Chapter 10
Russian Federation, Asian Territory

Uranium deposits and significant occurrences are reported from ten regions of Asian Russia. They include all significant districts and present production centers in Russia (➔ Fig. 10.1).

OECD-NEA/IAEA (2005) reports a total of 172 400 t U as remaining resources recoverable at <$80 per kg U, 131 750 t U of which are attributed to the RAR and 40 650 t U to the EAR-I category. Resources distribution by types of deposits amounts to 117 120 t U in volcanic-, 21 410 t U in sandstone-, and 33 870 t in vein-type deposits.

The *Streltsovsk Dis*trict in Transbaykalia is the prominent uranium district in Russia. In 2005, it had remaining reserves (RAR) of 117 120 t U in the <$80 per kg U category contained in volcanic-type deposits. Two other deposits with sandstone-type U mineralization in the *Transural* and *Vitim*/Transbaykalia Districts have cumulative resources of some 22 000 t U in the RAR + EAR-I, <$40 per kg U cost category.

Other regions contain in excess of 450 000 t U that are defined as explored, non-balance sheet inferred resources. Deposits in these regions were discovered, explored and technically and economically evaluated in the 1950s to 1980s, and require an up-to-date calculation of their resource cost categories.

Russia's cumulative uranium production from 1951 to end of 2005 is 123 000 t U. In 2005, active mining was restricted to the *Streltsovsk* (conventional underground) and *Transural* (ISL) districts while ISL production was planned to begin in 2006 in the *Vitim* District.

A mill at *Krasnokamensk* with a nominal production capacity of 3 500 t U yr^{-1} serves the Streltsovsk District. JSC "Priargunsky Mining and Chemical Production Association" (PPGHO) is the operator of this production center. JSC "Dalur" is the operator in the *Transural* (capacity 800 t U yr^{-1}) and JSC "Khiagda" in the *Vitim* (capacity 1 000 t U yr^{-1}) district. All mining enterprises belong to the state corporation "TVEL".

Since 2004, all uranium exploration is in the responsibility of the state-owned enterprise "Urangeologorazvedka" (formerly "Central Geological Exploration Division" or "Geologorazvedka"), which is financed by the federal "Ministry (or Committee) of Natural Resources" and, since 2004, by the "Federal Subsoil Resources Management Agency". Mining is in the hands of regional subsidiaries under supervision of "Atomredmetzoloto", a section of the "Ministry of Atomic Energy" (Minatom). All federal institutions related to uranium exploration and mining are based in Moscow.

The following compilation is based on Boitsov AV (1999), Boitsov AV and Nikolsky (2001), Boitsov VE (1996), IAEA 1995; Laverov et al. (1992a–c, 1995, 2000), Naumov (1999), OECD-NEA/IAEA (1997, 1999, 2005), amended by data of other authors cited in the sections of the various uranium regions, and pers. commun. by Boitsov AV, Boitsov VE, and Kazansky VI. [Note: After finalizing this manuscript a publication by Ischukova et al. (2002) became available addressing uranium deposits in volcano-tectonic structures and the reader is referred to this comprehensive volume for districts with volcanic-type U deposits in CIS countries and Mongolia.]

Historical Review

First reports on the discovery of uranium minerals of the present Asian territory of the Russian Federation date back to 1827 when C.F. Blondeau mentioned a "green uranite" (in later publications referred to as "chalcolith" (torbernite) from Siberia. The specimen was supposedly found near Yekaterinburg (formerly Sverdlovsk) on the eastern slopes of the central Ural mountains from where Leymerie (1859) reported "chalcolith" and Arzruni (1885) torbernite in talc schist from the Beresovsk gold mining district, located NE of Yekaterinburg.

Systematic exploration for uranium, however, did not get under way until 1944, efforts that began to meet with success in 1946. At that time deposits had been found in the Yenisey region, western Siberia. Next, uranium was discovered in the Aldan region in 1961, the Streltsovsk District in the Transbaykal region in 1963 (still the most important find), followed by discoveries in the Vitim and Transural districts in the late 1960s and 1970s. In total, twelve uranium regions or districts have been identified, four of which are in European Russia and eight in Asian Russia (➔ Fig. 10.1).

Despite the enormous scale of the exploration effort, vast areas remain virtually unexplored, notably the remote region bounded to the west by the Ural mountains, to the south by the 60th parallel, the northeast by the Chukotsky Peninsula and the southeast by Sakhalin Island. The reason for this apparent neglect was caused by major discoveries of ample uranium resources in the then-Soviet republics of Kazakhstan and Uzbekistan.

First *uranium mining* in the former imperial Russia took place in the central Asian regions of the country at the beginning of the 20th century. Famous mines were at Tyuya-Muyun in the Fergana Basin, now Kyrgyzstan (for details see there). From 1904 to 1914 about 700 t of uranium ore were mined and three quarters thereof were shipped to and beneficiated at St. Petersburg yielding 2.3 g radium (Chervinsky 1923/1925).

Uranium mining on present-day Russian territory started first in the *Stavropol* District, Caucasus region, in 1951 where it lasted until 1990 and produced 5 700 t U.

A small deposit, *Sanarskoye* in the western Transural region, was exploited by ISL methods and yielded 440 t U between 1968 and 1980. Two isolated small deposits, *Butugichag* and *Severnoye,* were mined in eastern and northeastern Siberia, respectively. At least a small quantity of uranium was presumably also produced during exploration work in the *Aldan* region in eastern Siberia. The presently (2006) active *Streltsovsk District* in Transbaykalia started up in 1968 and produced from ten deposits about 110 000 t U until 2005.

Fig. 10.1.

Russian Federation. Location of uranium regions, districts and areas (after Boitsov AV 1999; Laverov et al. 1992c, 1995). *Uranium regions and districts: Uranium regions and districts: NC* N Caucasus reg./Stavropol Dist., *EG* Ergeninsky reg., *KK* Karelian-Kolsky (Baltic Shield) reg., *ON* Onezhsky (Lake Onega) Dist., *LA* Ladozhsky (Lake Ladoga) Dist., *VU* Volga-Ural reg., *TU* Transural reg., *WS* West Siberian reg., *YS* Yenisey reg., *TB* Transbaykal reg., *ST* Streltsovsk Dist., *VI* Vitim Dist., *CTB* Central Transbaykal subreg., *AD* Aldan reg., *FE* Far East reg., *BU* Bureinsky Dist., *KH* Khankaisky Dist., *CH* Chukotsky reg., *SV* Severnoye, *CK* Chaika etc., *CP* Chaplinskoye, *OK* Okhotsk reg., *SK* South Kolima River reg. *Isolated U deposits/occurrences*: *a* Belskoye, *b* Briketno/Zheltukhinskoye, *c* Badielskoye, *d* Kedrovoe, *e* Kremnistoye, *f* Kavly, *g* Dzhigda, *h* Butugichag)

Annual uranium production in Russia is speculated at 300–400 t U until about 1970. It reached a peak of about 4 000 t U in the 1980s. In 1990, 3 776 t U were recovered, decreasing to 2 160 t U in 1995. A turn around in the downward trend was achieved with an increase to 2 605 t U in 1996 and to 3 280 t U in 2004.

10.1 Transural Region/Kurgan Area

The Transural region stretches for 600 km from the Sosva river southward to the Tobol river in southwestern Siberia but extends from Russia further south- and southeastward for several hundreds of kilometers into Kazakhstan. Major towns are Kurgan and Chelyabinsk (Fig. 10.2, 10.3).

A number of deposits and occurrences of basal-channel sandstone-type are reported. The most significant ones occur in the southern part of the region, to the south of Kurgan. They include *Dolmatovskoye* (10 200 t U RAR), *Dobrovolnoye* (7 700 t U RAR + EAR-I) and *Khokhlovskoye* (speculated 10 000 t U). Two small deposits are *Vinogradovskoye* and *Cherepanoskoyye* each containing less than 1 000 t U. Ore grades average 0.04–0.05% U. The total potential resources of the entire Transural region are thought to be on the order of 120 000 t U.

One deposit of surficial or sandstone type, *Sanarskoye*, located in the western extremity of the Transural region was mined by open pit and ISL methods from 1968 to 1980 yielding 440 t U. Ore grade was 0.08% U. The depleted deposit was hosted in a valley filled with Quaternary carbonaceous sandy sediments. Uranium was associated with organic matter.

The former operator was S.C. "Malyshevsk Mining Administration" based at Asbest, Sverdlovsk Province, established in 1967 originally for the supply of beryllium and tantalum to the nuclear industry recovered from pegmatites in the Ural mountains.

ISL mining began at Dolmatovskoye in 2002 with a nominal production capacity of 800 t U yr^{-1} (production was about 250 t U in 2005). Khokhlovskoye is in the development stage for U extraction by ISL techniques. Operator is the recently formed joint-stock company JSC "Dalur".

Source of information. Boitsov 1999; Laverov et al. 1992; and Loutchinin 1995a, 1995b unless otherwise stated.

Regional Geological Setting of Mineralization

The Transural uranium region is in the SW part of the West-Siberian Platform. The region is characterized by *Middle to Upper Jurassic* paleochannel systems, which occupy the southwestern alluvial coastal plain of the Jurassic sea in the eastern foreland of the Caledonian Ural mountains. The channels were incised into a basement of *Devonian* felsic volcanics, continental and marine sediments (Fig. 10.3).

Paleodrainage systems consist of 1–5 km wide channels filled with 30–120 m thick, permeable alluvial-fluvial sediments of *Bathonian-Kimmeridgian* age. Lithologies include beach gravel, conglomerate, sand, silt and mud containing high amounts of plant debris (av. 0.5–3% C_{org}). Three sedimentary cycles are distinguished, which are attributed to attenuating movements during the final folding and uplift phase in the Ural mountains. Subsequent to the orogenic activity, the river valleys degraded to chains of drainage lakes into which proluvial and limnic sediments were deposited during *Late Jurassic – Early Cretaceous* (Volga stage and Berriasian) time. These sediments consist of 30–150 m thick impermeable, pink, carbonaceous silt, clay and sand, which contain 100–300 ppm U in form of syngenetic uranium associated with dispersed plant remains. 300–700 m thick *Cretaceous and Tertiary* sediments increasing to the east, north and south rest on the Jurassic rocks.

The northern limit of the uranium region is conterminous with the northern boundary of the Late Jurassic – Early Cretaceous pink sediments, which in turn coincides with the boundary between the late Jurassic semi-arid and humid climate zones to the south and north respectively.

Principal Host Rock Alteration

Oxidation and re-reduction altered the U-bearing grey alluvial-fluvial sediments. Both alteration facies do not contain either Fe-oxides or carbonaceous matter. A redox interface resulted from downstream influx of oxygenated waters. Re-reduction documented by bleaching is assumed to postdate the deposition of the overlying, impermeable pink facies. Reducing agent was plant debris originally present in high amounts of up to 3% C and more.

Principal Characteristics of Mineralization

Principal *U minerals* are colloform U-oxides and coffinite. *Associated minerals* include chalcopyrite, ferriselite, jordisite, marcasite, pyrite, sphalerite, native selenium, and rhenium and vanadium oxides. Additional elements in detrital minerals are Sc, Y, and lanthanides. The uranium and associated minerals occur in disseminated form along redox interfaces. Isotope dating of U minerals yield an age of 135 ±7 Ma.

General Shape and Dimensions of Deposits

Individual deposits have resources from several hundreds to 12 000 t U mostly contained in several ore bodies. Ore grades range from 0.01 to 3% U and average 0.03–0.05% U.

