

Part I



Typology of Uranium Deposits

Introduction

A variety of global and regional classification schemes for uranium deposits have been proposed in the past by a number of geoscientists including Heinrich (1958), Roubault (1958), Ruzicka (1971), Ziegler (1974), Mickle and Mathews (1978), Mathews et al. (1979), Nash et al. (1981), Barthel et al. (1986), Dahlkamp (1989, 1993), McKay and Mieztis (2001) mainly for deposits in the western hemisphere and by Kazansky and Laverov (1977), Boitsov (1989, 1996), Stoikov and Bojkov (1991), Petrov et al. (1995, 2000), Mashkovtsev et al. (1997), Terentiev and Naumov (1997), and others for deposits in CIS (former Soviet Union) and associated countries.

Although these classification schemes remain largely valid, more recent information on uranium deposits, particularly in the former eastern block countries and new research data on earlier established and defined types of uranium deposits justify a rearrangement and refinement of the classification scheme, which is presented further below in abbreviated form.

The classification chapter is not restricted to types of economic deposits but includes types with marginal to no economic potential as well. Knowledge of these types are thought to be equally important as economic types, particularly in exploration, in order to recognize and understand criteria typical for subeconomic mineralization ranging in size from small mineralogical showings to almost economic occurrences in order to comprehend somewhat similar economic deposits and their parameters.

While many authors in the western hemisphere prefer a descriptive, typological classification with emphasis on geological setting and ore characteristics, authors of the CIS (former Soviet Union) and associated countries as well as China based their deposit classification systems primarily on metallogenetic aspects (unfortunately often without furnishing type examples of deposits, which hampers the matching of deposit types of the two systems).

In many cases, however, open questions still remain with respect to the specific provenance of (1) ore forming uranium and related solutions, (2) conditions of uranium mobilization, transport, and redeposition, and (3) repetitive redistribution. For these academic as well as practical reasons such as exploration, a typology based primarily on descriptive data has been given preference in order to provide a synopsis of principal criteria of deposit types to the benefit of economic geologists. The criteria may serve to determine target types in virgin regions and also to evaluate the economic significance of interim exploration results through correlation with established U districts and/or deposits.

The terminology selected for types and subtypes refers primarily to the host environment or geotectonic setting of the discussed type. On this basis, twenty principal types of uranium

deposits are distinguished. They include some forty subtypes and classes. Subtypes and classes have certain mutual parameters 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 characteristics of subtypes* and *prominent classes*. 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 as well as avoidance of confusion. Metallogenetic aspects have not been addressed and the reader is referred to respective synoptic descriptions in Dahlkamp (1993) and publications by other authors or to the documentation of individual districts and deposits presented in this volume.

The description also includes selected references, though not exclusively, of authors who 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.

Illustrations (► Figs. 1.1–1.20) are added to furnish schematic presentations of the geological setting of the various types, subtypes, and classes of deposits.

Finally, definitions and type descriptions offered by the author in this chapter are his own interpretations, though strongly influenced by discussions with many colleagues, of data collected in the field and from pertinent literature study, but they must not necessarily represent the final and correct version. The reader is therefore strongly encouraged to study the literature cited as references to form his own opinion, which may be contrary to the one presented here.

Definitions

Deposit: In the following classification scheme this term is not restricted to economic U deposits but in a broader sense to signify all U concentrations with U tenors distinctly elevated above common background U values of a corresponding (host) rock type.

Resources of deposits: small = <5 000 t U; medium = 5 000–20 000 t U, large = >20 000 t U. **Ore grades** (given as average of deposits): low = <0.15% U, medium = 0.15–0.5% U, high = >0.5% U.

Resource, production, and grade figures of type examples are best estimates based on published data and personal communication.

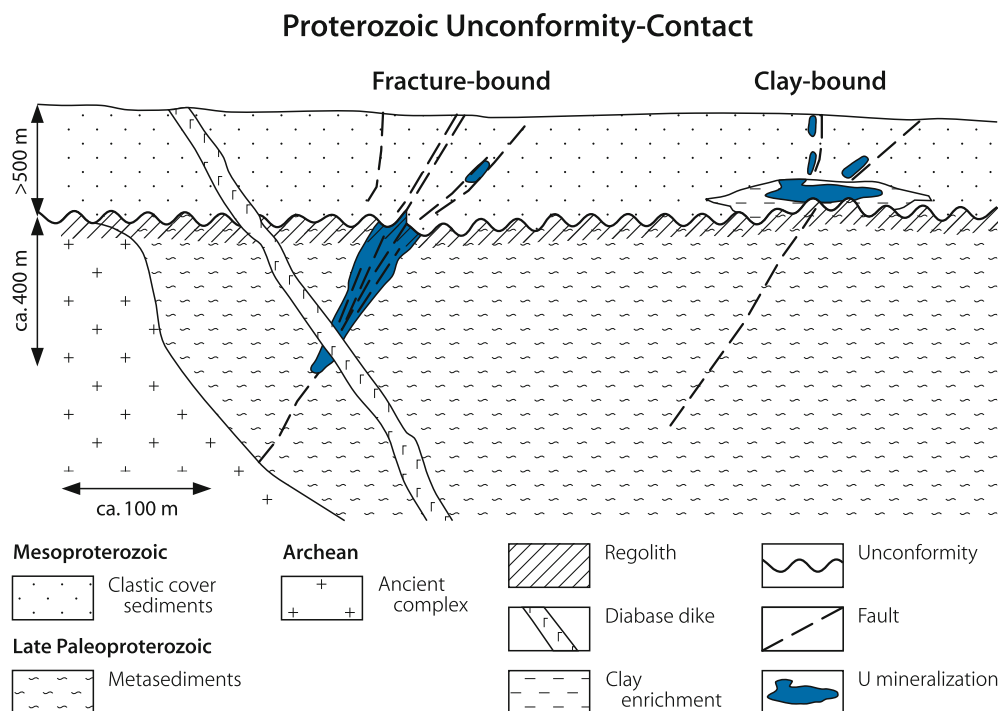
For more information see Sect. *Geological, Mineralogical, Mining, and Related Terms*.

Remarks

The formerly used “Vein Type” (which referred to granite-related and undifferentiated deposits) was abandoned as a principal deposit type since it causes confusion with other deposit types.

■ Fig. I.1.

U-deposit Type 1: unconformity-contact U deposits



Veins are not only associated with granites but also with volcanics or metasomatites, and they also occur in metasediments and sediments without any obvious link to a magmatic or metasomatic complex. Taking this into account, the term “vein” is now only used to describe the configuration of ore bodies in any respective geological environment as known from deposits grouped in types 4 to 7.

The term vein as used in types 4 to 7 deposits refers to true or classical veins composed of ore and gangue minerals that occur in the form of linear lenses, pockets, or disseminations in fissures, breccias, and stockworks in fractured rocks. Size and complexity of vein sets are variable. Distribution and intensity of mineralization are unpredictable. The bulk of vein material consists mainly of gangue while ore shoots occupy only from few percent to rarely 50% of the vein structure.

Principal uranium phases include pitchblende, uraninite, coffinite and/or alteration products thereof. Gangue minerals consist predominantly of quartz and/or carbonates. Uranium mineralization can be monometallic (without economic byproducts) or polymetallic (with at least one other metal as economic byproduct). The latter mainly includes Co, Ni, Bi, Ag, Cu, Pb, Zn, and/or Mo in the form of sulfides, arsenides, or sulfo-arsenides. Fe-sulfides or Fe-(hydro)-oxides are always present. Ore-related wall rock alteration is commonly restricted to a narrow margin (<1 m).

Type 1 Unconformity-Contact U Deposits (Fig. I.1)

Unconformity-contact deposits occur at and immediately above and below an unconformable contact that separates a crystalline

basement intensely altered by lateritic paleoweathering from overlying redbed-type sediments. All major deposits are of *Mesoproterozoic* age and represented by deposits in the Athabasca region, Canada. Some minor *Phanerozoic* deposits such as Le Roube are known from the southwestern Massif Central, France.

Subtype 1.1 Proterozoic Unconformity-Contact U Deposits (Athabasca Type)

Proterozoic unconformity-contact U deposits occur in a terrane of Lower Proterozoic metasediments with intercalated graphitic horizons that mantle Archean granite-gneiss domes. Middle Mesoproterozoic redbed-type arenaceous sediments rest upon this basement. The basement exhibits intense lateritic paleoweathering, and basement and overlying rocks show strong alteration effects associated with mineralized zones. Two varieties of deposits are known: (a) Clay-bound immediately overlying and (b) fracture-bound below the unconformity. Principal U minerals in both classes are pitchblende, uraninite, coffinite, minor brannerite, and some amorphous uranium-carbon material (carburan).

References general: Dahlkamp 1993; Jefferson et al. 2007; Jefferson and Delaney et al. 2007; Fogwill 1985; Hoeve and Quirt 1984; IAEA/Ferguson (ed) 1984; IAEA/UDEPO 2007; Lainé et al. (eds) 1985; Roy et al. 2006; Sibbald 1988; Sibbald and Petruk (eds) 1985; Sibbald and Quirt 1989; Thomas et al. 2000; Tremblay 1982.

a Clay-Bound

Clay-bound deposits are associated with massive clay and occur directly upon the Mesoproterozoic unconformity. Mineralization is commonly polymetallic composed of U with sulfides, arsenides, sulfo-arsenides, locally selenides and tellurides of Ni, Pb, and other metals; gangue minerals are mainly quartz and carbonates. The ore minerals range from disseminated to often massive in tabular to lenticular horizontal ore bodies in clay and argillic sandstone. Some mineralization extends along fractures into overlying sandstone and underlying metasediments. Resources range from small to very large and grades are very high (few 100 to >200 000 t U; 1–20% U).

Type examples: (a) Cigar Lake, Athabasca Basin, Canada (Resources: 135 000 t U, 15.3% U). *References:* Bruneton 1987, 1993; Fouques et al. 1986; (b) Key Lake, Athabasca Basin, Canada (Production 73 900 t U, 2.0% U). *References:* Ruhrmann 1986.

b Fracture-Bound

Fracture-bound deposits are hosted in metasediments immediately below the Mesoproterozoic unconformity. Mineralization is dominantly monometallic and occurs disseminated to massive in structures within Lower Proterozoic metasediments. Depths extension can be in excess of 400 m below the unconformity. Resources range from small to large and grades from medium to (rarely) high (few tens to 25 000 t U; 0.15–2% U).

Type example: Eagle Point, Athabasca Basin, Canada (Resources + Production: ~24 000 t U, 1.2% U). *References:* Eldorado Resources Ltd. 1987; Heine 1986.

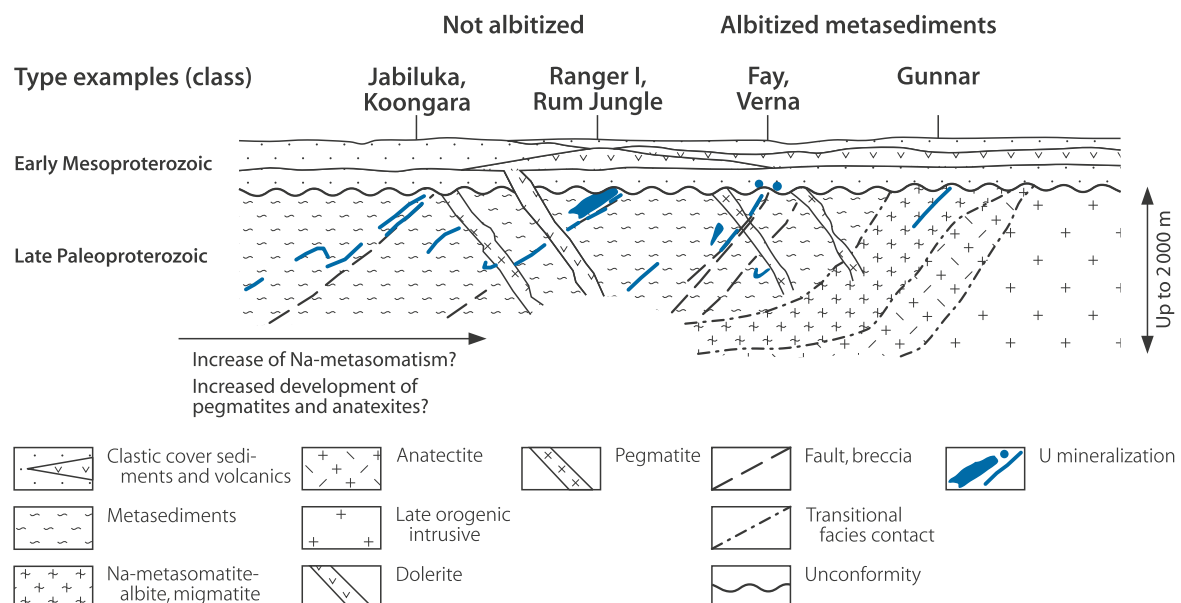
Subtype 1.2 Phanerozoic Unconformity U Deposits (Le Roube Type)

Type examples are known from the SW Massif Central, France, in an environment of Permo-Carboniferous clastic sediments with some volcanic components resting upon the post-Hercynian unconformity on altered Upper Proterozoic to Lower Paleozoic schists and gneisses containing minor graphitic horizons. Host rocks exhibit various alteration phenomena including variable redox conditions in the cover sediments. U minerals occur as disseminations and fine veinlets forming small ore bodies along the post-Hercynian unconformity most commonly where the unconformity is transected by faults. Resources are small and grades low (few tens to ca. 2 000 t U, 0.1–0.15% U).

Type example: Le Roube/Brousse-Broquiès Basin, Massif Central, France (Resources: ~2 000 t U, 0.1–0.15% U). *References:* George 1985; Schmitt and Clement 1986. (Remark: Although of minor economic significance, these deposits tend to indicate that unconformity related deposits could have formed at any time as long as the litho-stratigraphy, geotectonic, geochemical, and paleoclimatic conditions permitted the evolution of ore forming processes as known from the Athabasca region.)

Fig. I.2.

