorphic processes (at Ronneburg during the Hercynian Orogeny reflected by elevated U concentrations of ca. 100 ppm U in certain anticlinal structures as compared to a synsedimentary inventory of about 50 to 60 ppm U).

These uraniumiferous (meta-) sediments provided the primary U source.

At Ronneburg, a supplement U source is present in form of pitchblende veinlets of supposedly late to post-orogenic hydrothermal origin.

3. Ore grade uranium concentration by a combination of
 - structural ground preparation,
 - deep reaching weathering in a semiarid to arid climate associated with liberation of uranium by infiltration of oxygenated meteoric waters into the U source rocks,
 - fluid mobilization supposedly in response to tectonic activity and/or intrusion of igneous dikes (lamprophyres, porphyries) resulting in circulation of the U pregnant solutions down-

ward along permeable structures into reduced sediments, and

- precipitation of uranium in form of pitchblende mainly in subsidiary minifractures within the cementation zone.

After this ore forming event, supergene processes may have remobilized the uranium again (at Ronneburg at about 210–190 m.y. and 120–90 m.y. which are consistent with redistribution or introduction episodes of uranium in other deposits in central and western Europe).

Typical Dimensions/Resources

At Ronneburg, mineralized zones are up to several hundred meters long and wide and up to several ten meters, rarely in excess of 100 m thick. They enclose irregularly shaped ore bodies that vary from 20 to 500 m long, from few meters to few hundred meters wide and from less than 2 m to 100 m thick. In situ U contents range from 0.085 to 0.17% U₃O₈. Resources are in the order of 200 000 mt U₃O₈ contained in an area of 164 km².

Examples of Type 16 Strata-Controlled, Structure-Bound Deposits/Occurrences

China: Chienxinan/SW Guizhou; Chanziping/N Guangxi; Pukuitang/Hunan, Chengxian/Guangxi-Hunan-Guangdong region, SE China; Norgai/S Qinling area, Central China
Uzbekistan: Koscheka, Dzhanthuar/Kyzylkumsky, Navoi region

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