Deposits are from less than 1 to 25 km long, 50–1 500 m wide and up to 50 m thick and occur at a depth in excess of 300 m. Individual ore bodies have dimensions of <1 to 7 km long, 50–700 m wide, and 1.5–20 m thick. Ore bodies display in plan view an elongated lens or ribbonlike configuration and in section predominantly a lenticular and, more rarely, a roll shape. Lenses occur singularly or en echelon stacked at several levels separated by aquicludes. Some of the ore bodies trend along and others oblique to channel axes (Figs. 10.4, 10.5).

Fig. 10.2.
West Siberia. Paleogeomorphological map of the West-Siberian Platform illustrating the typical restriction of basal-channel sandstone-type U deposits of the Transural and West Siberian uranium regions to Jurassic (J_3) southern coastal alluvial plains (younger rocks not shown) of the Jurassic sea, which developed during a semiarid climate. Deposits of the Yenisey uranium regions occur within the Caledonian fold belt (after Loutchinin 1995a; Dolgushin et al. 1995; Laverov et al. 1992c). U regions: *TU* Transural, *WS* West Siberian, *YS* Yenisey. Deposits: *Bys* Bystroye, *Dob* Dobrovolnoye, *Dol* Dolmatovskoye, *Ked* Kedrovoye, *Kho* Kholovskoye, *Lab* Labyshkoye, *Mal* Malinovskoye, *Prg* Prigorodnoye, *Pri* Primorskoye, *San* Sanarskoye, *Smo* Smolenskoye, *Sol* Solonechnoye, *UU* Ust-Uyuk; in Kazakhstan: *Sem* Semizbayskoye, *Sen* Sensharskoye, *Tob* Tobolskoye

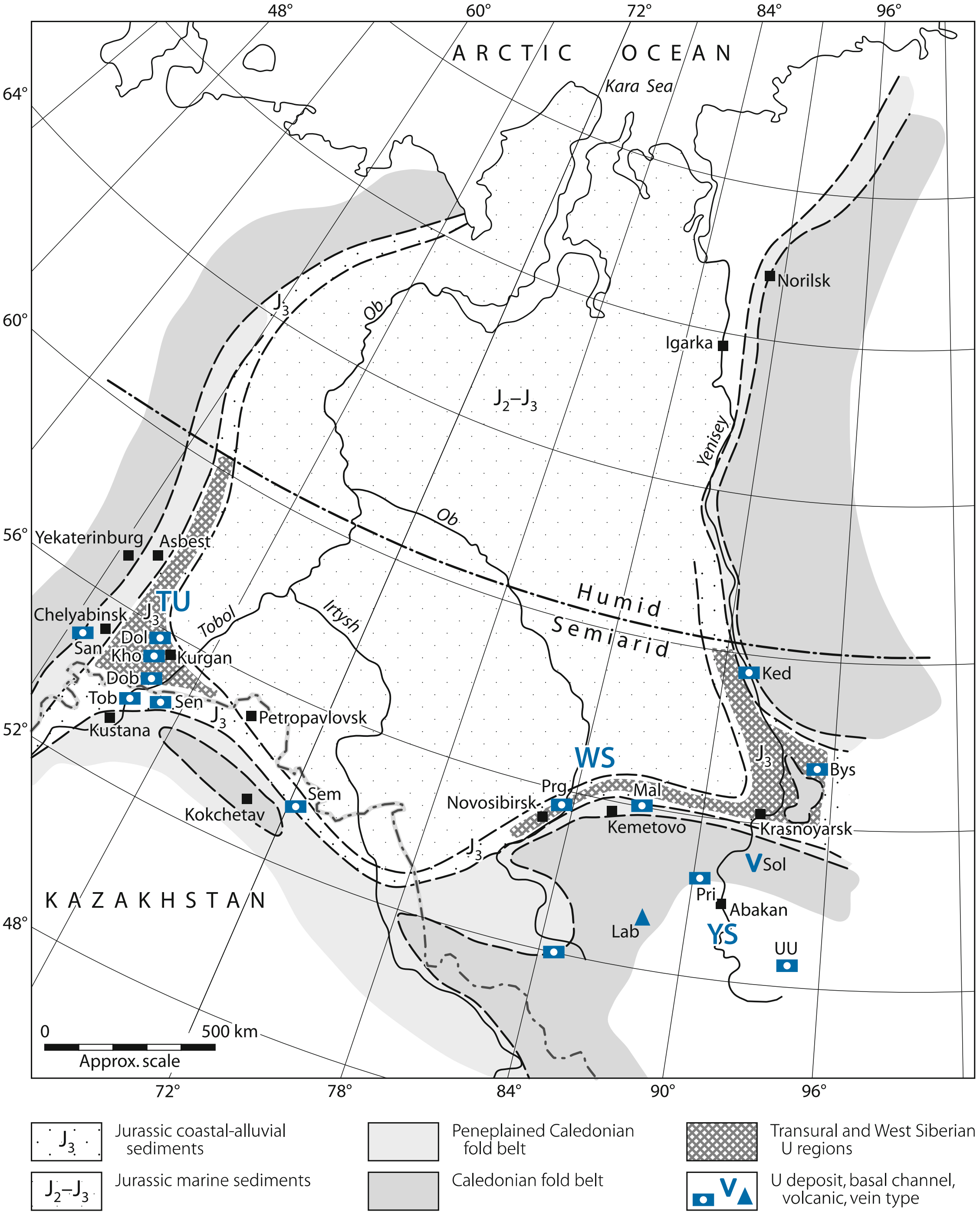
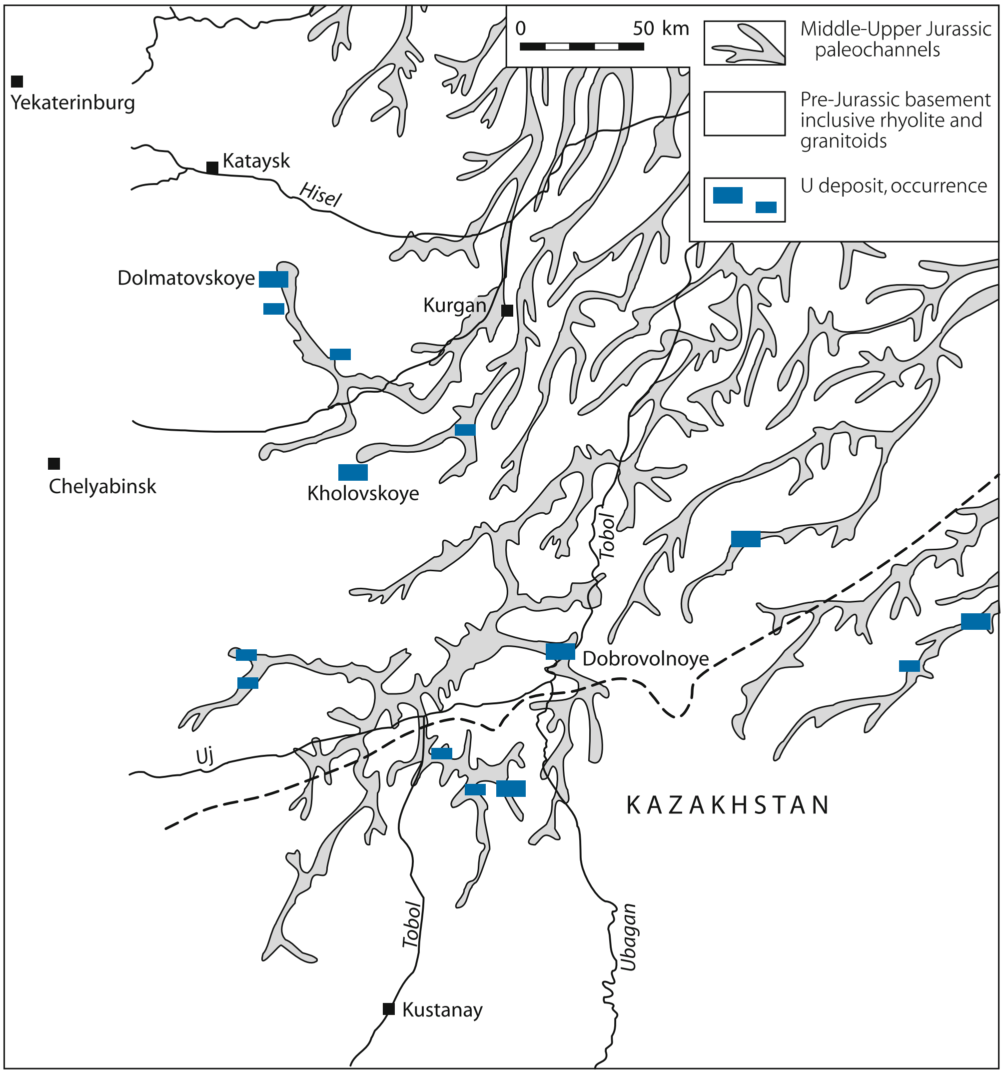


Fig. 10.3.

Transural region. Generalized paleogeological map of Middle to Late Jurassic paleochannel systems and related basal-channel sandstone-type U deposits and occurrences at the southwestern margin of the Middle-Upper Jurassic sea. Cretaceous to Quaternary cover not shown (after Loutchinin 1995a; Laverov 2000)



Principal Ore Controls and Recognition Criteria

Mineralization is primarily lithologically and geochemically controlled. Significant ore controlling parameters or recognition criteria of deposits of the Transural region include:

Host environment

- Basement of Devonian volcanics and continental and marine sediments
- Paleosurface weathered during semiarid climate
- Old peneplain incised by Middle to Late Jurassic paleodrainage systems
- Valleys filled with Middle to Late Jurassic continental clastic sediments
- Cover of Late Jurassic-Early Cretaceous impermeable, pink proluvial – limnic sediments overlain by thick Cretaceous to Recent sediments providing protection against erosion of ore hosts
- Rhyolite with 4–5 times background U contents presumably provided potential U sources

Host rocks

- 30–150 m thick alluvial-fluvial sediments composed of well permeable beach gravel, conglomerate, sand, silt, and mud of Middle to Late Jurassic age
- Reduced facies of grey color and high content of carbonaceous matter (av. 0.5–3% C_{org}) and minor sulfides

Alteration

- Oxidation with formation of redox fronts
- Re-reduction reflected by bleaching

- Reduction potential provided predominantly by organic matter and subordinately by sulfides
- Redox fronts developed downstream by channel invading vadose waters

Mineralization

- U-oxides/sooty pitchblende and coffinite
- Large number of associated elements
- Disseminated texture of mineralization
- Elemental zoning
- Lens- and roll-shaped ore bodies
- Ore bodies trending along and oblique to channel axes
- Ore restricted to grey facies containing in excess of 0.2% C_{org}
- Regional distribution of deposits correlating with extension of pink proluvial-limnic cover facies

Principal Aspects of Metallogenesis

Deposits are of epigenetic origin derived from oxygenated meteoric waters. Loutchinin (1995) postulates that the solutions must have entered the permeable grey alluvial-fluvial horizon at the valley heads in the western uplands. Elsewhere impermeable sediments of the pink proluvial-limnic facies prohibited the downward percolation of mineralizing solutions. The oxygenated solutions oxidized the originally reduced grey facies and established redox fronts along which uranium and associated elements (Mo, V, Se, and Re) were fixed in a zonal distribution typical for these types of deposits. Ore concentration was restricted to lithological intervals containing 1.5–2.5% C_{org}.

Since the mineralizing solutions could have entered the alluvial horizon only at the exposed valley heads, the source of uranium must have been located in this region of the Ural foreland. Rocks in this region include rhyolite with 4–5 times background U values.