U-deposit Type 2: Proterozoic subunconformity-epimetamorphic U deposits Strata-structure bound in Late Paleoproterozoic metasediments (Alligator Rivers type)



Type 2 Proterozoic Subunconformity- Epimetamorphic U Deposits (Alligator Rivers Type) (Fig. I.2)

Deposits in the Alligator Rivers ore field, Australia, which provide the type example, are strata-structure bound in Paleoproterozoic metasediments. They abut against a Late Paleoproterozoic unconformity upon which clastic sediments rest (Kombolgie Formation). Mineralization is monometallic composed of pitchblende, uraninite, minor coffinite, brannerite, locally thucholite, associated with some Fe-, Pb-, Cu-sulfides and traces of other metals; hematite is relatively common. Gangue minerals include chlorite, quartz, sericite, and minor carbonates. The ore minerals occur as relatively continuous, peneconcordant, strata-bound fracture and breccia filling within distinct Lower Proterozoic metasediment horizons. Migmatitic-granitic complexes occur nearby. Wall rocks are strongly altered. In contrast to the Athabasca deposits (Type 1), deposits in the Alligator Rivers ore field occur under a Late Paleoproterozoic unconformity, and the basement was only moderately affected by paleoweathering. Deposits have large resources and low to medium grades.

Type example: Jabiluka/Alligator Rivers ore field, NT, Australia (Resources: 173 000 t U, 0.33% U). **References:** Binns et al. 1980; Ewers and Ferguson 1980; Ferguson and Goleby (eds) 1980; Hancock et al. 1990; Hegge et al. 1980; IAEA/Ferguson (ed) 1984; IAEA/UDEPO 2007; McKay and Mieizitis 2001; Needham et al. 1988; Polito et al. 2005; Wilde 1988. (Note: Deposits in the Beaverlodge District, Saskatchewan, Canada, exhibit to some extent a similar geotectonic setting as deposits in the Alligator Rivers ore field. They also abut against a Late Paleoproterozoic unconformity and the basement was also only mildly affected by paleoweathering. The major difference is their distinct vein-type configuration and their lithological setting; they are hosted in albitized metasediments. As such, the Beaverlodge veins may be considered a subtype of subunconformity-epimetamorphic deposits but they may also

be attributed to undifferentiated (meta-)sediment hosted U vein deposits/Type 7.)

Type 3 Sandstone U Deposits (Fig. I.3)

Sandstone uranium deposits are confined to continental fluvial or marginal marine (mixed fluvial-marine) environments. Uranium occurs disseminated in reduced sandstones ($\pm$ arkosic) that are mostly flat-lying ($<5^\circ$) unless affected by post-ore tilting and are interbedded with and bounded by less permeable sediments. Impermeable shale/mudstone units often overlie and underlie mineralized sandstone beds. Tuffaceous sediments may be (particularly at better grade deposits) but not always interbedded in the stratigraphic column.

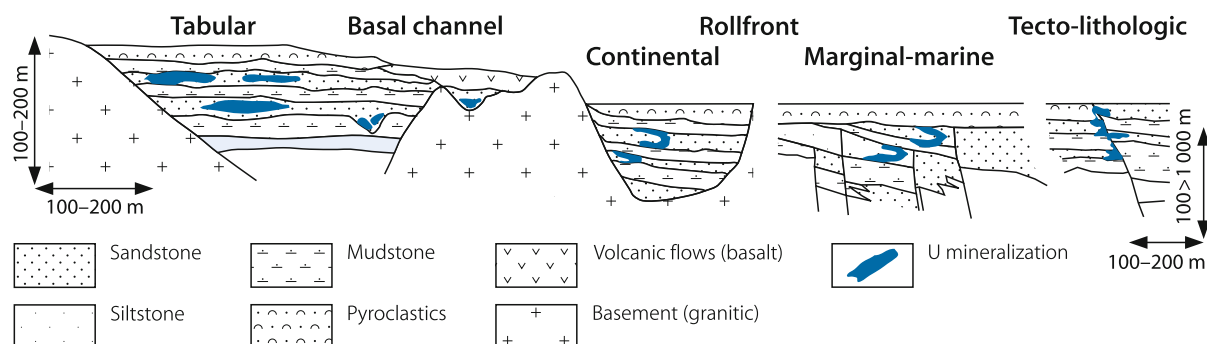
U precipitated most frequently at redox interfaces or by interaction with metals. Primary uranium minerals are generally of tetravalent U phases and consist dominantly of pitchblende and coffinite. Reducing conditions were provided by a variety of reducing agents including carbonaceous material (detrital plant debris, amorphous humate, marine algae), sulfides (pyrite, H_2S), hydrocarbons (petroleum, gas), and possibly intercalated mafic/ferro-magnesian minerals (e.g. chlorite). A distinction is made between *Phanerozoic* (post-Devonian) deposits (Ph) associated with terrestrial plant derived organics and (*b*) *Proterozoic* deposits (Pt) associated with marine, algae(?) derived organics.

Sandstone uranium deposits may be divided into four overall subtypes and further into classes that can be gradational into each other. Based on configuration and spatial relation to the depositional environment, rollfront and tabular subtypes in continental or marginal marine sediments are defined; and on distinct geomorphological setting into a basal channel subtype. In addition, the primary mineralization may be redistributed into secondary uranium "stack" ore bodies in the host sandstone defined as tectonic-lithologic subtype.

References general: Adams and Saucier 1981; Adams and Smith 1981; Granger and Finch 1988; Harshmann and Adams

Fig. I.3.

U-deposit Type 3: Sandstone U deposits, (Ph) Associated with organic material of terrestrial plant origin (Pt) Associated with organic material derived from algae



1981; IAEA (UDEPO) 2007; IAEA/Finch W (ed) 1985b; Karimov et al. 1996; Kazansky and Laverov (1977); Petrov et al. 1995; Thamm et al. 1981; Turner-Peterson et al. (eds) 1986.

Subtype 3.1 Rollfront U Deposits

(Russian terminology: *Exogenic infiltration; Strata-oxidation*)

Deposits consist of arcuate zones of uranium matrix impregnations that crosscut sandstone bedding extending from overlying to underlying less permeable horizons. The mineralized zones consist of elongate and sinuous bands approximately parallel to strata strike, and perpendicular to the direction of sedimentary deposition and groundwater flow. Redox interfaces control setting and configuration of these zones. The mineralized zones are convex down the hydrologic gradient. They exhibit diffuse boundaries with reduced sandstone on the down-gradient side and sharp contacts with oxidized sandstone on the up-gradient side (except in re-reduced sands; see *South Texas Subtype*).

Resources range from small to large and grades from low to medium (few 100 to several 1 000 t U, at grades averaging <0.05–0.25% U).

Further subdivision of rollfront deposits is based on emplacement either in intracratonic basins filled with continental alluvial/fluvial sediments or in mixed fluvial-marine sediments of coastal plains. Reductants may consist of detrital carbon, extrinsic hydrocarbons or H₂S, and/or Fe-sulfides that originated from influx of H₂S into the host sands.

a Continental Basin, U Associated with Intrinsic Reductant (Wyoming Type)

U occurs disseminated at the 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 with rocks containing anomalous U concentrations such as tuffs or granites. Most deposits occur within interbedded sequences of fluvial sandstones and volcanic rich sediments. Up-gradient alteration is characterized by oxidation reflected by variable hematitization or bleaching whereas down-gradient sandstone is in reduced state. The shape of deposits is strongly controlled by the hydrology of the host rocks. Some deposits have long tabular limbs against overlying and/or underlying carbonaceous-rich clayey-silty sediments. Resources are small to large at medium grades (few tonnes to several 1 000 t U; 0.05–0.2% U).

Type example: Highland Mine (Cz)/Powder River Basin, Wyoming, USA (Resources + production: ~10 000 t U, 0.07–0.13% U). *References:* Crew 1981; Harshmann and Adams 1981.

b Continental to Marginal Marine, U Associated with Intrinsic Reductant (Chu-Sarysu Type)

Deposits are similar to rollfront deposits in continental basins but host lithologies correspond to a sequence of mixed continental and marginal marine origin. Resources are medium to large but grades generally low.

Type example: Inkay (Mz-Cz)/Chu-Sarysu Basin, Kazakhstan (Global resources: 330 000 t U including 55 000 t U at 0.06% U). *References:* Petrov et al. 1995.

c Marginal Marine; U Associated with Extrinsic Reductant (South Texas Type)

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 certain deposits that 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 roll-front 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. Resources are small to medium and grades low to medium (<100 to several 1 000 t U; <0.05–0.25% U).

Type example: Rhodes Ranch (Cz)/McMullen County, South Texas Coastal Plains, USA (Resources + production: ~5 000 t U, 0.1–0.25% U). *References:* Adams and Smith 1981; Galloway 1985.

Subtype 3.2 Tabular/Peneconcordant U Deposits

(also referred to as *Peneconcordant* or *Blanket* deposits)

Tabular U deposits occur in extensive blanket sands formed in braided fluvial systems that unconformably overly or are eroded into underlying sedimentary or crystalline rocks. Mineralization consists of uranium matrix impregnation that generally forms irregularly shaped tabular or lenticular masses within selectively reduced sediments. The mineralized zones are, on a larger scale, oriented parallel (or peneconcordant) to the depositional trend but, on a small scale, they crosscut the bedding of the host sandstone. Uranium minerals occur as disseminations, sand grains coatings, fill of small interstices, and partial replacement of feldspar.

Further subdivision is based on uranium fixing agents such as (a) detrital plant debris or (b) amorphous organic material (e.g. humate) of intrinsic or extrinsic origin, respectively, or (c) metallic associations (e.g. vanadium) that occur in fluvial systems,

Individual deposits contain several hundreds of tonnes of U and up to 150 000 t U, at average grades ranging from 0.05 to 0.5% U, occasionally up to 1% U.

a Continental Fluvial, U Associated with Intrinsic Reductant (Arlit Type)

Tabular or lenticular U ore lodes are hosted in sediments rich in detrital carbonaceous matter (plant debris) of a continental paleoriver system composed of sandstone interbedded with claystone-shale beds. Uranium (with $\pm$ V, Mo, Zn, and Zr) occurs as pitchblende and coffinite disseminated in reduced, pyritic sandstone and as finely disseminated argillic-organic U complexes in shale. Uranyl-vanadates prevail in oxidized zones. Resources are small to large and grades low to medium (<100 to 75 000 t U; 0.2–0.5% U).

Type example: Arlit (Pz)/Tim Mersoï Basin, Niger (Resources + production: ~60 000 t U, 0.2–0.3% U). *References:* James and Hamani 1999; Pagel et al. 2003.

b Continental Fluvial, U Associated with (Extrinsic) Humate/Bitumen (Grants Type)

U is associated with humate/bitumen derived from redistributed carbonaceous matter. Mineralization is of disseminated nature and occurs in lenses within continental sandstone. The host sandstone was deposited in a mid-fan environment within an extensive fluvial-lacustrine sedimentary system. Moderate quantities of pyroclastics are present. Sand-shale proportions are typically 3/2 to 4/1 (60–80% sandstone). Alteration includes destruction of ilmenite-magnetite and significant pyritization. Feldspar is moderately to strongly altered. Resources are medium to large and grades medium.

Type example: Ambrosia Lake District (Mz)/southern Grants Uranium Region, New Mexico, USA (Production: ~75 000 t U; 0.1–0.3% U). *References:* Adams and Saucier 1981; Granger and Finch 1988; Turner-Peterson et al. (eds) 1986.

c Continental Fluvial Vanadium-Uranium (Salt Wash Type)

U associated with vanadium ($V > U$) occurs in reduced fluvial sandstone within a sequence of continental “redbed” type sediments. This suite comprises thin but widespread units of selectively reduced sandstone with interbeds of grey clay and carbonaceous debris. The most favorable sandstones parallel an adjacent contact with red oxidized sandstone and are overlain, underlain, or interbedded with grey lacustrine clays. Altered, reduced sediments show ilmenite and magnetite destruction and significant concentrations of pyrite. U resources of

individual deposits are commonly small and U grades low to high but high vanadium contents often make these deposits viable exploitation targets (<1–2 000 t U, 12 500 t V_2O_5 ; <0.15–0.3 U, <1.5% V_2O_5).

Type example: C-JD-7 deposit (Mz)/Uravan Mineral Belt/Colorado Plateau, USA (Resources + production: 2 100 t U, 12 500 t V_2O_5 , 0.21% U, 1.25% V_2O_5). *Reference:* Thamm et al. 1981.

Subtype 3.3 Basal Channel U Deposits (Chinle Type)

(Russian terminology: *Exogenic infiltration; Valley or Paleovalley, or U-REE in erosive paleovalley*; subdivided into: (a) Valley on Plain, (b) Valley on Plateau)

Basal channel U deposits are defined by their pronounced geomorphological setting in (a) distinct fluvial paleochannels or (b) paleodrainage systems composed of bifurcating channels that are incised into unconformably underlying sedimentary or crystalline rocks. Ore hosting channels are from some 10 m to 1.5 km in width and filled with 10 m to 150 m thick permeable alluvial-fluvial sediments.

U (pitchblende, coffinite) is predominantly associated with detrital plant debris and occurs in ore bodies, which exhibit in plan view an elongated lens or ribbon-like configuration and in section a lenticular or more rarely roll shape. Resources of individual deposits are mostly small but with rare exception can reach as much as 20 000 t U. Grades range from 0.02 to 3% U.

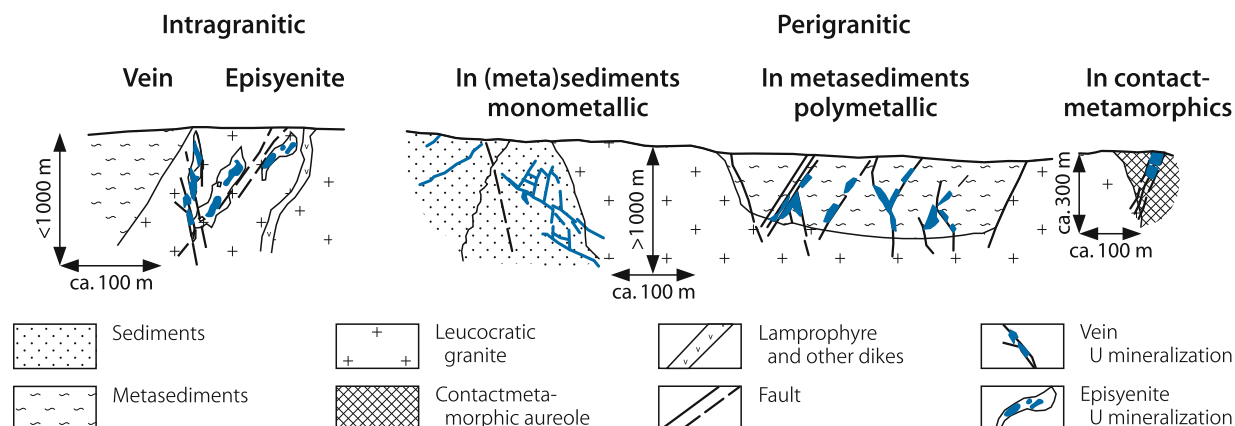
Type examples: (a) Monument Valley (Mz)/Colorado Plateau, USA (Production: 3 560 t U, 9 530 t V_2O_5 , 0.27% U, 0.94% V_2O_5). *References:* Chenoweth and Malan 1973; (b) Dalmatovskoye (Mz)/Transural (Resources 10 200 t U, 0.039% U); (c) Khiagda (Cz)/Vitim District, Russia (Resources: 15 500 t U, 0.05% U). *References:* Naumov et al. 2005; Boitsov 1999.

Subtype 3.4 Tectonic-Lithologic U Deposits

Tectonic-lithologic deposits are discordant to strata. They occur in permeable fault zones and adjacent sandstone beds in reducing environment created by hydrocarbons and/or detrital organic matter. Extrinsic uranium (liberated from sediments) may have precipitated (a) in fault zones from where it permeated tongue-like into permeable sand horizons or (b) intrinsic U was redistributed from tabular sandstone ore bodies into crosscutting faults to form locally rather thick ore bodies (termed *stack* deposits). Resources are small to medium and grades low to medium (few 100 to 10 000 t U or more, 0.1–0.4% U).

Fig. I.4.

U-deposit Type 4: granite-related U deposits (in veins, stockworks, and episyenites)



Type examples: (a) Ambrosia Lake District (Mz)/Grants Uranium Region, USA (Resources + production of individual ore lodes: up to several 100 t U, 0.1–0.4% U). *References:* Adams and Saucier 1981; Granger and Finch 1988; Turner-Peterson et al. (eds) 1986; (b) Mikouloungou/Franceville Basin (PC), Gabon (Resources: <10 000 t U, 0.25% U). *References:* Diouly-Osso and Chauvet 1979; Gauthier-Lafaye et al. 1980.

Type 4 Granite-Related U Deposits (in Veins, Stockworks, and Episyenites) (Fig. I.4)

Granite-related U deposits include: (1) true veins composed of ore and gangue minerals in granite or adjacent (meta-)sediments and (2) disseminated mineralization in granite internal episyenite bodies (a dequartzified, micaceous, vuggy alteration product of granite) that are often gradational into veins. In the Hercynian orogenic belt of Europe, these deposits are associated with large batholiths of peraluminous leucogranite modified by late magmatic and/or autometamorphic processes. U mineralization occurs within or at the contact or peripheral of the intrusion. Resources are small to large and grades low to high (<10 to >25 000 t U, <0.1–0.6%, locally up to several percent U). Three subtypes of deposits are distinguished based on the spatial setting with respect to the granitic pluton and host rocks.

References general: IAEA/Fuchs H (ed) 1986; Kolektiv 1984, 2003; Petrov et al. 2000; Poty et al. 1986; Wismut 1999.

a Endo- and Contact-Granitic Deposits (Limousin-Vendée Type)

Endogranitic deposits are commonly monometallic and consist of (a) mostly discontinuous, linear ore bodies within

distinct veins or stockworks localized in fractured granite or (b) disseminations in pipes or columns of episyenite. *Contact-granitic veins* persist from inside the granite across and beyond the granite contact but also exist only in enclosing rocks in vicinity of the contact. Other features are similar to endogranitic veins. Depths extension of endo- and contact-granitic veins can be as much as 700 m while episyenite ore bodies are known to depths of almost 1 000 m (Bernardan, France).

Type example endogranitic vein deposits: Fanay-Les Sagnes/La Crouzille District, Massif Central, France (Production 4 500 t U, 0.18% U). *References:* Leroy 1978a,b.

Type example episyenite deposits: Bernardan/La Marche District; Massif Central, France (Production >7 300 t U, av. 0.57% U). *References:* Guiollard and Milville 2003; Leroy and Cathelineau 1982.

Type example contact-granitic deposits: L'Écarpière ore field/Vendée District, France (Production 4 100 t U, 0.1% U). *References:* Chapot et al. 1996.

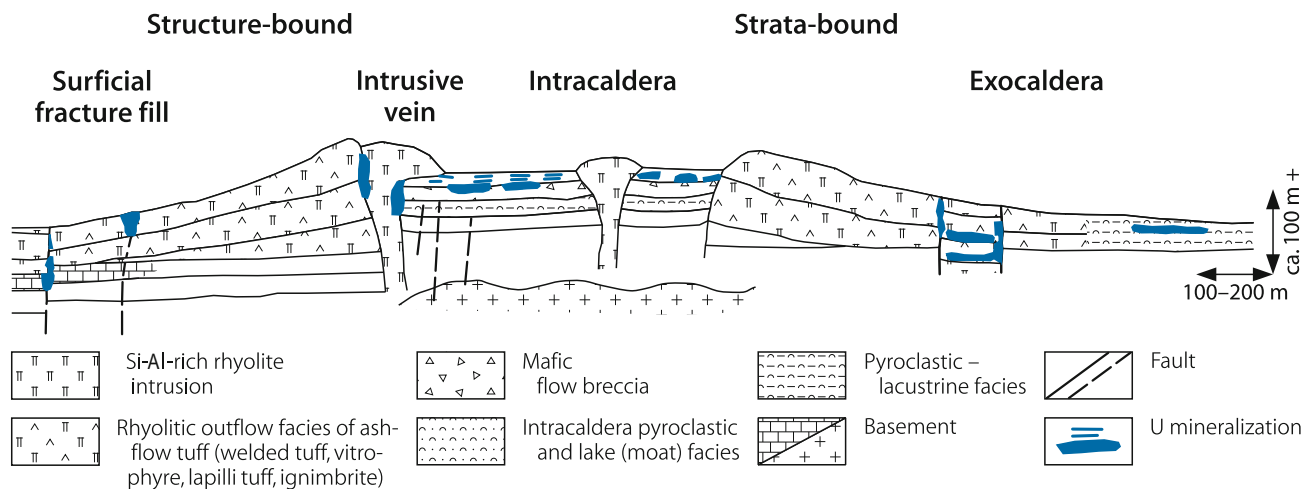
b Perigranitic Deposits in (Meta-)Sediments (Bohemien-Erzgebirge Type)

Perigranitic veins can be monometallic (essentially pitchblende and gangue minerals) or polymetallic (U, Co, Ni, Bi, Ag or other metals in economic quantities). The U and other elements are not genetically related. Both monometallic and polymetallic veins can persist as much as 2 000 m deep. Ore occupancy of host structures is generally low (5–30%).

Type example of monometallic veins: Příbram/Central Bohemian pluton, Czech Republic (Production: ~48 000 t U, 0.18% U). *References:* Komínek 1997; Kolektiv 1984, 2003; Petroš et al. 1986.

■ Fig. I.5.

U-deposit Type 5: volcanic U deposits (in veins, stockworks, and stratiform lodes)



Type example of polymetallic veins: Jáchymov, Erzgebirge, Czech Republic (Production: almost 10 000 t U, 0.1–1% U). *References:* Kolektiv 1984, 2003; Kominek and Veselý 1986.

c Perigranitic Deposits in Contact-Metamorphosed Rocks (Iberian Type)

Perigranitic deposits in the contact-metamorphic aureole of a granite intrusion have monometallic mineralization in the 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.

Type example: Nisa/Alto Alentejo District, Iberian Meseta, Portugal (Resources + production: 2 000 t U, 0.1% U). *Reference:* Basham and Matos Dias 1986.

Type 5 Volcanic U Deposits (in Veins, Stockworks, and Stratiform Lodes) (Fig. I.5)

(Russian terminology: *Endogenic hydrothermal; Molybdenum-uranium, Apatite-uranium, or Fluorite-uranium deposits, or Deposits in volcanic depressions*)

Volcanic U deposits occur mainly within or close to caldera complexes in the form of predominantly structure-bound and minor strata-bound mineralization in effusive and intrusive volcanic rocks.

Structure-bound mineralization includes (a) intrusive veins or stockworks in volcanic intrusions, diatremes, flows or bedded pyroclastic units and (b) surficial fracture fills in similar lithologies. *Strata-bound mineralization* consists of

disseminations and impregnations in permeable and/or reactive flows, flow breccias, tuffs, and intercalated pyroclastic and clastic sediments. Distinction of strata-bound mineralization is based on its (a) intracaldera or (b) exocaldera host environment, the latter is mixed with non-volcanic clastic sediments.

Uranium minerals (pitchblende, coffinite, U^{6+} minerals) preferentially associate with Mo-sulfides and pyrite. Other metallic minerals/elements include minor to traces of As, Bi, Hg, Li, Pb, Sb, Sn, W. Associated gangue minerals include fluorite, quartz, carbonates, baryte, jarosite.

Two principal subtypes are recognized: (1) Deposits indiscriminately hosted by mafic to felsic volcanic rocks in calderas underlain by granite, and (2) deposits associated with felsic volcanic complexes. Large deposits are confined to the *first variety*, e.g. at Strel'tsovsk, Russian Federation and Dornod, Mongolia. The *second variety* contains commonly small and low-grade deposits, e.g. in the Gan-Hang volcanic belt, SE China; at Michelin/Labrador, Canada; Nopal/Sierra de Peña Blanca, Mexico; and McDermitt, USA.

Subtype 1 deposits can have large resources and low to medium grades (several 10 000 t U, <0.25% U) whereas resources of Subtype 2 are commonly small (<1 000 t U) and grades very low to low (0.02–0.1% U).

References general: Dayvault et al. 1985; Goodell 1985; Ischukova 1997; Mashkovtsev et al. 2002; Petrov et al. 2000.

Note: (1) Most of the volcanic U occurrences also comply with criteria defining other types of deposits particularly of vein, surficial (fracture fill), and tabular sandstone types except for their singular volcanogenic relationship and mostly subeconomic magnitude. (2) Subtype 5.2 U concentrations, particularly in rhyolitic pyroclastics, may be more important as potential U sources for other types of deposits, particularly for those of sandstone type, than for consanguineous deposits.

Subtype 5.1

U Deposits Associated with Mafic-Felsic Volcanics in Calderas Underlain by Granite (Streltsovsk Type)

(Russian terminology: *Endogenic hydrothermal; Fluorite-uranium deposits associated with andesite-rhyolite in erosional-tectonic basins*)

Deposits consist of structurally controlled ore bodies contained in veins and intermittently at several levels in stratified mafic to felsic volcanic sheets intercalated with terrestrial sediments. Intense fracturing, and brecciation along steep and shallow dipping faults control location and dimension of ore bodies. Rocks along these structures exhibit polystage alterations. Some prominent veins persist to depths in excess of 1 000 m and extend into underlying granite and enclosed metamorphic xenoliths (Streltsovskoye-Antei, Argunskoye).

Mineralization is largely polymetallic. U is associated with Mo (>300 ppm) Fe, Pb sulfides, quartz, carbonates, phyllosilicates, locally albite and fluorite. The ore minerals form disseminated, banded, streaky, and massive ore in irregularly shaped (a) vein, stockwork, and (b) tabular-stratiform ore lodes of highly variable dimensions.

Resources range from small to large at low to medium grades (<1 000–70 000 t U, 0.07–0.25%).

a Vein-Stockwork Deposits (Streltsovskoye-Antei Type)

This mode of deposits is characterized by veins and/or stockworks that cut the caldera infill but also extend locally into the basement.

Type examples: (a) Streltsovskoye, (b) Antei (in granite)/Streltsovsk Caldera, Transbaykal, Russia (Resources + production: (a) 70 000 t U, 0.19% U; (b) 40 000 t U, 0.2% U). *Reference:* Ischukova 1997.

b Tabular-Stratiform U Deposits (Yubileinoe Type)

This mode of mineralization occurs at several stratigraphic levels controlled by peneconcordant, fractured intervals of the volcanic and sedimentary units.

Type example: Yubileinoe/Streltsovsk Caldera, Transbaykal, Russia (Resources + production: 10 000 t U, 0.19% U). *Reference:* Ischukova 1997.

Subtype 5.2

U Deposits Associated with Felsic Volcanic Complexes

a Structure-Bound/Veins-Stockworks (Nopal Type)

Deposits occur in rhyolitic ignimbrite, rhyolitic breccias, dacite flows, and granodiorite controlled by (a) intensely

altered, broken zones at crosscutting fault sets as exemplified by Nopal I (see below) in which U minerals occur as disseminations or coatings in a pipe-shaped body filled with silicified tectonic breccia; or (b) ring fracture systems with U impregnations, stringers, and veinlets that cut tectonic breccia and silica cemented rocks as typical for the Moonlight Mine (see below). Ore distribution is irregular changing from poor to locally rich sections. Most mineralization consists of uranyl-phosphates and -silicates, and limonite. Pitchblende associated with minor Fe-, Mo-, and other sulfides occurs in unoxidized environment. Resources are small and grades low to medium (<1 t to a few 100 t U, <0.1% to 0.5% U).

Type examples: (a) Nopal I/Sierra de Peña Blanca, Mexico (Resources + production: ~300 t U, 0.25% U). *References:* George-Aniel et al. 1991; Leroy et al. 1987; (b) Moonlight/McDermitt, USA (Production: <10 t U, <0.12% U). *Reference:* Dayvault et al. 1985.

b Structure-Bound/Surficial Veinlike (Cotaje Type)

Deposits occur near surface in zones of intensely broken and altered rhyolitic to rhyodacitic ignimbrite and tuff layers with intercalated volcanic breccias. Sooty pitchblende, coffinite, and uranyl phosphates associated with minor Mo, Fe, Pb, and Zn sulfides are irregularly distributed in narrow veins and disseminated throughout the cataclastic rock. Resources are small and grades low.