The main stage of uranium mobilization is attributed to an early weathering period under semiarid conditions affecting the peneplain formed during the waning stage of tectonic activity in the Ural region.

10.1.0.1 Dolmatovskoye

This deposit (Fig. 10.4) is located about 50 km S of the town of Dolmatovo. Original in situ resources amount to 10 200 t U (RAR). Ore grade is 0.039% U. A number of ore bodies occur at a depth of 360–500 m in an 11 km long main and an 8 km long tributary paleovalley. The valleys are locally up to 3 km wide. Channel facies are Middle-Upper Jurassic alluvial sediments composed of pink oxidized and grey reduced sandy gravel, sandstone and conglomerate interbedded with silty mudstone. Overburden consists of Cretaceous and younger sediments. The channels are incised for about 100 m deep into Upper-Middle Paleozoic slate, limestone and, towards the headwaters to the SW, into Devonian rhyolite and rhyolite-porphyry. Faults trend E-W, NW-SE, and NE-SW.

Uranium is present as coffinite and pitchblende. Ore grades range from 0.01 to 3% U. High-grade U sections may contain Mo, Re, Sc, and REE minerals. Uranium distribution is controlled by redox boundaries in sand-gravel aquifers. In plan view, most ore bodies are lenticular in shape markedly elongated along the valley axis. In cross-section, they show a lenticular or roll-shape. Ore bodies occur individually or stacked at several levels separated by argillaceous aquicludes. Individually ore bodies are from 400 to 4 500 m long, 50–700 m wide, and 2–12 m thick. Rolls can be as much as 20 m thick (Naumov et al. 2005; Boitsov 1999).

10.1.0.2 Dobrovolnoye

Dobrovolnoye is located 100 km SW of Kurgan. RAR and EAR-I are estimated at 7 700 t U at an ore grade averaging 0.053% U. Dobrovolnoye is in the northern Turgai Basin where it covers a 17 km long stretch in the Ubagan paleovalley (Fig. 10.5). Middle-Upper Jurassic alluvial-fluvial sediments subdivided into three sedimentary cycles fill the valley. Each of the cycles contains uranium.

Four main ore bodies are delineated in three aquifers at a depth of 485–690 m with approximately 80% of the resources positioned at a depth of about 570 m. The ore bodies are of elongated lens or ribbonlike configuration but some display also rolls shapes. Some of the ore bodies trend along and others oblique to the channel axes. Individual ore bodies are from 1 to 7.5 km long, 50–800 m wide, and from 1.5 to 17.5 m thick. Ore grades range from 0.01 to 3% U (Loutchinin 1995a, 1995b; Boitsov 1999).

10.1.0.3 Khokhlovskoye

The deposit was discovered 1992 close to the Shumikha settlement. Speculative resources amount to 10 000 t U. Ore grade is 0.036% U. Host rocks are Upper Jurassic alluvial-fluvial sediments in a paleovalley incised into pre-Mesozoic shale, limestone, tuffite, and tuff-sandstone. A 10–50 m thick mineralized horizon occurs at a depth of 525–620 m. It was traced for 14 km along the paleochannel. Individual ore bodies are up to 12.8 m thick and average 6.2 m. Uranium tenors range from 0.01 to 0.3% U. Coffinite and pitchblende are the principal U minerals (Boitsov 1999).

10.2 West Siberian Region/Novosibirsk-Kemerov Area

The region extends as a relative narrow curvilinear belt along the southeastern edge of the West-Siberian Platform, from the south of Novosibirsk eastward for some 900 km to beyond Krasnoyarsk. The eastern portion around Krasnoyarsk adjoins with the Yenisey uranium region (see below). The belt coincides largely with the alluvial coastal plain of the Jurassic sea (Figs. 10.2, 10.6).

Known deposits are of basal channel sandstone type. Largest deposit is *Malinovskoye* (see below). The Malinovskoye area additionally includes the *Spirinskoye* and *Usmanskoye* U occurrences both hosted in the Jurassic Usmanskaya channel, and the *Novoalexandrovskoye* occurrence in the Tyshtymskaya channel (Fig. 10.7). Other, smaller deposits with resources on the order of 1 500–5 000 t U occur elsewhere in the region. They include *Prigorodnoye* located some ten kilometers to the NE of Novosibirsk, *Smolenskoye* in the southwestern part of the region both hosted in Tertiary paleochannels, and *Bystroye* in a Jurassic paleochannel near the eastern boundary of the region (Fig. 10.6). Host rocks of many deposits are clastic sediments with limited permeability.

Total in situ resources of the West Siberian region in the up to $80 per kg U cost category are estimated at approximately 40 000 t U. Ore grades of deposits are on the order of several hundreds ppm U.

Sources of information. Boitsov 1999; Boitsov and Nikolsky 2001; Dolgushin et al. 1995.

10.2.0.1 Malinovskoye

Malinovskoye is a basal channel sandstone-type deposit located 60 km SW of the town of Mariinsk. In situ resources are estimated at about 15 000 t U. Average ore grade is less than 0.06% U.

Malinovskoye is in the Jurassic, N-S-trending, 50 km long and 1–3 km wide Malinovskaya paleovalley (Fig. 10.7). Depth increases from 70 m in the headwaters to 300 m in the downstream section. The channel is incised into a basement of Cambrian volcanic-sedimentary rocks into which granite and diorite were intruded, and Devonian terrestrial and continental volcanic sediments intruded by post-Devonian granite and syenite. Mesozoic sediments as much as 300 m thick rest on the

Fig. 10.4.

Transural region, Dolmatovskoye deposit. a Schematic geological map at a level about 300 m below surface showing the distribution of alteration zones and U ore bodies in a Middle to Late Jurassic paleochannel. Overlying Cretaceous-Quaternary sediments not shown. b Geological SW-NE cross-section (after Naumov et al. 2005)

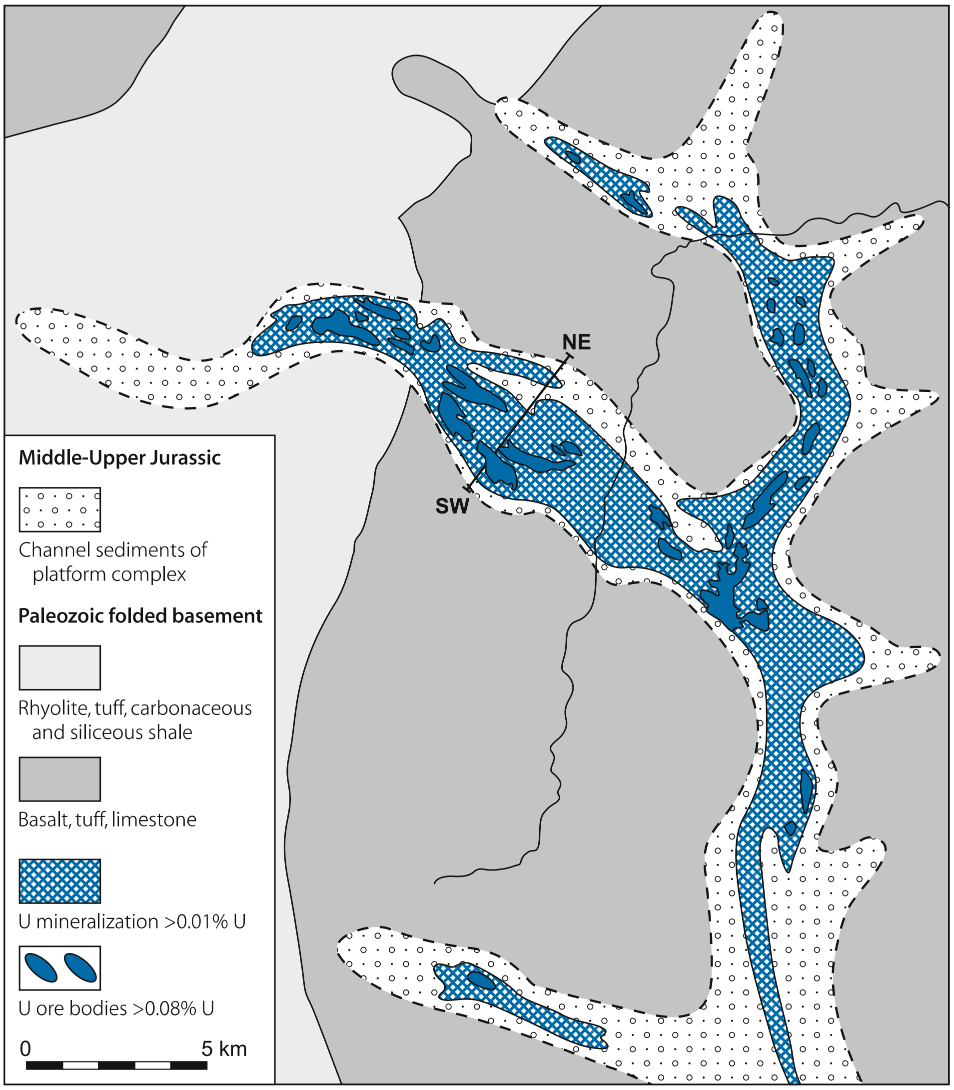
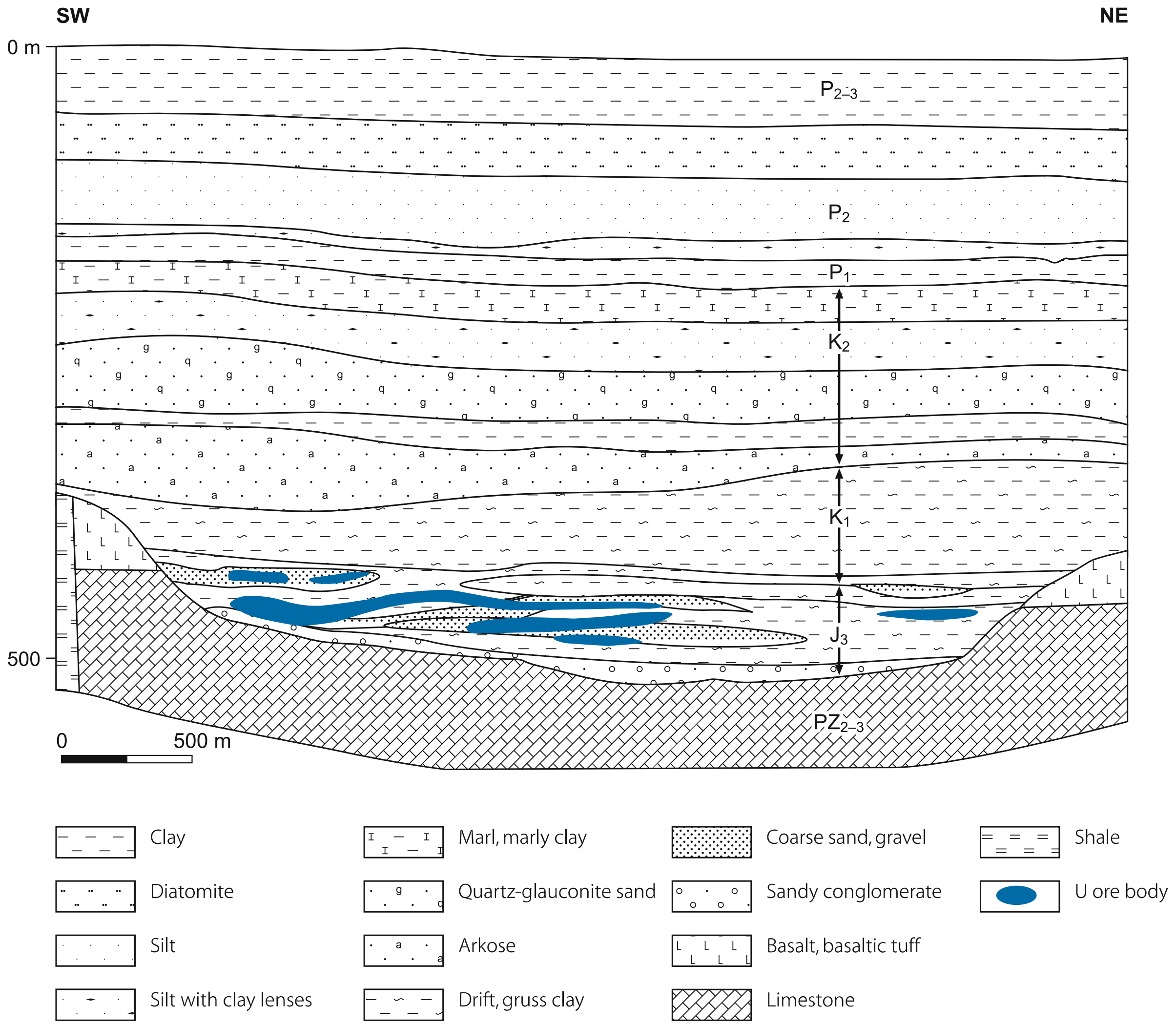


Fig. 10.4. (Continued)



channel facies. They start with 50–110 m thick, pink, Lower Cretaceous clays, which are overlain by up to 200 m thick Lower to Middle Cretaceous sands interbedded with kaolinitic clays.