Type examples: Cotaje/Sevaruyo, Altiplano, Bolivia (Resources: 35 t U, 0.06% U). *References:* Leroy et al. 1985; Pardo-Leyton 1985.

c Diatreme Hosted (Maoyangtou Type)

U associated with other metals and commonly fluorite coats and fills fractures in cryptoexplosive breccia pipes. Resources are small and grades low.

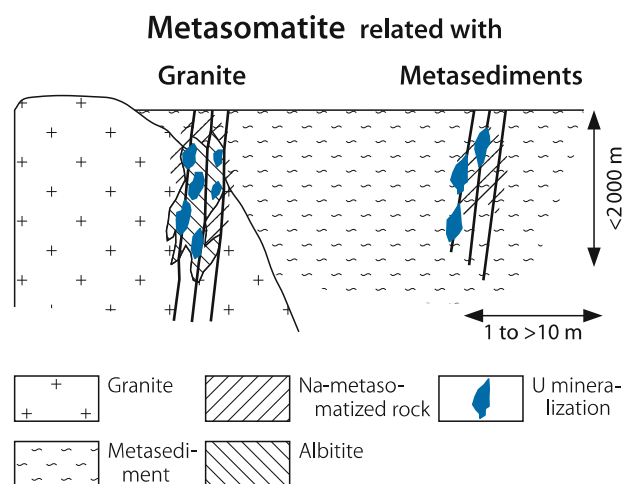
Type example: Maoyangtou/Wuyishan volcanic belt, Fujian Province, SE China (Resources: <100 t U, <0.1% U). *Reference:* Wang and Li 1996.

d Strata-Bound – Intracaldera (Aurora-Cottonwood Type)

Mineralization is hosted by mafic to intermediate tuffs, flows, and flow breccias overlain by tuffaceous lacustrine (moat) sediments. Disseminated pitchblende, coffinite, and locally uranyl phases associated with pyrite occur ± stratiform in almost completely altered porous intervals mainly along flow tops and brecciated

■ Fig. I.6.

U-deposit Type 6: metasomatite-related U deposits (in veins and stockworks)



layers, but also penetrate upwards and downwards into fracture zones. Resources range from few tens to several 1 000 t U, and grades from 0.02 to rarely 0.1% U.

Type examples: Aurora-Cottonwood Creek/Mc Dermitt, USA (Resources + production: ~7 000 t U, 0.04% U). *Reference:* Dayvault et al. 1985; Orajaka 1981.

e Strata-Bound – Exocaldera (Margaritas Type)

Mineralization consists of pitchblende and/or uranyl species associated with molybdenite, powellite, and locally pyrite, which occur erratically in fractures, joints, and voids of variably altered rhyolitic ash-flow tuff or peneconcordant in a sequence of pyroclastics interbedded with lacustrine or fluvial/alluvial sediments. Resources range from few tonnes to over 1 000 t U, at grades from 0.02 to rarely 0.2% U.

Type example: Margaritas/Peña Blanca, Mexico (Resources + production: ~2 000 t U, 0.1% U). *Reference:* Goodell 1985.

Type 6 Metasomatite-Related U Deposits (in Veins and Stockworks) (Fig. I.6)

Metasomatite U deposits are confined to areas of tectono-magmatic activity affected by intense Na- or Na- and carbonate-metasomatism that has produced albitized facies up to albitite, aegirinite, alkali-amphibole rocks, and carbonatic-ferruginous facies along deep rooted fault systems. Granite, gneiss, migmatite, or metasediments or metavolcanics are the parent lithologies. Deposits are structurally controlled by intersections, bifurcation, or abrupt bending of faults. Ore bodies are of variable shape and size composed of

disseminated grains and thin veinlets of ore minerals. Principal U phases are uraninite, U-Th-oxides, and U-Th-silicates. Two subtypes are defined on the basis of precursor rock facies: Metasomatized granite and metasomatized metasediments/metavolcanics. Resources range from small to large and grades from low to medium (<100 to >25 000 t U, <0.1–0.15% U).

References general: Avrashov/Bendix (ed) 1980; Belevtsev and Koval 1995; Collot 1981; Fritsche 1986; Kazanzky and Laverov 1977; Mineeva 1984.

Subtype 6.1 Metasomatized Granite (Kirovograd Type)

U minerals occur disseminated and in veinlets within intervals of closely spaced jointing, shearing, and brecciation in albitic aegirine granite, albitic arfvedsonite-aegirine granite, and albitite that occupy pre-metasomatic fault zones in anomalously uraniferous granite. Ore minerals include uraninite ± Th rich, uranothorianite, uranothorite, thorite, some brannerite, and coffinite associated with accessory Fe- and Pb-sulfides, REE minerals, apatite, and fluorite. Hematite and carbonates are locally abundant.

Deposits of the Kirovograd District have resources up to several 10 000 t U contained in discontinuous ore bodies to depths in excess of 1 000 m. In contrast, most deposits of this subtype elsewhere in the world are only few 100 m deep and have commonly resources from few tens to few thousands t U at grades averaging between <0.1 and rarely about 1% U.

Type examples: (a) Michurinskoye/Kirovograd District, Ukrainian Shield, Ukraine (Resources + production: ~27 000 t U, 0.1% U). *References:* Bakarzhiev et al. 1995a,b, 1997; Belevtsev and Koval 1995; Miguta and Tarkhanov 1998; Pavlenko 2005.

(b) Ross Adams/Bokan Mountain, Alaska, USA (Production: 750 t U, 0.1–0.2% U). *References:* Collot 1981; Thompson et al. 1980, 1982.

Subtype 6.2 Metasomatized Metasediments/Metavolcanics (Zheltie Vody Type)

(Russian terminology: *Ferro-uranium formation* or *Iron-uranium formation associated with sodic and carbonate metasomatites*)

The Zheltie Vody District (type example) is in the Krivoy Rog Basin, a large synclinorium of Proterozoic carbonate, quartzite, schist, and ferruginous metasediments. These rocks are folded into large isoclinal folds with steep axes. Stocks and dikes of microcline granite have intruded along lineaments. Repeated brittle tectonism caused deep faulting and strong fracturing. Metasediments and granites are intensely altered along lineaments by early Fe-Mg-metasomatism (resulting in stratiform iron ore), followed by Na-metasomatism, carbonate-metasomatism, and finally silicification (secondary quartzites). U mineralization is restricted to fractured sections in Na- and carbonate-metasomatite zones in which it occurs in the form of lenses, shoots, and stratiform bodies with finely disseminated U minerals, and as veins. U minerals include uraninite, pitchblende, coffinite, brannerite, and nenadkevite associated with sulfides, apatite, malacon, and carbonate.

U mineralization at Zheltorechenskoye/Zheltie Vody persists to depths of some 2 000 m. U-hosting metasomatites

decrease at depth below about 1 000 m. Uraninite peters out synchronously at this depth and gives way to uraniferous malacon-apatite.

Type example: Zheltorechenskoye/Zheltie Vody District, Krivoy Rog Basin, Ukrainian Shield, Ukraine (Resources + production: estimated ~20 000 t U, 0.12% U). *Reference:* Bakarzhiev et al. 1995b; Belevtsev et al. 1984a.

Type 7 Undifferentiated (Meta-)Sediment Hosted U Deposits (in Veins and Shear Zones) (Fig. I.7)

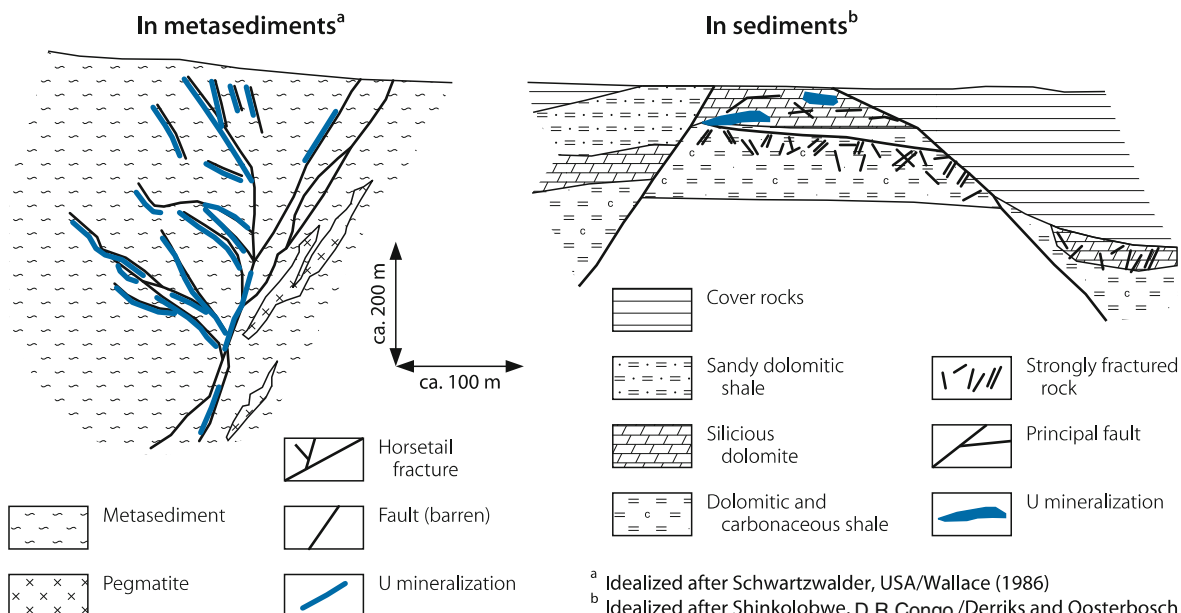
Three varieties are recognized: Monometallic and polymetallic veins, and monometallic shear zone fillings. The two vein modes are similar in structural control, ore and gangue mineral association, and wall rock alteration to perigranitic monometallic and polymetallic veins in (meta-)sediments. Major differences include absence of granitic or other magmatic complexes and a relative continuity of mineralization. Resources are small to high and grades low to high (<10 to >25 000 t U, <0.1 to >1% U).

a Monometallic Veins (Schwartzwalder Type)

Uranium (mainly pitchblende, uraninite, coffinite) and gangue minerals with only traces of other metallic minerals form

Fig. I.7.

U-deposit Type 7: undifferentiated (meta-)sediment hosted U deposits (in veins and shear zones)



stringers, veinlets, and veins within larger tensional structures but particularly in horsetail fractures, which branch from the main lodes. Mineralization is relatively continuous although grades are highly variable. Resources are small to high and grades low to high (<100–20 000 t U, 0.1–0.5% U locally several percent U).

Type example: Schwartzwalder/Front Range, USA (Production: ~7 000 t U, 0.4% U). *Reference:* Wallace 1986.

b Polymetallic Veins, Stockworks (Shinkolobwe Type)

Uranium (pitchblende, uraninite, coffinite) associated with Co, Cu, Fe, Mo, Ni, Pb, Zn and gangue minerals occur in veins, stockworks, breccia matrix, as well as replacement masses and disseminated particles and aggregates in broken host rocks. Major faults are barren. Mineralization is fairly continuous but highly variable in grade and magnitude. At Shinkolobwe and other deposits in the Katanga copper belt of Congo and Zambia, ore distribution is discordant to strata but ore always occurs in beds underlying the cupriferous strata, which locally contain anomalous U concentrations, at the base of a thick sequence of sediments of shallow marine origin. Resources are small

to high and grades low to high (<100 to 25 000 t U, 0.1 to >1% U).

Type example: Shinkolobwe/Katanga Copper Belt, Democratic Republic of Congo (Resources + production: ~25 000 t U, 0.1 to >1% U). *Reference:* Derriks and Vaes 1956.

c Monometallic Shear Zone Fillings (Rožná Type)

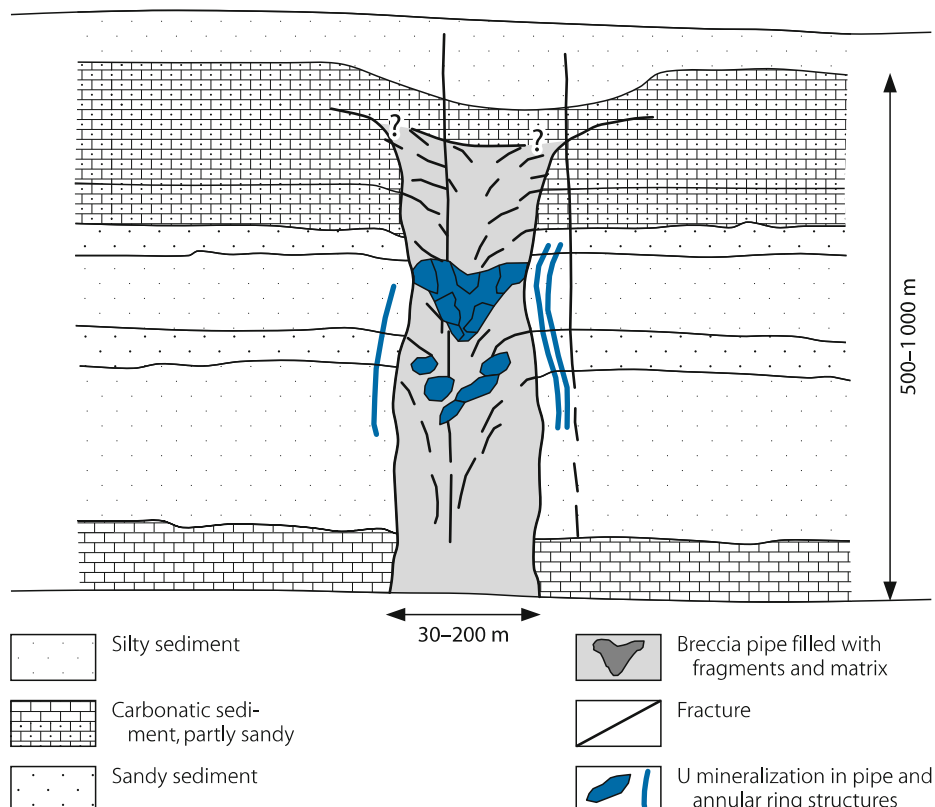
Ore bodies consist of stringers and disseminations of U phases (mainly pitchblende, coffinite) without or only minor gangue in small, narrow structures (fissures, joints, etc.) that group to lenticular ore shoots subparallel to the strike of the host strata. Prominent shear and breccia zones control position and dimension of ore shoots. Classical veins are rare.

Ore bodies comprise lower grade ore composed of U impregnations in a system of subparallel, anastomosing, and intersecting structures, which border and enclose variably fractured rock segments with better grade ore. Better grade ore shoots occur predominantly in the form of bundles of subparallel fracture fillings or network style mineralization.

Resources are small to medium and grades low (<20 000 t U, <0.1% U).

■ Fig. I.8.

U-deposit Type 8: collapse breccia pipe U deposits (Arizona Strip type)



Type example: Rožná/Western Moravia, Czech Republic (Resources + production: ~20 000 t U, 0.1% U). *References:* Kolektiv 1984, 2003.

Type 8 Collapse Breccia Pipe U Deposits (Arizona Strip Type) (Fig. I.8)

Circular, vertical pipes (10–300 m in diameter, <1 000 m deep) filled with highly brecciated material constitute the host for mineralization. Pipe infill is composed of coarse fragments and fine matrix material that down-dropped by collapse of strata into a dissolution cavern in a basal soluble rock (limestone, gypsiferous rocks). Mineralization consists of U (pitchblende, coffinite, alteration products thereof) and various metallic minerals (Fe, Cu, Ni, Co, Mo, Pb, Zn, As, traces of Ag, Au, Hg, Sb, V) associated with a variety of gangue minerals. These minerals occur as veinlets in annular ring fractures surrounding the pipe, and as stringers and irregular impregnations of permeable ($\pm$ sandy) matrix material within the pipe. A Fe-sulfide cap (80% sulfide) often tops the uppermost U mineralization in a pipe. Alteration is commonly weak and of

little extension into wall rocks. Resources of individual pipes are small and grades medium to high (few tonnes to ~2 000 t U, 0.2–1% U). Cu and Ag may locally be significant co-products.

Type examples: Hack Canyon Mines/Arizona Strip, Arizona, USA (Production: ~1 300 t U, 0.55% U). *References:* Carlisle 1983; Wenrich and Sutphin 1989, 1994.

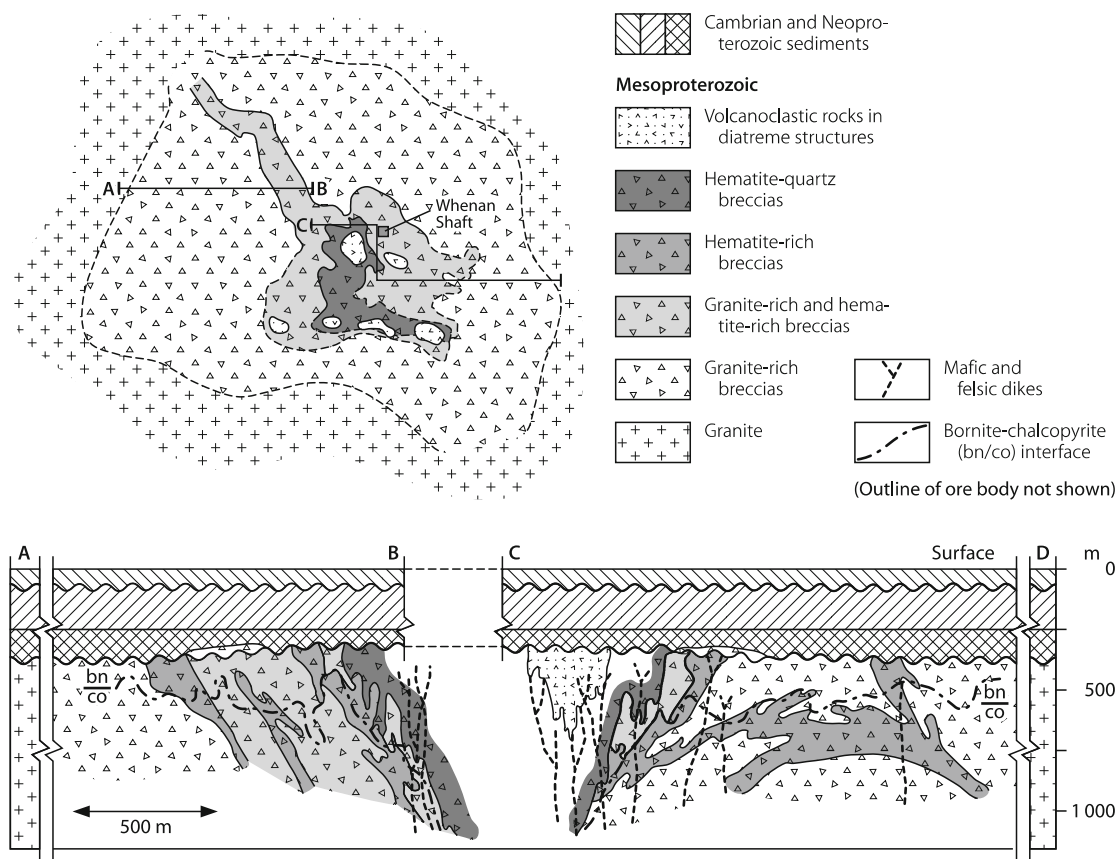
Type 9 Polymetallic Hematite-Breccia-Complex U Deposits (Olympic Dam Type) (Fig. I.9)

This type of deposits has been attributed to a broad category of worldwide known iron oxide-copper-gold deposits but Olympic Dam is the only known representative of this type with significant by-product U resources.

The Mesoproterozoic Olympic Dam deposit contains uranium in association with copper, gold, silver, and REE in a hematite-rich granite breccia complex. This breccia is within a granite intrusion that exhibits regional iron, potassium, and/or sodium metasomatism. The granite is part of a

Fig. I.9.

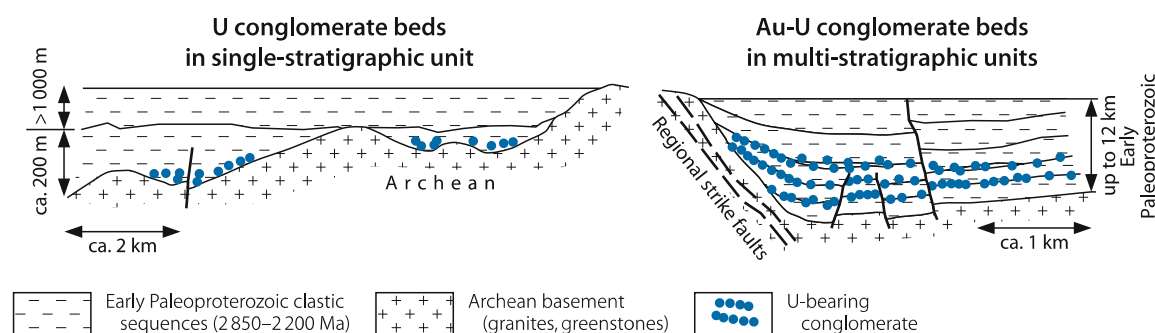
U-deposit Type 9: polymetallic hematite-breccia-complex U deposits (Olympic Dam type)



Idealized after Olympic Dam, Australia/McKay and Miezitis 2001 based on Reeve et al. (1990)

■ Fig. I.10.

U-deposit Type 10: Paleoproterozoic quartz-pebble conglomerate U deposits



suite of Mesoproterozoic plutonic intrusions and co-magmatic continental felsic volcanics. Neoproterozoic to Cambrian, flat-lying marine sediments of the Stuart Shelf, approximately 300 m thick, rest unconformably upon the breccia complex.

Hematite-rich and heterolithic hematitic breccias are the principal host for economic Cu-U mineralization. U minerals (fine-grained pitchblende, minor coffinite and brannerite) occur as disseminations, microveinlets, and aggregates intergrown with copper sulfides and breccia material, and partly as replacement of breccia constituents. Narrow, better grade uranium mineralization occurs preferentially in bornite-chalcocite ore in hematite breccias. High-grade U zones transgress locally the bornite-chalcocite interface. U is recovered as by-product of Cu, Au, Ag.

Type example: Olympic Dam/Gawler Craton-Stuart Shelf, S Australia (Resources + production: 1.4 million t U at 0.04% U, 42.7 million t Cu at 1.1% Cu, 1 905 t Au at 0.5 g t⁻¹, 2.9 g t⁻¹ Ag, approx. 0.2% La, 0.3% Ce). **References:** Reeve et al. 1990; McKay and Mieziis 2001; WMC 2004.

Type 10 Paleoproterozoic Quartz-Pebble Conglomerate U Deposits (● Fig. I.10)

(also referred to as *Oligomictic conglomerate* or *Lower Proterozoic conglomerate* or *Paleoconglomerate* or *Modified paleoconglomerate type*)

Quartz-pebble conglomerate U deposits are restricted to early Paleoproterozoic intracratonic basins (older than 2.3–2.4 Ga) downwarped into Archean basement that includes granites. Host rocks consist of typically trough cross-bedded, oligomictic quartz-pebble conglomerate layers with a pyritiferous matrix interbedded with quartzite and argillite beds. This suite

occurs as basal units in fluvial to deltaic braided stream systems.

Placer uraninite is the principal primary uranium phase. It is locally associated with gold, REE, and/or other detrital metallic oxide and sulfide minerals. The variable ore mineral assemblages are a function of different geological source provinces and hydrodynamic mineral separation during fluvial transport. Fluvial transport and accumulation of uraninite was conditioned by the reducing character of the early, oxygen-poor earth atmosphere prior to oxyatmoverion. Post-depositional redistribution and mineral crystallization mainly by diagenetic processes led to the formation of modified placers composed of a suite of authigenic ore and associated minerals such as brannerite, rutile, anatase, coffinite, pyrite, and others. Two economic subtypes are noticed: Monometallic and polymetallic (Au + U). Economic deposits are confined to the *Blind River-Elliot Lake* area, Canada, where predominantly monometallic uranium was formerly mined, and the *Witwatersrand Basin*, South Africa, where uranium is recovered as by-product of gold. Resources are large but grades low (several 100 000 t U; 0.01 to locally 0.12% U).

References general: Button and Adams 1981; Pretorius 1981; IAEA/Pretorius(ed) 1987.

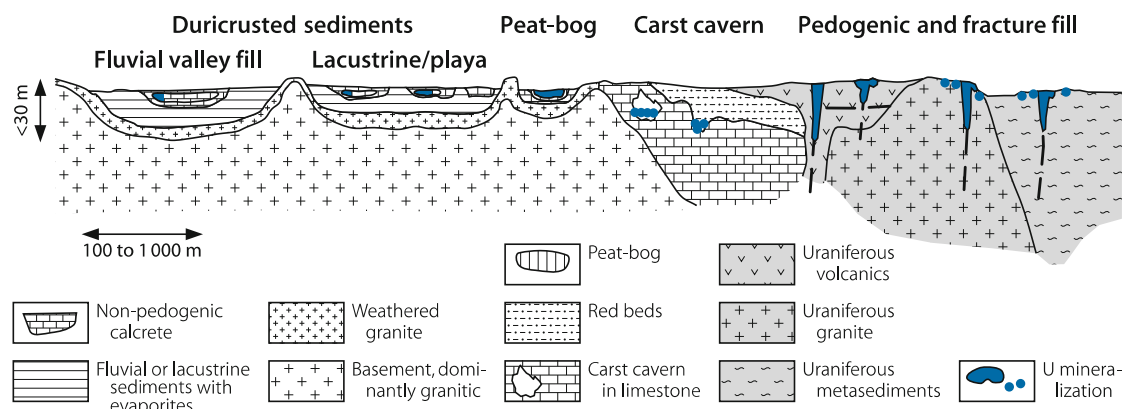
Subtype 10.1 Monometallic (or U-Dominant with REE) U Deposits (Elliot Lake Type)

Detrital heavy minerals (dominated by uraninite and REE minerals) and later formed authigenic phases occur as disseminated matrix components in pyritic (5–20 wt.-%), oligomictic quartz-pebble conglomerate horizons (termed reef), from 0.5 to >3.5 m thick. Quartzite units are interbedded with the conglomerate beds. This suite forms the basal section of a sequence, about 50 m thick, in paleovalleys scoured into Archean basement.

Uraninite, uranothorite, uranothorianite, monazite, and xenotime are the prevailing detrital minerals. Authigenic minerals

Fig. I.11.

U-deposit Type 11: surficial U deposits



include U-Ti-oxide phases (brannerite), coffinite, thucholite, and locally gummite.

Type example: Elliot Lake-Quirke Lake District/Ontario, Canada (Resources + production: >400 000 t U, 0.05–0.12% U; U was the primary commodity produced with occasional recovery of Th and some REE, particularly Y). *References:* Robertson 1989; Ruzicka 1988.

Subtype 10.2 Polymetallic Au with U Deposits (Witwatersrand Type)

Ore and associated minerals occur as detrital and redistributed matrix components in quartz-pebble conglomerate horizons in multi-stratigraphic cycles within six large fluvial-deltaic fans on the north and west side of the Witwatersrand Basin. Host rocks consist of pyritic, oligomictic quartz-pebble conglomerate beds, commonly only few cm to several tens of cm thick, interbedded with quartzite, arkose, shale, and volcanics. Carbonaceous material occurs in several horizons.

Detrital ore minerals include uraninite, uranothorite, native gold, and platinoid (Os, Ir, Ru, Pt) species. Postdepositional modification of the placers led to several generations with a multitude of authigenic ore and associated minerals including brannerite and thucholite.

Important concentrations of U ore are restricted to distinct narrow zones occupying ca. 2% of the entire Upper Witwatersrand System within a belt trending parallel to the former coastline.

Type example: Witwatersrand Basin, South Africa (Resources + production: >500 000 t U, av. 0.01–0.03% U, 5–12 ppm Au; recovery of U as by-product to Au except in a few mines, e.g. Africander/Vaal Reefs with 0.12% U and 1.1 ppm Au). *References:*

Anhaeuser and Maske (eds) 1986; Hallbauer 1986; Pretorius 1976a,b; von Backström 1975, 1976.

Type 11 Surficial U Deposits (Fig. I.11)

Surficial uranium deposits are broadly defined as young (Tertiary to Recent) near-surface uranium concentrations in rocks and soils. Uranium occurs almost exclusively as uranyl species present as impregnation and void filling or coating, or adsorbed on host constituents (organics, clay, etc.). Mineralization is strata-bound in selectively indurated sedimentary formations or unconsolidated sediments in surficial depressions, dissolution caverns, or structure-bound in high background U rocks. Based on host environment, four principal subtypes are recognized.