The paleovalley is filled with 70–120 m thick, alluvial sediments of the Late Jurassic-Early Cretaceous Bazhenovsky Horizon. Mineralized lithologic facies are grey, carbonaceous sands of variable grain size alternating with conglomerates, clay and silt beds. Coalified vegetal remains are abundant, particularly in the basal part of the channel. Thin, 0.1–0.5 m thick lignite seams are locally intercalated. The filtration factor varies in the aquifer between 0.65 and 17.

Mineralization is found over an 18.5 km long channel interval. It envelops a 2.6 km long, 100–300 m wide, and as much as 50 m thick ore zone at a depth of 100–300 m below surface. Ore occurs in lenticular and roll-shaped lodes within in two stratigraphic horizons, which are separated by an aquiclude. One horizon is 1.8 km long, 16–90 m wide, 1–15 m thick and occurs at a depth of 247–300 m in the eastern part of the paleochannel. The other horizon is 2.5 km long, 50–250 m wide, 0.7–20 m thick, and 277–300 m deep.

Mineralization consists primarily of disseminated sooty pitchblende. Pitchblende and coffinite occur subordinately. Ore grades vary between 0.013 and 0.139% U but go locally as high as 1.32% U. Associated elements average <0.045% Mo, <0.1% V, 0.01–0.15% Cu, 0.01–0.15% Pb, 0.01–0.15% Zn, <0.002 Sc, <0.015% Y, <0.02% Ge. Carbonate content is 0.5% CO_2. The clay fraction averages 17%.

10.3 Yenisey Region

The Yenisey uranium region occupies the upper Yenisey River-Altay-Sayan area, with the town of Abakan in its center. Early reports going back to 1925 report V-U mineralization in Permian carbonaceous or coal beds at Minussinsk and Abakan in the Paleozoic Minussinsk Depression, which covers over 16 000 km^2. Post-World War II exploration discovered a number of uranium occurrences. Ten occurrences of various types are reported (Figs. 10.2, 10.8). Representative occurrences of sandstone type include *Primorskoye* and *Ust-Uyuk,* of vein, type *Labyshkoye,* and of volcanic, type *Solonechnoye*. The first two occurrences have resources in excess of 5 000 t U and grades ranging from 0.1 to 0.3% U while the others contain between few hundreds to few thousands t U at grades of less than 0.1% U.

Fig. 10.5.

Transural region, Dobrovolnoye deposit. a Paleogeological map at level 500 m below surface documenting the distribution of U ore bodies and alteration zones in a Middle to Late Jurassic paleochannel. Overlying Cretaceous-Quaternary sediments not shown. b Geological SW-NE cross-section (after Loutchinin 1995b)

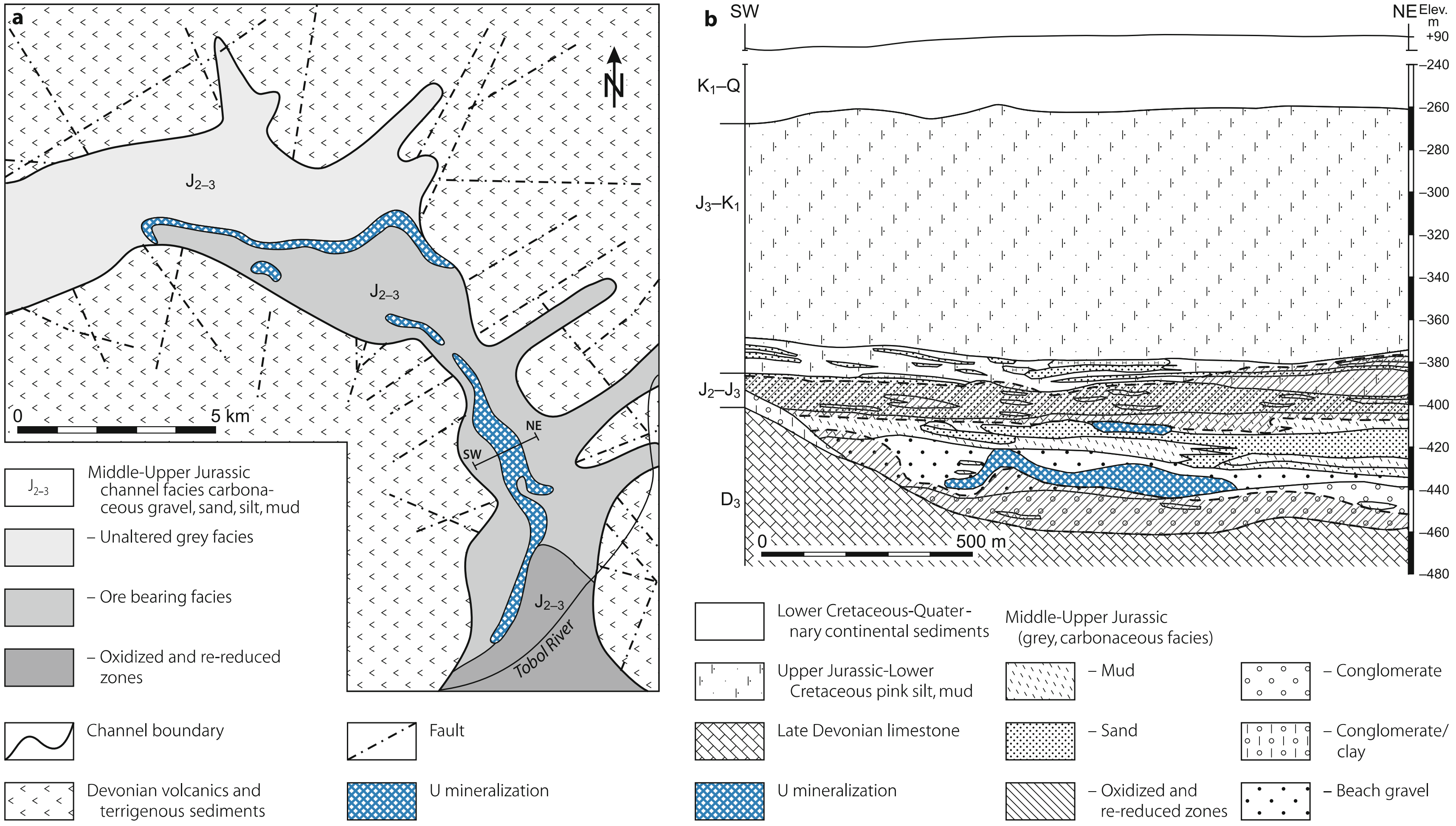
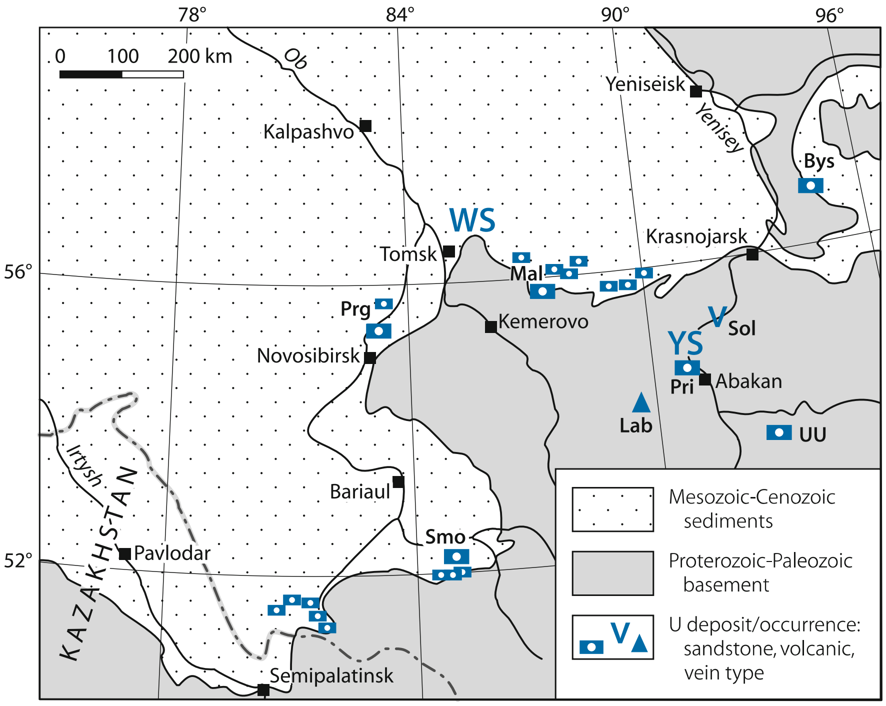


Fig. 10.6.
West Siberian (*WS*) and Yenisey (*YS*) regions. Regional geological map with location of U deposits and major occurrences. Deposits in the West Siberian region are typically of basal-channel type in Upper Jurassic alluvial-fluvial sediments whereas the Yenisey region contains deposits of various types in Paleozoic-Proterozoic rocks (after Dolgushin et al. 1995) *U regions*: *WS* West Siberian, *YS* Yenisey. *Deposits*: *Bys* Bystroye, *Lab* Labyshkoye, *Mal* Malinovskoye, *Prg* Prigorodnoye, *Pri* Primorskoye, *Smo* Smolenskoye; *Sol* Solonechnoye, *UU* Ust-Uyuk



Total resources of the Yenisey region are estimated at 40 000 t U in the $130 per kg U cost category. They include 8 000 t U in the RAR + EAR-I class and 32 000 t U in the EAR-II class.

Source of information. Boitsov and Nikolsky 2001.

Regional Geology and Mineralization

The Yenisey uranium region is an orogenic terrane with uplifts and depressions. Proterozoic – Lower Paleozoic granite-metamorphic complexes constitute the cores of uplifts. They are locally mantled by early orogenic felsic and mafic continental volcanics of Lower Devonian age. Depressions are filled with late orogenic continental sediments, predominantly pink sandy siltstone of Upper Devonian-Carboniferous age. Jurassic sediments cover part of the older rocks. Major faults trend about ENE-WSW, N-S to NNW-SSE, and NNE-SSW.

10.3.0.1 Primorskoye

Primorskoye was discovered 75 km N of Abakan in 1970. It is a tabular sandstone-type deposit. Estimated resources are 7 600 t U. Ore grade averages 0.25% U.

Uranium occurs in an alternating sequence of Upper Devonian sandstone, siltstone, and claystone of lacustrine origin in the Minussinsk Basin. Mineralization is bound to 0.3–0.5 m thick lenses of grey, highly carbonaceous (up to few percent carbon) sediments. Ore bodies display two configurations, irregular tabular or lenticular associated with argillaceous limnic facies, and ribbon-like in fluvial sand and clay facies within channel systems (Fig. 10.9). Principal U mineral is coffinite while pitchblende occurs in minor amounts. Texture of ore is finely disseminated. Ore grades range from 0.05 to 2% U. Isotope datings of ore minerals yield ages of 340–370 Ma (Mashkovtsev et al. 1995).

10.3.0.2 Ust-Uyuk

Ust-Uyuk is a basal-channel sandstone-type deposit located about 300 km SE of Abakan. Resources are in excess of 5 000 t U. Grades are on the order of several hundreds ppm U.

Ust-Uyuk is hosted in a paleochannel within the Tuvinsky Basin. Host rocks are Upper Devonian alluvial sediments composed of alternating sandstone, siltstone, mudstone, and tuff. U phases are dominated by finely disseminated coffinite. Pitchblende and sooty pitchblende are present in minor quantities. Mineralization occurs in form of elongated lenses but also of roll shaped bodies commonly positioned at the contact of pink and grey facies.

10.3.0.3 Labyshkoye

Labyshkoye was discovered about 250 km WSW of Abakan in 1960. The vein-type deposit is hosted in Cambrian marble, quartzite, and granite. Resources amount to some 1 500 t U. Grades are on the order of 0.1–0.3% U.

10.3.0.4 Solonechnoye

Solonechnoye is situated about 240 km NNE of Abakan and was discovered in 1961. It is a small (some 3 000 t U) volcanic-type deposit hosted by Lower Devonian felsic and mafic effusive rocks and tuff. Grades are several hundred ppm U.

Fig. 10.7.

West Siberian region, Malinovskoye deposit. a Generalized geological map; b W-E cross-section showing the position of the deposit at the basal eastern flank in the paleochannel; c Enlargement of the ore interval with U grade distribution along drill holes (after Dolgushin et al. 1995; Naumov et al. 2005; Boitsov and Nikolsky 2001). Explanation for a *Paleochannels*: *1* Malinovskaya, *2* Usmanskaya, *3* Tishtimskaya. *U occurrences*: *Nov* Novoaleksandrovskoye, *Spi* Spirinskoye, *Usm* Usmanskoye

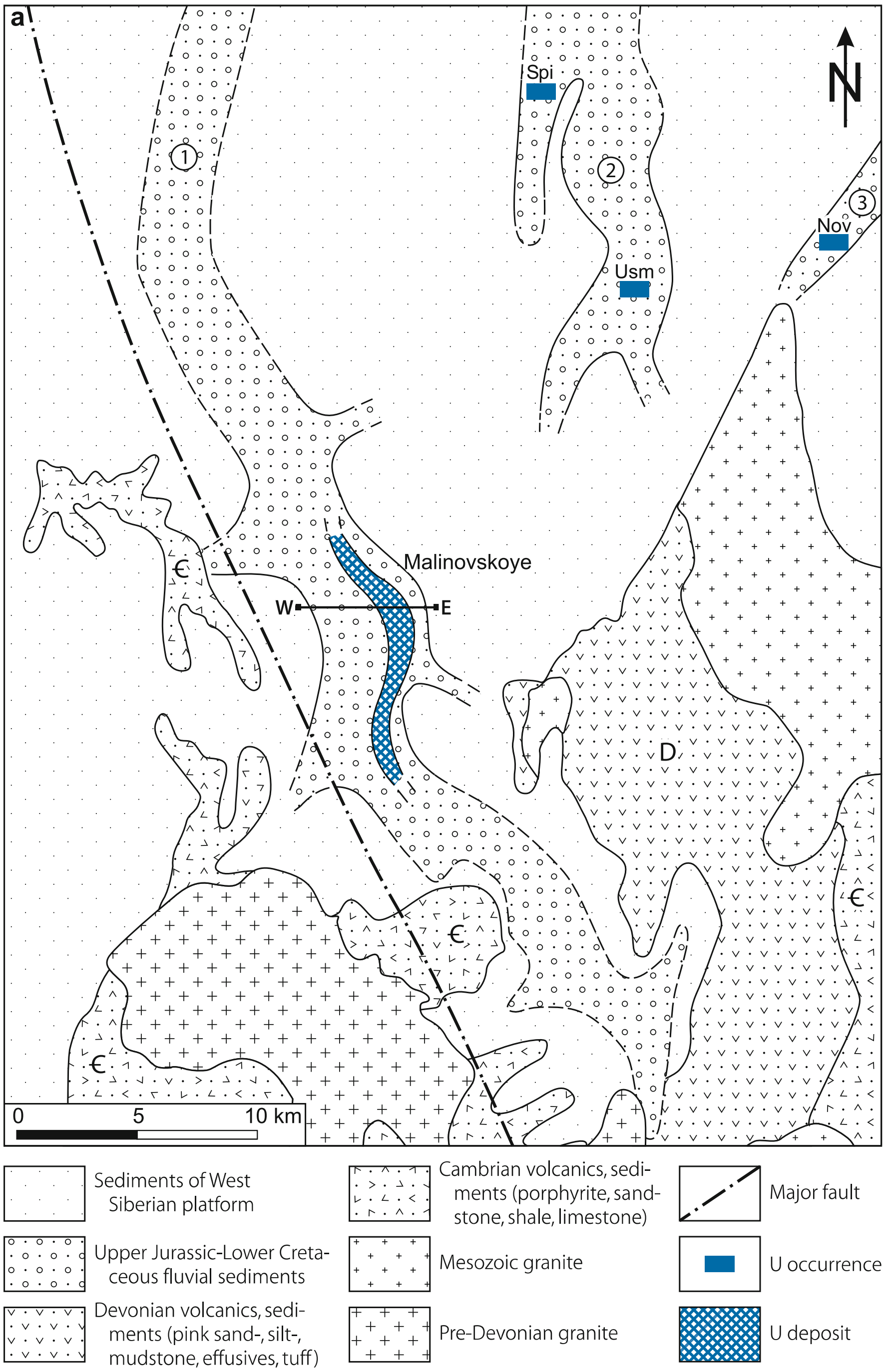
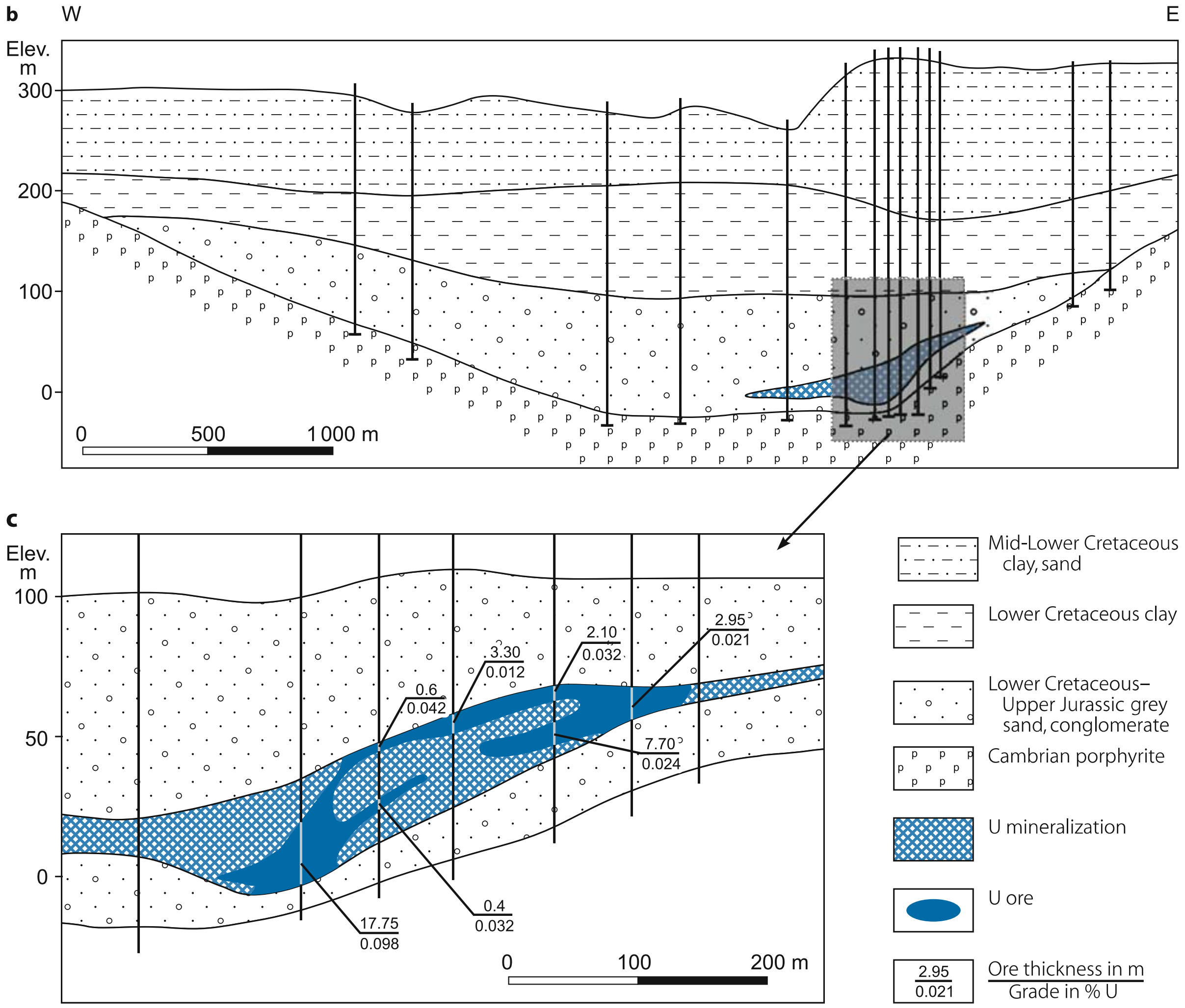


Fig. 10.7. (Continued)



10.4 Transbaykal Region

A number of uraniferous areas are established in the Transbaykal region between Lake Baykal to the west and the Chinese-Mongolian border to the east and south. Most prominent are the *Streltsovsk* and *Vitim* districts (Fig. 10.10); the first was the sole active mining district in Asian Russia during the 1990s and early 2000s while deposits in the Vitim District were tested for ISL mining in 2006. Other areas with numerous, mostly small uranium occurrences are mentioned by Pelmenev (1995) and Vishnyakov (1995) for the *Central Transbaykal subregion*.

10.4.1 Streltsovsk District, Asian Russia

The district is 12 km SE of the town of Krasnokamensk in eastern Transbaykalia, Chita Province, approximately 40 km to the west of the Chinese border formed by the middle course of the Argun River (Figs. 10.10, 10.11). The Streltsovsk District is by reserves, grades, and production unique among volcanic-type U deposits of the world.