References general: Arakel 1988; Boyle 1984; Briot 1978; Butt et al. 1984; Carlisle 1983; Carlisle et al. 1978; Hambleton-Jones 1976, 1984; IAEA/Toens (ed) 1984; Mann and Deutscher 1978; Pagel 1984; Samama 1984.

Subtype 11.1 Duricrusted Sediments

(also referred to as *Calcrete*, *Silcrete*, *Groundwater-calcrete*, or *Valley-calcrete* type)
(Russian Terminology: *Exogenic infiltration*; *Ground-oxidation*)

In regions of arid to semi-arid climates, *nonpedogenic* calcrete, dolocrete, silcrete, or gypcrete that cement or replace young sediments along the groundwater table constitute the host for two modes of tabular U(-V) deposits in (a) fluvial, alluvial and eolian channel fills and (b) evaporative lacustrine playa facies.

a Fluvial Valley-Fill (Yeelirrie Type)

Mineralization in duricrusted valley sediments forms flat-lying lenses, up to few meters thick, with most of the mineralization emplaced immediately beneath the present water table. U minerals (carnotite, rarely other uranyl species) occur disseminated, as fracture coating and vug lining in earthy or porcellaneous calcrete etc., and as grain coating in clay-quartz sediments immediately below the calcrete. Resources are commonly small to medium and grades mostly low (<10–5 000 t U, 0.02–0.07% U) except for the type example deposit.

Type example: Yeelirrie/Yilgarn Block, Australia (Resources: 45 000 t U, 0.12% U). *Reference:* Cameron 1984.

b Lacustrine/Playa (Lake Maitland Type)

Mineralization is similar to (a) but hosted by duricrusted layers in shallow lake or playa sediments. Resources are small and grades low (<10 to 4 000 t U, <0.02–0.08% U, occasionally 0.15% U).

Type example: Lake Maitland/Yilgarn Block, Australia (Resources: 3 000 U, <0.06% U). *Reference:* Cavaney 1984.

Subtype 11.2 Peat-Bog (Flodelle Creek Type)

In humid climate regions, U is accumulated in vegetal organic and clay-rich shallow depressions (swamps, bogs, muskegs) composed of <65% vegetal organic matter, often peat, embedded in alluvial pelitic-psammitic sediments when these depressions are located in U source areas. No discrete U minerals occur. U is probably present as urano-organic complexes and/or adsorbed on organic material, clay, marl, or silt particles. Resources are

small and grades low (<1 to 50 t U, few 100 ppm U, rarely up to 0.2% U).

Type examples: Flodelle Creek, Stevens Co., NE Washington State, USA (Resources+production: ~50 t U, few 100 ppm U). *Reference:* Johnson et al. 1987; Otton et al. 1989.

Subtype 11.3 Karst Cavern (Pryor-Little Mtns. Type)

U mineralization is contained in the floor veneer of fallen blocks and insoluble residues of limestone embedded in loosely consolidated sand, silt, and clay in limestone caverns. Uranium minerals (tyuyamunite, metatyuyamunite) coat or fill fractures and solution voids, line rock components, and impregnate the matrix of the cavern fill. Resources are small but grades high (few tonnes to several 10 t U; 0.4 to >1% U, 0.6–4% V₂O₅).

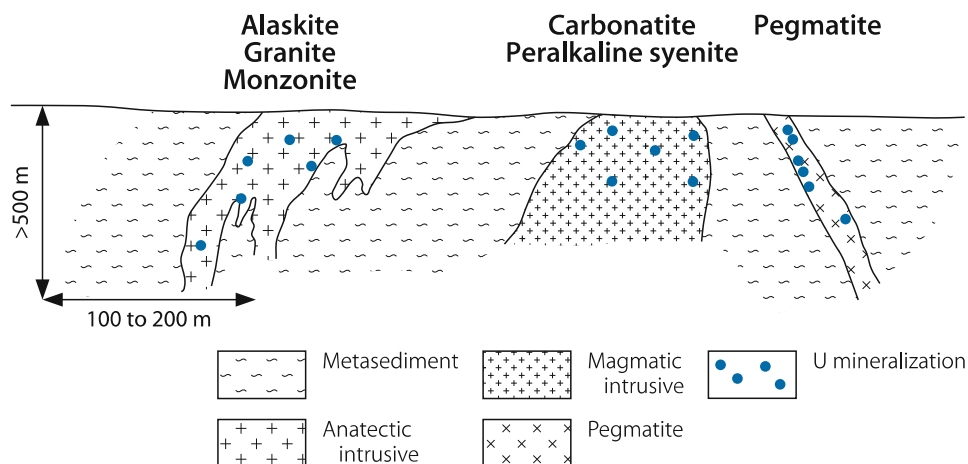
Type examples: (a) Pryor-Little Mtns/Montana-Wyoming, USA (Production 100 t U, 0.4–1.07% U, 0.6–4% V₂O₅). *Reference:* Bell 1963. (b) Tyuya-Myuyun/Osh Province, Kyrgyzstan (Resources+production: ~50 t U, 1.4% U, 3.8% V₂O₅, 3% CuO). *Reference:* Aleksandrov 1922; Kazansky 1970.

Subtype 11.4 Surficial Pedogenic and Structure Fill

This category comprises surface-bound U concentrations in soils and pedogenic encrustations (laterite/ferricrete, calcrete, silcrete, etc.), as well as dissemination, coating and filling of near-surface cataclastic zones (shears, fissures, joints) in rocks with anomalous U background tenors. Occurrences are commonly of minute to small size and low grade (<1 t U, <0.1% U) except a few cases.

■ Fig. I.12.

U-deposit Type 12: intrusive U deposits



Type examples: Daybreak Mine, Washington, USA (Production: 20 t U, 0.3% U). *References:* US-AEC 1959.

Type 12 Intrusive U Deposits (Fig. I.12)

Intrusive deposits consist of disseminated primary U minerals, dominantly uraninite, uranothorianite, and/or uranothorite in rocks of intrusive magmatic or anatectic origin. Five major subtypes are identified: alaskite, quartz-monzonite, carbonatite, peralkaline syenite, and pegmatite. The first four subtypes are all of very low grade (ca. 20–400 ppm U) but may contain large resources. Only pegmatite deposits may average up to 0.1% U but resources are generally low (few tonnes to few hundred tonnes U).

The only deposits mined in the western hemisphere are the Rössing alaskite, Namibia, and the Bancroft (Madawaska) pegmatite deposits, Canada. In addition, uranium was extracted as by-product from porphyry copper/quartz-monzonite deposits (Bingham, Twin Buttes) in the western USA, and from the Phalaborwa carbonatite, South Africa.

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

Subtype 12.1 Alaskite U Deposits (Rössing Type)

Alaskite U deposits are associated with alaskite bodies of variable shape and dimensions. Uranium minerals (uraninite, betafite, and alteration products thereof) occur as inclusions in quartz, feldspar, and biotite disseminated throughout the alaskite, and in interstices and microfractures. Resources can be large but grades are low.

Type example: Rössing, Namibia (Resources+production: >200 000 t U, 0.03–0.04% U). *References:* Berning 1986; Berning et al. 1976; Brynard and Andreoli 1988.

Subtype 12.2 Quartz-Monzonite/Copper-Porphyry Cu-U Deposits (Bingham Type)

This type of U concentration is associated with base (mainly Cu, Mo) and noble metals in highly differentiated quartz-monzonitic complexes (copper porphyries) altered by Mg- and K-metasomatism and late hydrothermal activity. No uranium mineral is listed but U may be present as disseminated uraninite or uranothorianite.

Type example: Bingham, Utah, USA (20–50 ppm U in Cu-Mo ore; U was extracted from leach containing 8–12 ppm U. Former

annual production of U as by-product is estimated at 60–80 t). *References:* John 1978; Lanier et al. 1978.

Subtype 12.3 Carbonatite Cu-U Deposits (Phalaborwa Type)

Differentiated, cupriferous carbonatite complexes contain increased U background concentrations in addition to other metals. At Phalaborwa, South Africa, the only deposit of this type mined, recoverable ore minerals (chalcopyrite, bornite, titaniferous magnetite, baddeleyite, uranothorianite) are widely disseminated or in veinlets throughout an almost vertical dipping carbonatite-phoscorite pipe. Resources are small and grades very low (<100 ppm U).

Type examples: Phalaborwa, South Africa (Resources+production: several 1 000 t U, 0.004% U, 0.51% Cu; recovery of U as by-product to Cu and other metals). *References:* Camisani-Calzolari et al. 1986; IAEA 1986a; Phalaborwa Mining Co. 1976.

Subtype 12.4 Peralkaline Syenite U Deposits (Kvanefjeld Type)

Domes or stocks of differentiated agpaite-peralkaline nepheline syenite contain disseminated U-Th minerals of refractory nature (steenstrupine, eudialyte, monazite) in late lujavrite facies with the best U-Th concentrations at or near the contact of intrusive apophyses and sheet-like lujavrite bodies. Resources are small to large and grades low (<500 ppm U).

Type examples: Kvanefjeld, Illimaussaq, Greenland (Resources: >25 000 t U, 0.03–0.04% U). *References:* Bohse et al. 1974; Kunzendorf et al. 1982; Sørensen et al. 1974.

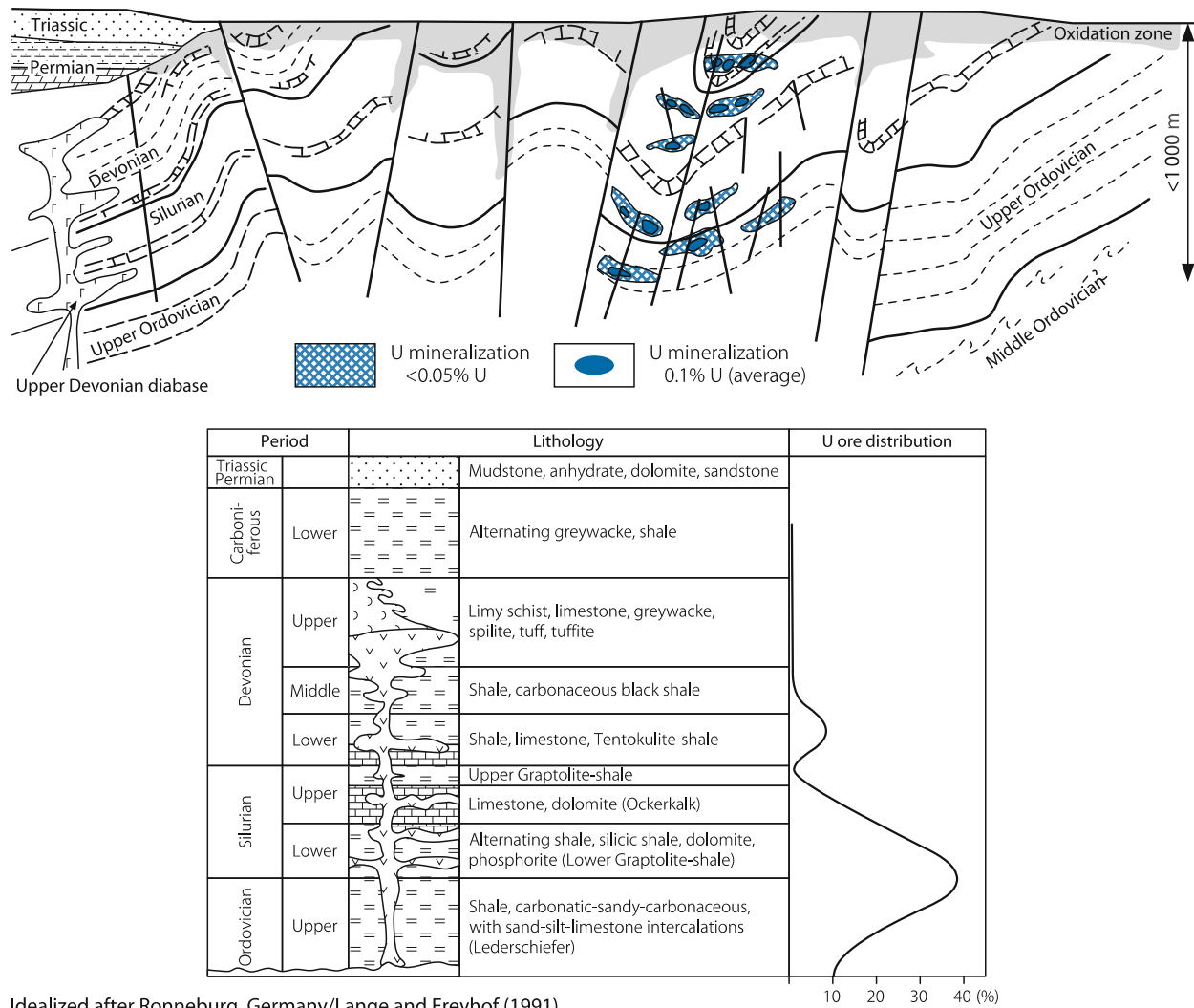
Subtype 12.5 Pegmatite U Deposits (Bancroft Type)

Granitic, rarely syenitic, pegmatite dikes may contain randomly distributed small U ore bodies. Uraninite, uranothorite, and alteration products thereof are the principal U phases.

Type examples: Madawaska/Bancroft District, Grenville orogenic belt, Canada (Production: ~200 t U, 0.05–0.15% U). *References:* Alexander 1986.

Another pegmatite variety, *rare metals pegmatite*, contain Sn, Ta, Nb, and Li mineralization with variable U, Th, and REE grades as known, e.g. from the Greenbushes and Wodgina pegmatites (West Australia). Although the U and Th contents of the Greenbushes pegmatites are very low (av. 6–20 ppm U, 3–25 ppm Th), mineral processing enrich U+ThO₂ combined up to 0.4% in

■ Fig. I.13.
U-deposit Type 13: uraniferous carbonaceous shale-related stockwork deposits (Ronneburg type)



tantalum concentrates and tin smelting of Greenbushes ore increases U+ThO₂ contents up to 1% in slags.