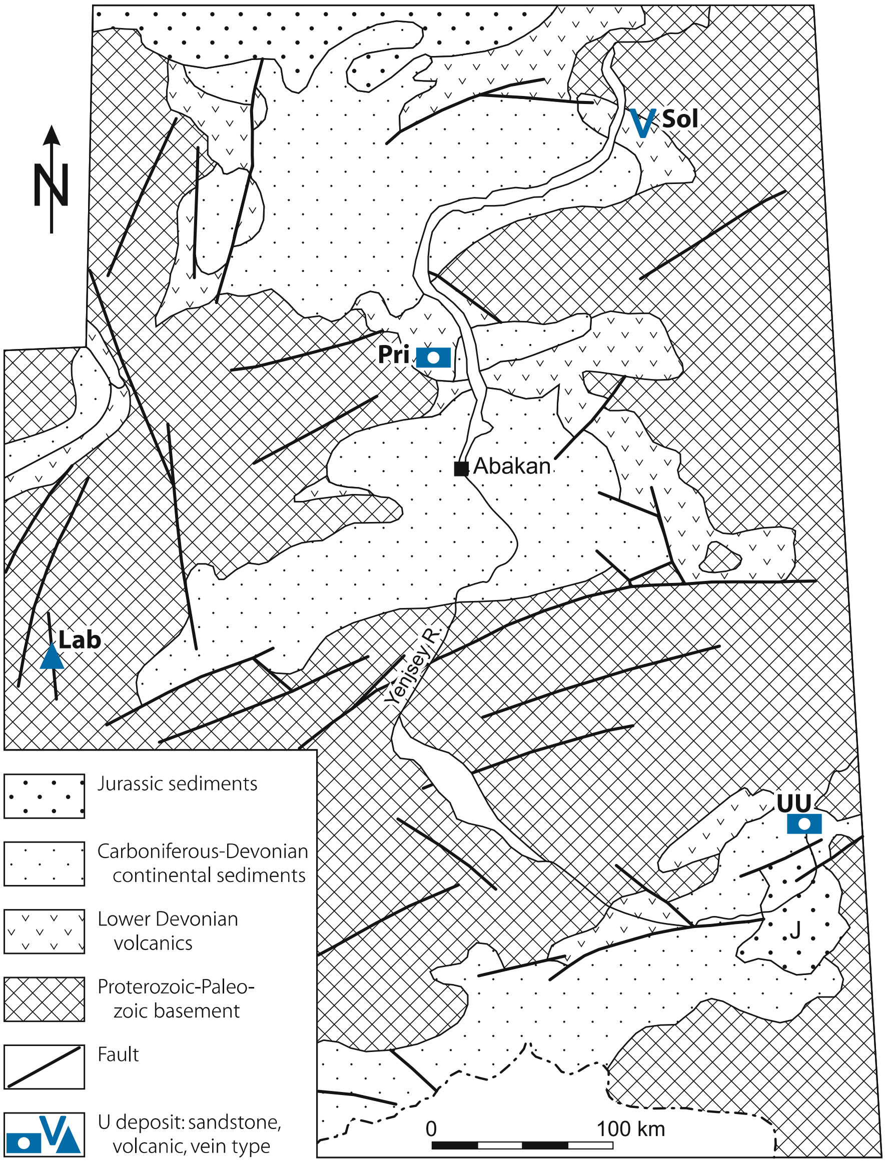
Mineralization is related to a volcanic caldera and largely controlled by structures. Deposits are therefore classified as structure-bound volcanic type. Two principal ore varieties are distinguished, monometallic uranium and polymetallic uranium-molybdenum (-fluorite) ores.

The first deposit was discovered in 1963 by drilling below fluorite veins that carried minor uranium mineralization. By 1979, nineteen uranium deposits had been found within an area of about 150 km² in size (Fig. 10.11, Table 10.1). Largest deposits are *Streltsovskoye, Tulukuyevskoye,* and *Octyabrskoye* in Jurassic-Cretaceous volcanic-sedimentary rocks, and *Antei* and *Argunskoye* in Paleozoic granite and Proterozoic marble of the basement, respectively.

Original in situ resources of the district were estimated at some 280 000 t U (Laverov et al. 1992b, c). OECD-NEA/IAEA (2005) reports remaining reserves of **11 7120 t** U RAR in the up to $80 per kg U category including 42 900 t U in the less than $40 per kg U cost category.

Since the begin of mining in 1968 (Tulukuyevskoye), ten deposits have produced uranium, eight by underground workings and two by open pits (Table 10.1). Some of the mines produced also molybdenum and some fluorite. Open pit extraction was at *Tulukuyevskoye*, which was partly also mined underground, and at *Krasny Kamen*. Both deposits are depleted. Underground mining took place at *Streltsovskoye* (largely

Fig. 10.8.
Yenisey region, Abakan area/upper Yenisey river. Generalized geological map with location of U deposits (after Laverov et al. 1992c). ***La*** **Labyshkoye,** ***Pr*** **Primorskoye,** ***So*** **Solonechnoye,** ***UU*** **Ust-Uyuk**



depleted), *Antei*, *Luchistoye*, *Martovskoye*, *Novogodneye*, *Shirondukuyevskoye*, *Vesennee,* and *Yubileinoye*. In situ ore grades of these deposits average 0.1–0.3% U at a cutoff grade of 0.039% U. In 2004 *Antei* and *Streltsovskoye* were in operation. The other six underground operations were on standby. Antei, the deepest mine with workings between 400 and 900 m below surface, is practically a depth extension of Streltsovskoye.

Cumulative production of the Streltsovsk District through 2005 is in excess of 100 000 t U. Annual production averaged almost 3 500 t U during the 1980s but dropped in the 1990s from 3 776 t U in 1990 to 2 160 t U in 1995. A turn around was achieved with 2 605 t U in 1996 rising to 2 880 t U in 2004. Mining capability is 6 700 t ore per day.

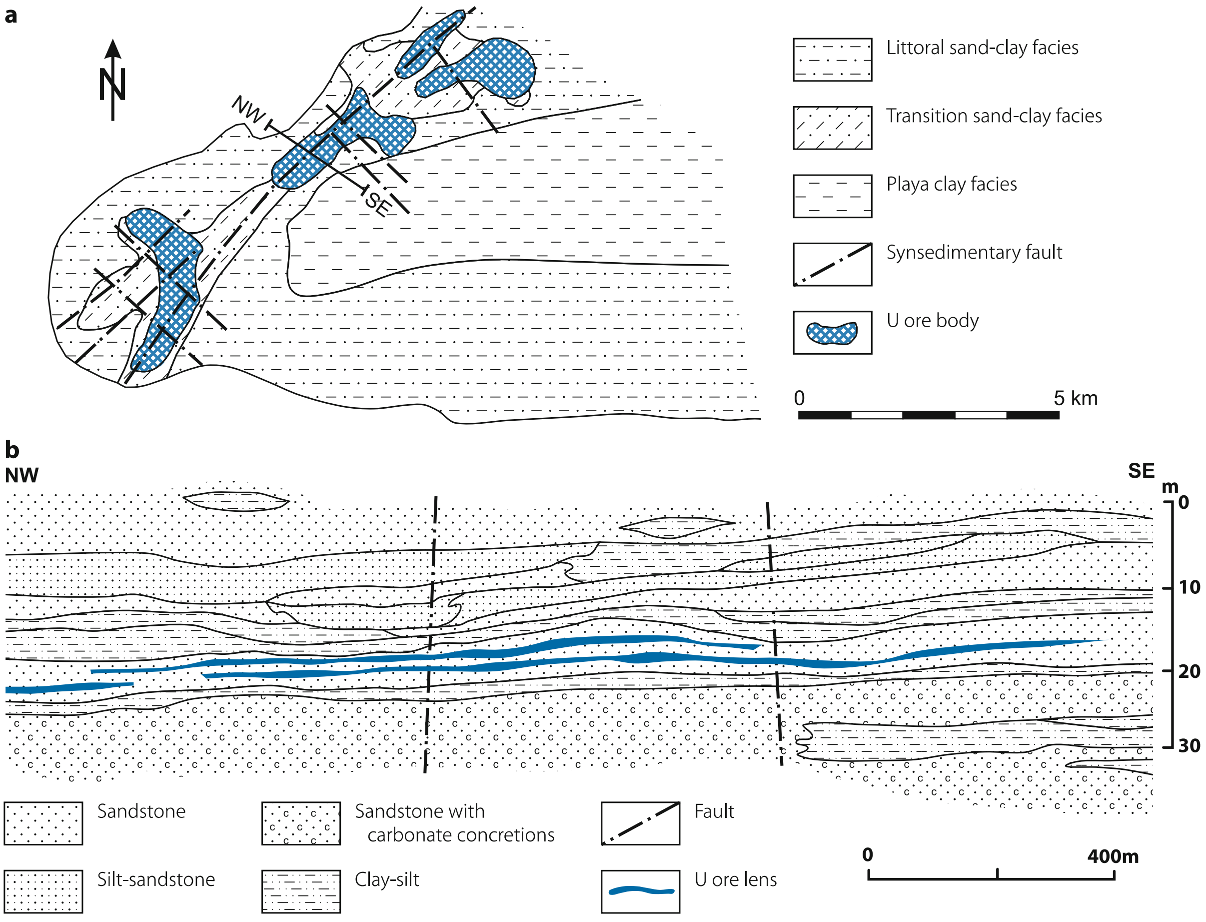
Most of the ore was and is recovered by conventional methods. Since the mid 1990s, some low-grade ore is also treated by heap leaching and in place leaching methods. Open pit mining ceased in 1997.

A hydrometallurgical plant with an sulfuric acid leach circuit is located 15 km from the town of Krasnokamensk. It started operation in 1974 and has a nominal capacity of about 3 500 t U yr^{-1} and a daily throughput of 4 700 t ore. Up to 1995 the plant also treated ore from the Dornod uranium district located some 500 km to the southwest, in northeastern Mongolia.

Mining and milling operator is JSK "Priargun Mining and Chemical Production Association" (PPGHO) with headquarters at Krasnokamensk, a joint stock company owned by the state.

Source of information Aleshin et al. 2003a,b, 2005; Andreeva et al. 1990, 1996a,b; Boitsov et al. 1995; Chernyshev and Golubev

Fig. 10.9.
Yenisey region, Primorskoye deposit. a Schematic geological map illustrating the control of ore bodies by an intermediate sand-clay facies within an Upper Devonian lacustrine environment. b NW-SE lithologic-stratigraphic profile with position of ore lenses (after Mashkovtsev et al. 1995)



1996; Ischukova 1989, 1995, 1997; Laverov et al. 1992a–c, 1993, 2000; Kazansky 1995; Miguta and Modnikov 1993; OECD-NEA/IAEA 1993–2005; Nikolsky and Schulgin 2001; and other sources. Additional information is available in earlier papers cited by the here listed authors and more recent literature listed in Bibliography. Among new publications, which became available after finishing this manuscript, the interested reader is in particular referred to the book "Uranium deposits in volcano-tectonic structures" by Ischukova et al. (2002).

Regional Geological Setting of Mineralization

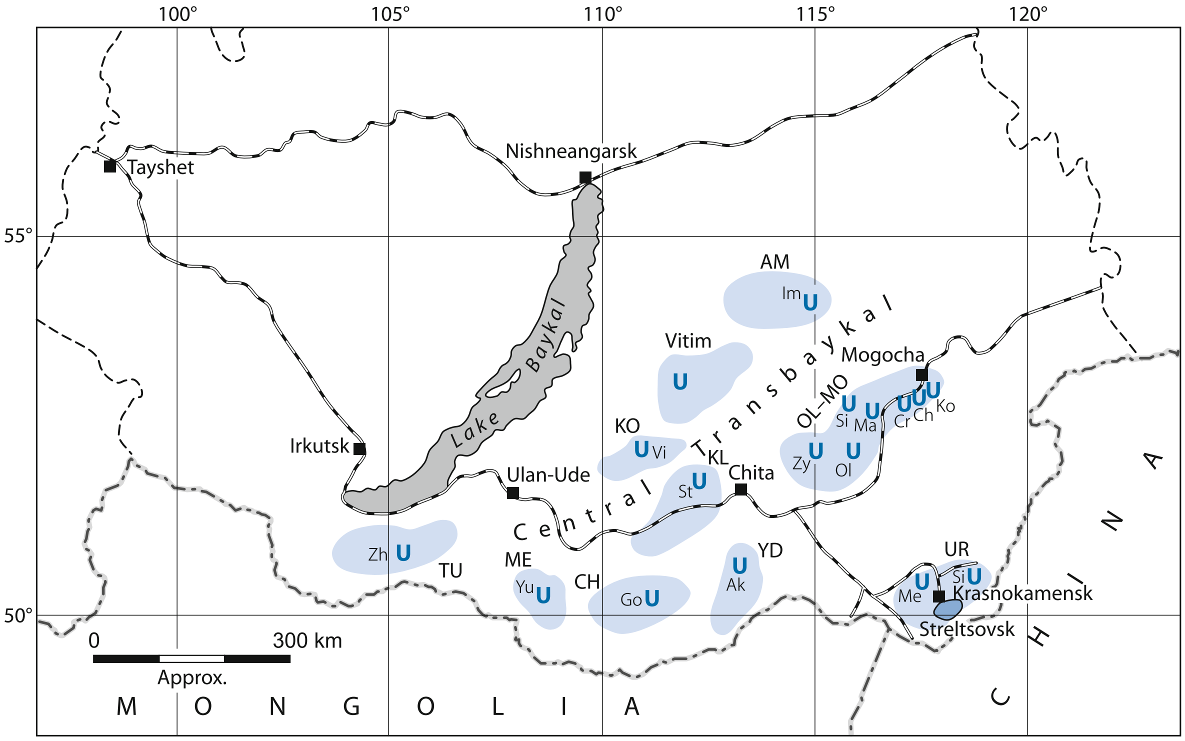
The district coincides with the Tulukuyevsk (also referred to as Streltsovsk) Caldera, a Lower Cretaceous-Upper Jurassic volcanic-sedimentary complex composed of two joint calderas, a major eastern and a minor western caldera. The caldera measures some 15 km in diameter and 150 km^2 in size. The Tulukuyevsk Caldera is within the Mongol-Priargun continental volcanic belt. The belt has been traced for more than 1 000 km across Transbaykalia in Russia, northeastern Mongolia and northeastern China where it contains the Dornod uranium district, and uranium showings in the Manzhouli area, respectively.

The position of the Tulukuyevsk Caldera is controlled by the conjugation and intersection of several repeatedly reactivated, deep reaching, submeridional and NE-SW-oriented shear zones (Figs. 10.11, 10.12). The caldera tops a Paleozoic granite batholith of the Transbaykal Massif, a separate tectonic block of the Paleozoic Ural-Mongolian fold belt. Xenoliths of Proterozoic metamorphics (gneiss, amphibolite, dolomitic marble) and pegmatite occur in the granite.

Caldera lithologies include over 60 facies ranging from mafic to felsic volcanics and intercalated clastic sediments. The rocks are grouped into two volcano-sedimentary series: The upper *Turgin (Turginskaya) Series* is of Lower Cretaceous age and largely restricted to the central-eastern part of the caldera. It consists primarily of felsite, rhyolite with intercalated basalt and andesite sheets, and sandstone and conglomerate beds. The lower *Priargun (Priargunsky) Series* is of Upper Jurassic age and exposed almost all around the upper unit and occupies most of the western caldera. It includes three

Fig. 10.10.

Transbaykal region. Schematic map with location of the Streltsovsk, Vitim (details see Fig. 10.11 and Fig. 10.12, respectively) and other districts and related ore fields (OF) in Central Transbaykalia (after Pelmenev 1995; Vizhnyakov 1995a–c). Ore fields in Central Transbaykalia (deposits/occurrences in brackets): *AM* Amalat OF (*Im* Ima or Imskoye); *Ol-MO* Olovo-Mogocha area: Olov OF (*Ol* Olovskoye,*Zy* Zyulzinskoye); Korolevo-Chasovo OF (*Cr* Crystalnoye, *Ch* Chasovoye, *Ko* Korolevskoye); *Si* Sigirlinskoye, *Ma* Mayak; *UR* Urulyunguevsky depression (*Me* Meridionalnoye, *Si* Sirotininsk) (overlaps N part of Streltsovsk/Tulukuyevsk Caldera) contains two stratiformU deposits in Lower Cretaceous argillized rocks; *KO* Kholoisky OF (Vitlauskoye); KL/Khiloksky OF (Stepnoye); *YD* Yuzhno Daursky OF (Akuinskoye, Barun-Ulacha, Vostochnoye); *CH* Chikoisky OF (Gornoye, Berezovoye); *ME* Mensensky OF (Yugalskoye); *TU* Tunguisky OF (Zhuravlinoye) (See Fig.10.11 for details of the Streltsovk and Fig.10.20 for the Vitim ore fields)



alternating basalt and trachydacite sheets interbedded with thin horizons of dacitic tuff, ignimbrite, sandstone and conglomerate. A basal conglomeratic bed rests unconformably on the basement.

A generalized litho-stratigraphic column shows the following principal facies units (from top to bottom):

Lower Cretaceous Turgin (Turginskaya) Series

- Felsite sheet, up to 260 m thick: up to 10 m thick quartz porphyry and 1–15 m thick fluidal felsite horizons
- Plagioclase trachybasalt horizon, 30–140 m thick
- Pink conglomerate horizons, 40–90 m thick

(Three andesite horizons composed of andesite-basalt, plagioclase basalt, and andesite with trachybasalt are intercalated in the middle and lower sections of the Turgin Series.)

Upper Jurassic Priargun (Priargunskaya) Series

- Upper basalt sheet, up to 180 m thick: lava and lava breccia
- Upper fluidal trachydacite sheet, up to 75 m thick
- Middle basalt horizon, 10–240 m thick: massive basaltic lava, lava-breccia, and conglomerate; restricted to the southern part of the deposit
- Lower trachydacite sheet, 60–350 m thick: massive and fluidal trachydacite, tuff, lava, and ignimbrite horizons
- Lower basalt sheet, up to 400 m thick: lava sheets and conglomerate lenses, thickness depends on basement relief
- Basal conglomerate horizon, up to 50 m thick: paleoweathered conglomerate, sandstone, siltstone layers

Total thickness of the caldera fill varies between 200 and 1 400 m, and averages 500–800 m. Intercalated sedimentary beds are from few meters to 100 m thick. Gently dipping stratified effusive sheets and sedimentary rocks dominate the eastern part of the caldera. Subvolcanic felsite, rhyolite and syenite-porphyry necks occur at intersections of major fault zones with crosscutting structures.

Numerous, about NE-SW-, N-S-, NW-SE-, and E-W-trending faults cut the caldera and adjacent terrane (Figs. 10.11, 10.12). Major faults persist into the basement. Late Cretaceous block faulting generated grabens adjacent to the caldera. Coal-bearing clastic sediments of Late Cretaceous and younger ages fill the grabens.

Ischukova (1997) alludes to the ore-controlling significance of major N-S-, NE-SW- and NW-SE-oriented, steeply inclined fault zones. N-S-oriented structures, such as the *Meridional Shear Zone,* are 500–900 m wide and consist of closely spaced

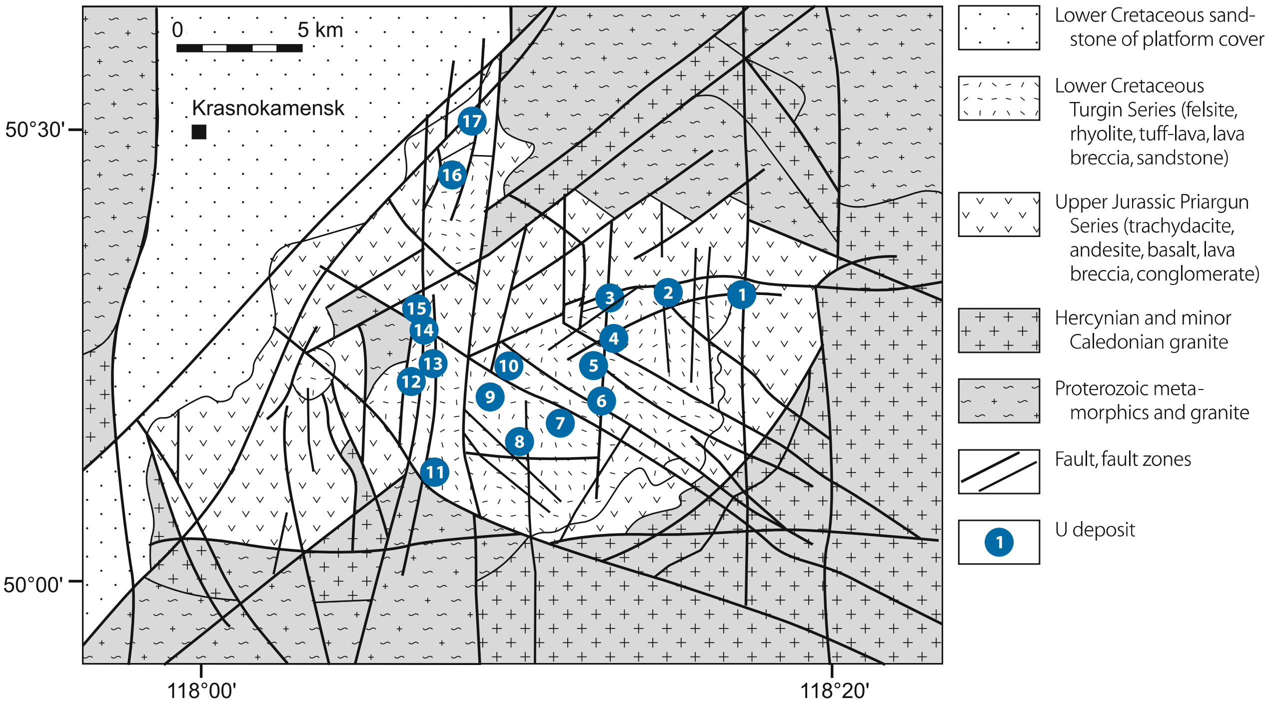


Fig. 10.11.
Streltsovsk region, generalized map showing the regional geological setting of the Lower Cretaceous-Upper Jurassic Tulukuyevsk (also named Streltsovsk) Caldera and location of uranium deposits (after Nikolsky and Schulgin 2001). *U-deposits: 1* Shirondukuyevskoye and Vostochno-Shirondukuyevskoye, *2* Streltsovskoye and Antei, *3* Oktyabrskoye, *4* Martovskoye, *5* Luchistoye, *6* Malo Tulukuyevskoye, *7* Yubileinoye, *8* Novogodneye, *9* Vesennee, *10* Tulukuyevskoye, *11* Yugo Zapadnoye, *12* Krasny Kamen, *13* Pyatiletneye, *14* Zherlovoye, *15* Argunskoye, *16* Bezrechnoye, *17* Dalnee

faults. They control U deposits where they are intersected by NW-SE- or NE-SW-trending shear zones. A prominent representative of the NE-SW system is the 3–5 km wide *Argunskaya Shear Zone*. It consists of numerous NE-SW- and E-W-oriented faults associated with intervals of closely spaced fractures/joints, which developed in response to repeated reactivation throughout the Proterozoic and Paleozoic and during the Mesozoic sedimentary-volcanogenic activity.