Type 13
Uraniferous Carbonaceous Shale-Related Stockwork Deposits (Ronneburg Type)
● Fig. I.13)

[Chinese terminology: *Carbonaceous-carbonate-siliceous-pelite* type, subdivided into pelite, carbonate, and silicite (or silicic breccia) subtypes; or – genetically – into (a) sedimentary-diagenetic, (b) phreatic infiltration (or leaching-accumulative), and (c) hydrothermal-reworked subtypes]

This type of uranium deposits consists of strata-controlled, structure-bound U concentrated in stockworks of minifractures

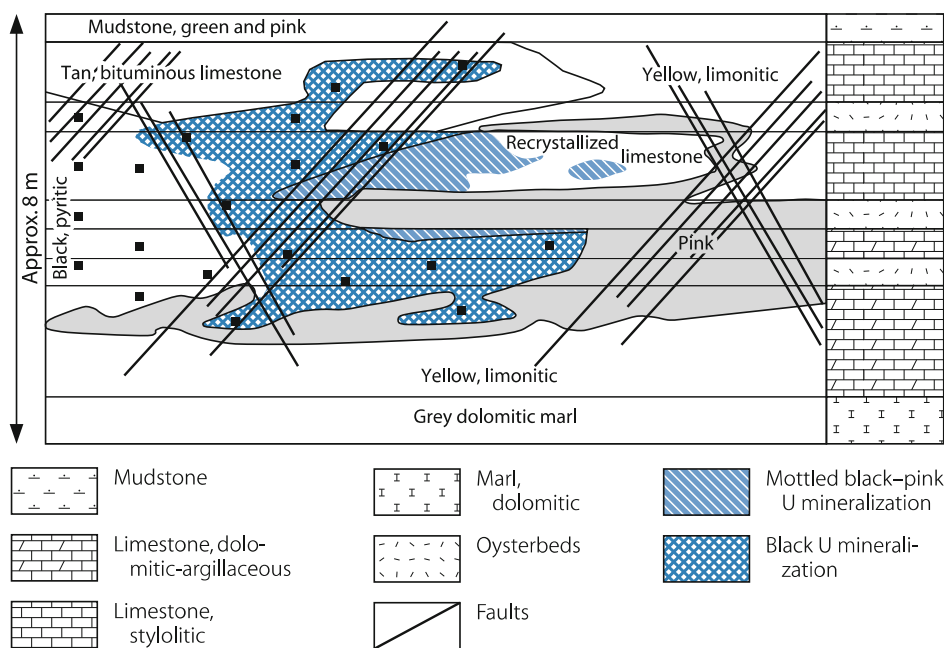
within or immediately adjacent to carbonaceous, pyritic (black) shale/pelite beds. Host rocks include argillaceous and siliceous black carbonaceous shales with more or less intercalations of calcareous (dolomitic) and phosphorite nodule beds, as well as carbonaceous sandy and carbonatic shales, and limestone-dolomite above and/or below the carbonaceous shale horizons. High organic carbon (up to 9% C), sulfide (up to 3.5% S), and anomalous trace element (U, Mo, Ni, V, As, Sb) contents are typical for the carbonaceous shale.

Mineralization is restricted to segments of intense microfracturing (fissures, joints, cleavages) controlled by major faults, thrusts, and their intersections. These microfracture systems form stockwork ore bodies within the cementation zone below a supergene oxidation profile. Weakly mineralized zones surround the stockwork ore bodies.

Ore minerals (pitchblende, rare coffinite, with subordinate sulfides, arsenides of various metals) fill and coat in unpredictable manner joints and cleavages and impregnate porous wall rocks for short distances from mineralized fractures. Ore-related

Fig. I.14.

U-deposit Type 14: uraniferous bituminous-cataclastic limestone deposits (Mailuu-Suu type)



Idealized after Mailuu-Suu, Kyrgyzstan/Roslyi (1975)

alteration is constraint to narrow aureoles of bleaching and hematization around mineralized structures. Resources of individual deposits are small to large and grades low (<100 to several 10 000 t U, <0.05–0.15% U).

Type example: Gera-Ronneburg District/Thuringia, Germany (Resources+production: ~200 000 t U, 0.075–0.14% U). *References:* Lange and Freyhoff 1991; Wismut 1999.

Type 14 Uraniferous Bituminous-Cataclastic Limestone Deposits (Mailuu-Suu Type) (Fig. I.14)

(Russian terminology: *Exogenic epigenetic infiltration: Vanadium-uranium deposits in carbonate sediments*)

Uranium mineralization is structure-bound in organic-rich (bituminous/petroliferous) calcareous sediments ($\pm$ impure limestone, dolomite, marlstone), sandwiched between arenaceous-argillaceous continental sediments. Repeated oxidation and reduction processes have altered the host rock.

The position and configuration of the ore zones and ore bodies are controlled by fractured intervals in intraformational folds and flexures. Uranium minerals (pitchblende, nivenite, coffinite, and U-V minerals e.g. montroseite) form lenticular and roll shaped ore bodies in which U minerals are irregularly distributed in stylolites, sutures, microfissures (which also contain solid bitumens), interstices between carbonate grains, and leached-

out voids. Associated elements include Fe, V, Mo, As, Ni, Co, Pb, and Cr.

Type example: Mailuu-Suu/Karamazar region, Kyrgyzstan (Production: estimated ~10 000 t U, 0.1–0.2% U). *References:* Roslyi 1975; Thoste 1999.

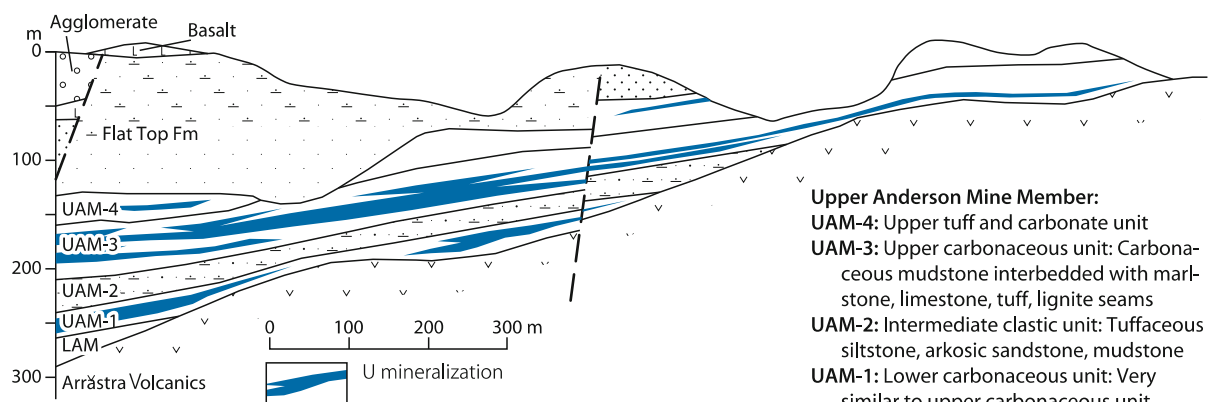
Type 15 Uraniferous Carbonaceous Lutite (Lacustrine) Deposits (Anderson Mine Type) (Fig. I.15)

This type, as exemplified by the Anderson Mine (see below), constitutes an intermediate member between lignite and sandstone-type U mineralization.

Carbonaceous lacustrine, locally paludal sediments with tuffaceous components provide the host rocks. They include carbonaceous lutite horizons with widespread, peneconcordant, low-grade U accumulations (<100 to 200 ppm U) associated with anomalous tenors of V, Mo, Li, F, B, Cu, and Ni. These low grade uraniferous horizons encompass irregular shaped zones with better grade mineralization of up to 0.3% U. Most of the mineralization is in thin-bedded, slightly silicified, pyritic, carbonaceous mudstone and siltstone, lignitic mudstone, and bioturbated marlstone in which ore minerals occur as fine disseminations in the matrix and discontinuous microveinlets or patches. Highest U concentrations occur in lignitic coal and as halos around root remains, often associated with framboidal pyrite. Principal U mineral is colloform coffinite that generally associates with carbonaceous matter and humate. Pitchblende is

■ Fig. I.15.

U-deposit Type 15: uraniferous carbonaceous lutite (lacustrine) deposits (Anderson Mine type)



Idealized after Anderson Mine,
USA/Sherborne et al. 1979

Early to Middle Miocene

Flat Top Formation: Arkosic siltstone,
sandstone, conglomerates interbedded
with bentonitic/tuffaceous siltstone

Anderson Mine Formation: Tuffaceous,
paludal, lacustrine sediments

Upper Anderson Mine Member:

UAM-4: Upper tuff and carbonate unit

UAM-3: Upper carbonaceous unit: Carbona-
ceous mudstone interbedded with marl-
stone, limestone, tuff, lignite seams

UAM-2: Intermediate clastic unit: Tuffaceous
siltstone, arkosic sandstone, mudstone

UAM-1: Lower carbonaceous unit: Very
similar to upper carbonaceous unit

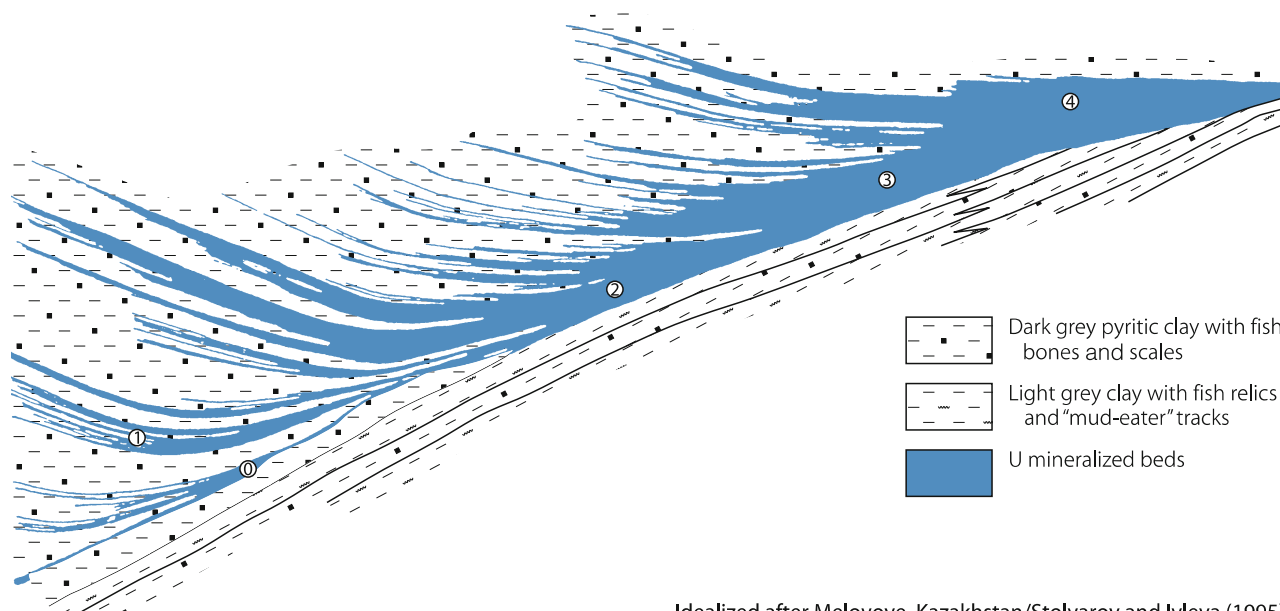
LAM: Lower Anderson Mine Member (Lower
clastic unit): Arkosic and volcanic sand-
stone-conglomerate, reworked andesite
lapilli bentonitic siltstones

Oligocene(?) to Eocene(?)

Arrastra Volcanics: Basalt, andesite, andesitic
tuff, interstratified conglomerate

■ Fig. I.16.

U-deposit Type 16: uraniferous organic phosphorous deposits (Mangyshlak type)



Idealized after Melovoye, Kazakhstan/Stolyarov and Ivleva (1995)

rare. Elements enriched to various degrees in carbonaceous uranium ore include Mo, V, As, S, and in lesser amounts Ag, Au, B, Cu, Ga, Ge, Mn, and Ti.

Oxidized zones contain very fine carnotite as cement, fine coatings and coarse-fibrous fillings in fractures and along bedding planes, or with hematite in jasper pods. It also occurs as

uraniferous silica in massive jasper and in small silica veinlets. Oxidized mineralization is confined to fractured, highly silicified, oxidized mudstone, tuff, limestone, and marlstone with abundant megascopic plant debris.

Resources are small to medium and grades low (<10 to > 10 000 t U, <0.1–0.6% U).

Type example: Anderson Mine/Date Creek Basin, Arizona, USA (Resources: >12 000 t U, <0.06% U including 5 000 t U at 0.03–0.12% U, av. 0.06% U). *References:* Otton 1981, 1986; Sherborne et al. 1979.

Type 16 Uraniferous Organic Phosphorous Deposits (Mangyshlak Type) (Fig. I.16)

(Russian terminology: *Exogenic sedimentational-diagenetic; Rare-earth – uranium deposits in clays with fish remains*)

U-Sc-REE mineralization is bound to detritus of phosphatized fish remains in superjacent stacked clay beds enriched in fish bones, fish scales, and pyrite and melnicovite concretions. These mineralized beds are intercalated in a dark clay unit and occur in shallow (low energy) marine Tertiary basins in the northern Caspian Sea region/Kazakhstan-Russia. U resources are medium to large (<50 000 U) but grades are very low (av. 0.02–0.06% U, 0.5–2.1% total REE, 10–70 ppm Sc).

Type example: Melovoye/Karagiin OF, Pricaspian District, Mangyshlak Peninsula, W Kazakhstan [Remaining resources: 44 000 t U; mined ore averaged 0.042% U (fish bone concentrate 0.185% U, 30% P_2O_5), 0.178% REE (mainly Ce, La, Y, Nd), 0.06% Ni, 4.32% P_2O_5 , 11.1% S (in pyrite)]. *References:* Abakumov 1995; Laverov et al. 1992b, c; Petrov et al. 1995; Stolyarov and Ivleva 1995.

Type 17 Uraniferous Minerochemical Phosphorite Deposits (Idaho Phosphoria and Florida Land Pebble Types) (Fig. I.17)

Uraniferous phosphorite deposits consist of synsedimentary, stratiform disseminated uranium in marine phosphorite of

continental-shelf origin. U is bound in cryptocrystalline fluor-carbonate apatite. Phosphorite deposits constitute large uranium resources, but at a very low grade (several million t U, av. <20 to 300 ppm U).

Two main varieties of uraniferous phosphorite are recognized: (a) bedded phosphorite (Idaho Phosphoria type) and (b) land pebble (Florida type). Both are of widespread extension (up to several 1 000's of km²) and exhibit a rather uniform U distribution throughout a given bed.

a Bedded Uraniferous Phosphorite

Bedded uraniferous phosphorite consists of phosphatic shale with oolitic, pisolitic, pelletal, and laminated textures interbedded with fine-grained miogeosynclinal facies (black shale, mudstone, chert, rare carbonate beds). Bedded phosphorites formed distal to shore-line and commonly contain a higher uranium content as nodular phosphorite.

Type example: Permian Phosphoria Formation/Montpelier, Idaho, USA (Resources: several million t U, 60–200 ppm U). *Reference:* McKelvey et al. 1956.

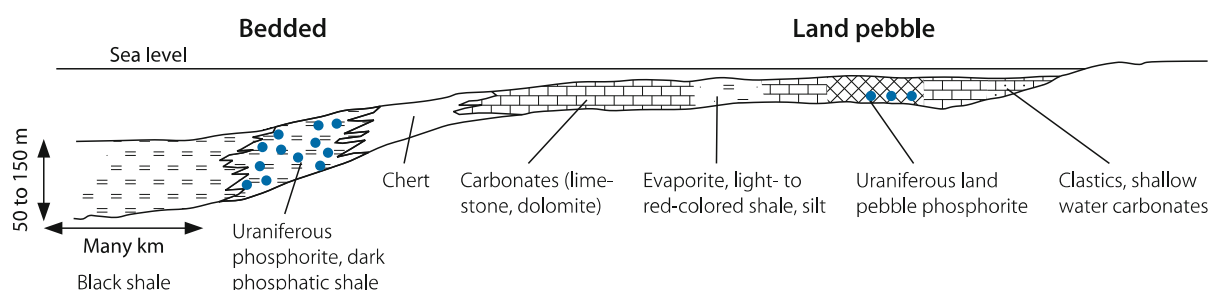
b Land-Pebble Phosphate

Land-pebble phosphate mineralization is composed of U enriched apatite pebbles within nodular phosphorite beds interbedded with fine- to medium-grained shallow marine facies (sand, clay) and carbonate beds. The “land pebbles” formed proximal to shore line by local reworking and leaching of nodular phosphorite leading to secondary U enrichment in the pebbles.

Type example: Pliocene Bone Valley Formation/Land Pebble District, central Florida, USA (Resources: >500 000 t U, grades average ca. 150 ppm U over <1–10 m thickness, and 2 500 km²). *Reference:* Altschuler et al. 1958.

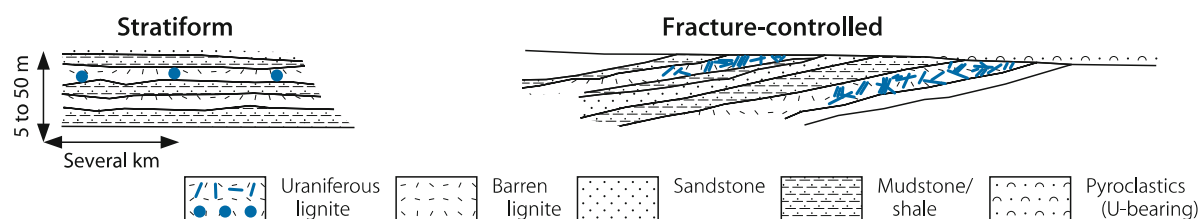
Fig. I.17.

U-deposit Type 17: uraniferous minerochemical phosphorite deposits (Idaho Phosphoria and Florida Land Pebble types)



■ Fig. I.18.

U-deposit Type 18: uraniferous lignite/coal deposits (Cave Hills and Freital types)



Type 18 Uraniferous Lignite/Coal Deposits (Cave Hills and Freital Types) (● Fig. I.18)

Uraniferous lignitic seams are interbedded with $\pm$ carbonaceous clastic sediments in paludal, low-lying, poorly drained shallow depressions located either on coastal plains (paralic lignite) or within land-locked basins (limnic lignite). Uraniferous felsic pyroclastics (rhyolitic tuff, etc.) often overlie and/or are intercalated with the seams. Granite or other rocks with anomalous U contents are common near these basins.

Uranium occurs in lignite/coal mixed with mineral detritus (silt, clay), and in immediately adjacent carbonaceous mud and silt/sandstone beds. Pyrite and ash contents are high. U is largely adsorbed on carbonaceous matter or bound in uranyl-humate. Discrete U minerals can locally occur. A variety of metallic trace elements are commonly present.

U occurs in two modes: (a) as *stratiform-syngenetic*, uniformly disseminated mineralization and (b) as *mixed stratiform/fracture-controlled epigenetic*, spotty and irregularly distributed mineralization. Resources are commonly small (<5 000 t U). Grades of syngenetic U mineralization are very low (<150 ppm U) and of epigenetic deposits low to medium (0.03–0.15% U).

Type example of mixed stratiform-fracture-controlled mineralization: (a) Cave Hills-Slim Buttes/SW Williston Basin, S Dakota, USA (Production: 290 t U, <0.1% U). *Reference:* Denson and Gill 1965. (b) Freital-Gittersee/Döhlen Basin,

Saxony, Germany (Production 3 700 t U, 0.12% U). *References:* Wismut 1999.

Type 19 Uraniferous Stratiform Black Shale Deposits (Ranstad and Chattanooga Types) (● Fig. I.19)

Stratiform black shale hosted uranium mineralization consists of syndimentary, uniformly disseminated uranium adsorbed on organic and clay particles in marine organic-rich, pyritic shale with thin coalified, phosphatic and/or silty intercalations. Discrete primary U minerals are absent. Other metals (Cu, Cr, Mo, Mn, REE, V, P) occur in small quantities. The organic matter is of sapropelic-bituminous or humic, coaly nature derived from planktonic marine algae and land plant (wood spores) debris. Limestone, sand/siltstone, and shale strata complete the stratigraphic sequence.

Mineralized black shale beds are of fairly uniform thickness (few meters to some 10 m), widespread extension (several 100s to 10 000s km²), and host enormous quantities of uranium but of very low U tenors. Better grades are confined to beds (dm to m thick) rich in organics, particularly humic-coaly material. If phosphate nodules are present, they normally contain more U than the surrounding shale. Resources are large and grades very low (several 100 000 t U to many million t U; 50–400 ppm U).

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

■ Fig. I.19.

U-deposit Type 19: uraniferous stratiform black shale deposits (Ranstad and Chattanooga types)

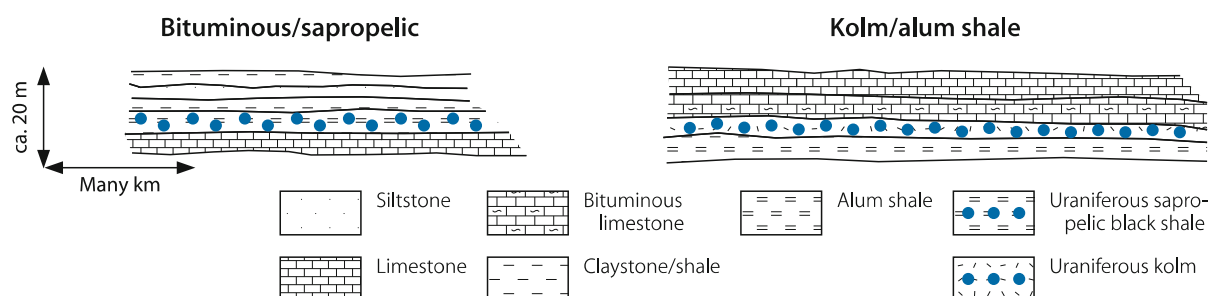
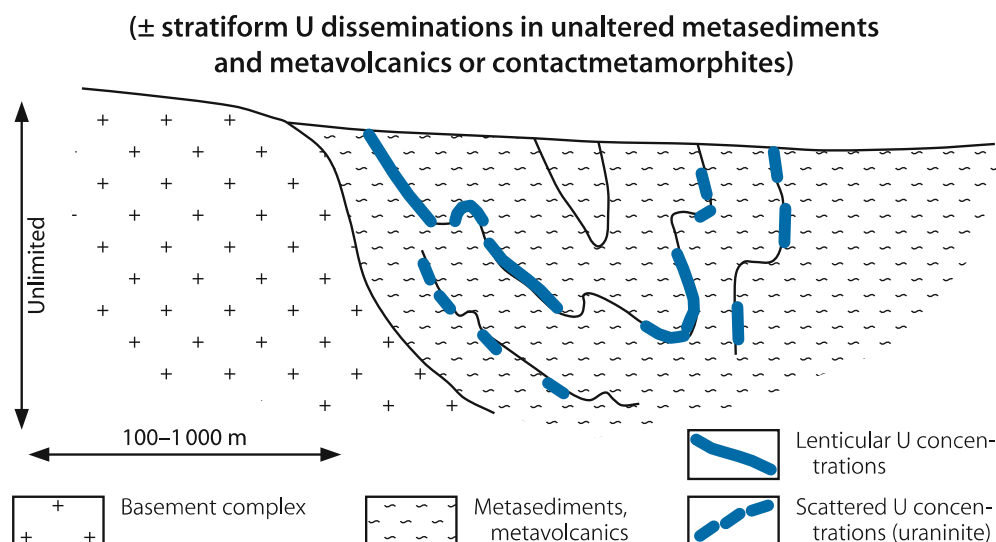


Fig. I.20.

U-deposit Type 20: uraniferous synmetamorphic and contact-metamorphic deposits (Forstau and Mary Kathleen types)



Based on U-associated organic substances two varieties of mineralization are distinguished: U associated (a) with humic/kolm in alum shale (Ranstad type) and (b) with bituminous/sapropelic black shale (Chattanooga type).

Type example for humic/kolm in alum shale: Ranstad, Sweden (Estimated resources: ~250 000 t U at 200–300 ppm U, including 65 000 t U at 300–380 ppm U). *References:* Carlsson and Nojd 1977.

Type example for bituminous-sapropelic black shale: Gassaway Member, Chattanooga Shale, USA (Estimated resources calculated for a restricted area in central Tennessee: >4 million t U, 57 ppm U). *References:* Mutschler et al. 1976; MSR and D 1978.

small and grades low (<1–1000 t U) whereas resources of contact-metamorphic deposits range from small to medium (<1 to >10 000 t U). Grades in both modes are low (<0.01–0.15% U).

Type example for synmetamorphic deposits: Forstau/Salzburg State, Austria (Resources: 700 t U, <0.1% U). *References:* Dahlkamp and Scivetti 1981.

Type example for contact-metamorphic deposits: Mary Kathleen/Queensland, Australia (Resources+production: 12 000 t U+REE, 0.1% U). *References:* McKay and Mieziotis 2001.

References and Further Reading

For details of publications see Bibliography.

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Type 20 Uraniferous Synmetamorphic and Contact-Metamorphic Deposits (Forstau and Mary Kathleen Types) (Fig. I.20)

Synmetamorphic (or metamorphic) and contact-metamorphic uranium mineralization, which resulted from regional and/or contact-metamorphism of uraniferous sediments or volcanics in a closed thermo-dynamic system, consists of disseminated uranium distributed strata-(pene-) concordant in small lenses or patches erratically scattered in metasediments, stratified metavolcanics, and mixed metasedimentary/metapyroclastic layers or contact-metamorphic equivalents (e.g. skarn at Mary Kathleen). Uraninite is typical for higher grade and pitchblende for low-grade (greenschist) metamorphosed facies. REE and/or other metals (as sulfides, sulfo-arsenides, etc.) may be present. Resources of synmetamorphic deposits are commonly

Quirt 1984; Hoeve and Sibbald 1978; Hoeve et al. 1980; IAEA 1986a; IAEA/Ferguson 1984; IAEA/Finch 1985b; IAEA/Fuchs 1986; IAEA/Pretorius 1987; IAEA/Toens 1984; IAEA/UDEPO 2007; Ischukova 1997; James and Hamani 1999; Jefferson et al. 2007; Jefferson and Delaney 2007; John 1978; Johnson et al. 1987; Jong Hwan Kim 1988; Karimov et al. 1996; Kazansky 1970; Kazanzky and Laverov 1977; Kolektiv 1984, 2003; Komínek 1997; Komínek and Veselý 1986; Kotzer and Kyser 1995; Lainé et al. 1985; Lange and Freyhoff 1991; Lanier et al. 1978; Laverov et al. 1992; Leroy and Cathelineau 1982; Leroy 1978a,b; Leroy et al. 1985, 1987; Mann and Deutscher 1978; Mashkovtsev et al. 1997, 2002; Mathews et al. 1979; Maurice 1982; McKay and Miezitis 2001; McKelvey et al. 1956; Mickle and Mathews 1978; Miguta and Tarkhanov 1998; Mineeva 1984; MSRandD 1978; Mutschler et al. 1976; Nash et al. 1981; Naumov et al. 2005; Needham et al.

1988; Orajaka 1981; Otton 1981, 1986; Pagel 1984; Pagel et al. 2003; Pardo-Leyton 1985; Pavlenko 2005; Perelman 1980; Petroš et al. 1986; Petrov et al. 1995, 2000; Phalaborwa Mining Co. 1976; Polito et al. 2005; Poty et al. 1986; Pretorius 1976a,b, 1981; Reeve et al. 1990; Robertson 1989; Roslyi 1975; Roubault 1958; Roy et al. 2006; Ruhrmann 1986; Ruzicka 1971, 1988; Samama 1984; Shcherbakov 1966; Schmitt and Clement 1986; Sherborne et al. 1979; Sibbald and Petruk 1985; Sibbald 1988; Sørensen et al. 1974; Stoikov and Bojkov 1991; Stolyarov and Ivleva 1995; Terentiev and Naumov 1997; Thamm et al. 1981; Thomas et al. 2000; Thompson et al. 1980, 1982; Thoste 1999; Tourigny et al. 2007; Tremblay 1982; Turner-Peterson et al. 1986; US-AEC 1959; von Backström 1975, 1976; Wallace 1986; Wang and Li 1996; Wenrich and Sutphin 1989, 1994; Wilde 1988; Wismut 1999; WMC Oct. 2004; Ziegler 1974.