Shallow dipping fault systems include gently pitching, gouge filled faults/fractures at the contact between the basement and overlying sedimentary-volcanogenic strata, and at the interface of the Priargun and Turgin series. In the latter case, the fault/fracture systems preferentially cut tuffaceous and sedimentary horizons in the footwall of felsite sheets.

Principal Host Rock Alteration

Proterozoic and Paleozoic (Pt_2-Pz_2) polychronic granitization and updoming were accompanied by silica-alkaline metasomatism (Ischukova 1997).

Late Paleozoic high-temperature metasomatism modified wall rocks along faults to K-feldspar (microcline) rocks, albitite (albite-1), greisen with fluorite, sulfides, and occasionally cassiterite, and, in the western Tulukuyevsk Caldera, skarn. Fine-scaled muscovite of these facies yield an age of 250–230 Ma (Arakelyants et al. in Andreeva et al. 1996).

Late Mesozoic tectonic events were linked with intense pneumatolytic-hydrothermal activity of acid nature and resulted in halos of silica-potassic-sodic alteration and greisens along reactivated shear zones. Principal alterations include albitization (albite-2), silicification, hydromicazation, sericitization/beresitization, carbonatization, chloritization, argillization, and hematitization. [*Note*: In Russian studies, the term *hydromica* is usually applied to mixed–layered minerals of the illite-smectite type with a low (<15%) content of swelling interlayers.] The mode of alteration depends on the lithology and displays a zoning. Silicification, sericitization/hydromicazation prevail in the volcanic and sedimentary rocks while albitization is more typical for the crystalline basement. The types of wall rock alteration also correlate with the three types of ore mineral parageneses.

Pre-ore alteration phases are reflected by hydromica-carbonate-quartz, sericite-carbonate-quartz, and kaolinite-carbonate-quartz facies. Syn-ore alteration is manifested by linear albitization and hematitization, as well as silicification, carbonatization, and argillization. For more alteration-related information see Sect. 10.4.1.1: *Streltsovskoye-Antei*.

Principal Characteristics of Mineralization

Principal uranium mineral is pitchblende. Coffinite and brannerite are less common. Associated ore minerals include molybdenite, jordisite, femolite, pyrite, marcasite, and galena.

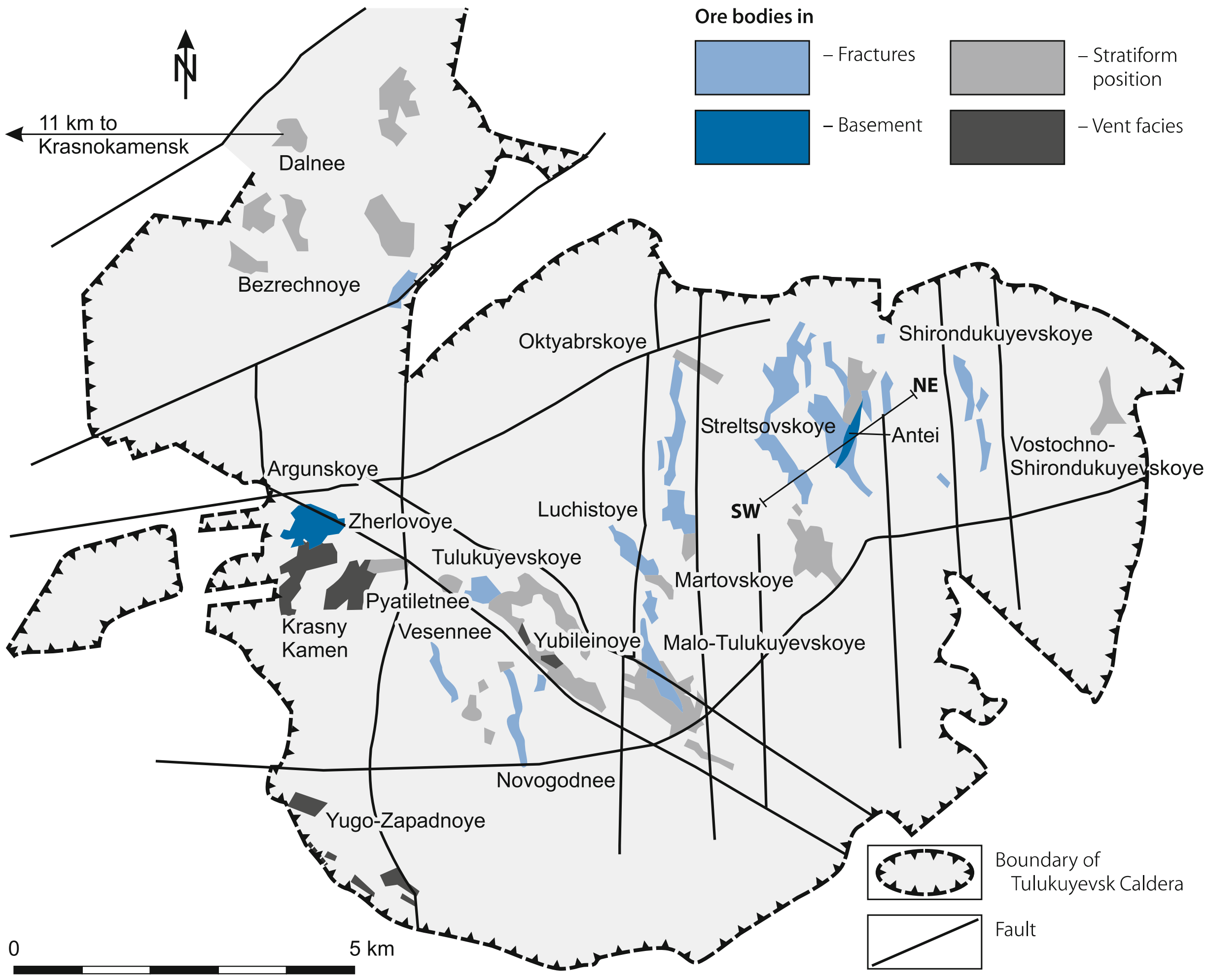
Table 10.1.
Streltsovsk District, dimensions and status (2006) of individual deposits (after Ischukova 1997; Laverov et al. 1992; and other sources)

Deposit	Shape	Stratigraphy	Lithology	Length (m)	Width (m)	Depth interval (m a.s.l.)	Reserves (1 000 t U)	Grade (av.% U)	Co-/by-product	Status
Streltsovskoye	ve-stw	Jur-Cret	Bas, dac, fels, cgl	4 000	2 500	+720 to +300	71	0.19	Mo	Active UG
Antel	ve-stw	Up Pz	Grt	1 000	100	+350 to −700	40	0.30	Mo + F	Active UG
Argunskoye	stw	L Pt+Pz	Dol,grt	1 000	300	+550 to −350	30	0.17	Mo	Devel.prosp (UG)
Oktyabrskoye	stw-ve	Up Jur	Dac,bas	1 000	180	+600 to +250	23	0.25	Mo	Devel.prosp (UG)
Tulukuyevskoye	stw-ve	L Cret	Fels, ss, cgl	1 300	250	+720 to +450	37	0.24	Mo	Depleted OP,UG
Krasny Kamen	ve-stw	L Cret	Fels	400	100		0.25	0.14		Depleted OP,UG
Shirondukuyevskoye	stw-ve	Jur-Cret	Fels, ss, cgl, bas			+600 to +300	10	0.18		Standby UG
Luchistoye	stw	L Cret	Fels, cgl	1 000	200	+700 to +400	10	0.21	Mo	Standby UG
Martovskoye	ve-stw	L Cret	Fels, cgl	1 300	200	+700 to +480	5	0.17	Mo	Standby UG
Yubileinoye	tab, stw	L Cret	Fels, ss	1 000	250	+660 to +300	10	0.19		Standby UG
Vesennee	ve, tab	L Cret	Fels, ss				1.4	0.21		Standby UG
Novogodneye	ve, tab	L Cret	Fels, ss				4	0.25		Standby UG
Malo Tulukuyevskoye	stw-ve	Up Jur	Dac, bas				12	0.19	Mo	Devel.prosp (UG)
Zherlovoye	ve	L Cret	Fels, eff (rhy)	550	200	+450 to 0	?	0.07		Explored
Pyatiletneye	ve-stw	L Cret	Fels, rhy	500	250		7	0.10		Explored
Yugo Zapadnoye	ve-stw	L Cret	Fels, rhy	1 500		+600 to +200	5	0.10		Explored
Bezrechnoye	tab,stw	L Cret	Cgl, ss				1	0.09		Explored
Dalnee	tab,stw	L Cret	Ss, tuff, cgl, fels		<6 m thick	+600 to +400	7	0.12		Explored
Vostochno-Shirondukuyevskoye	tab,stw	L Cret ?	Cgl, ss?				1.5	0.11		Explored

Depth interval: a.s.l. = above sea level, surface is about 650–750 m a.s.l.; *Reserves, Grade*: estimated original in situ; *Shape: stw* stockwork, *tab* tabular/lensoid/stratiform, *ve* vein; *Lithology: bas* basalt, *cgl* conglomerate, *dac* dacite/trachydacite, *dol* dolomitic marble, *eff* effusive, *fels* felsic, *grt* granite, *por* porphyry, *rhy* rhyolite, *ss* sandstone.

Fig. 10.12.

Streltsovsk District, simplified map with surface projected contours of uranium deposits in the Lower Cretaceous-Upper Jurassic Tulukuyevsk Caldera (NE-SW section indicates position of Fig. 10.13) (after Krotkov et al. 1997)



In oxidized intervals, primary U minerals are predominantly altered to uranophane and sooty pitchblende, and molybdenite to ilsemannite and uranium-molybdates (iriginite, umohoite, mourite). Gangue minerals include albite, ankerite, calcite, dolomite, chlorite, fluorite, sericite, and quartz. Pitchblende and other ore and gangue minerals are present in several generations.

Ischukova (1997) established 6 ore-related mineral parageneses:

1. Kaolinite and hydromica (pre-ore argillization)
2. Cryptocrystalline quartz–carbonate-sulfide
3. Albite-brannerite (first ore phase)
4. Quartz-molybdenite-coffinite-pitchblende (major ore phase)
5. Quartz-molybdenum-sulfide phase
6. Calcite-fluorite-dickite (post-ore phase)

Boitsov et al. (1995) distinguish *three principal ore varieties,* from oldest to youngest: albite-coffinite-brannerite, quartz-molybdenite-pitchblende, and chlorite-carbonate-pitchblende. The first two assemblages contain less than 6% carbonate and typically occur in the volcano-sedimentary suite and basement granite. The carbonate-bearing paragenesis has in excess of 25% carbonate when hosted in basement dolomite (Argunskoye), and 6–25% carbonate when it occurs in andesite, basalt, or conglomerate. Although the spatial distribution of the three varieties is primarily related to specific host rock lithologies, the assemblages often show telescoping.

These authors further subdivide mineralization according to the prevailing ore minerals into *four ore types*:

- *Pitchblende ore* is predominantly composed of pitchblende, with minor (commonly less than 20% of U components) coffinite, brannerite, and locally uranophane and sooty pitchblende. Associated Mo minerals are femolite, ilsemannite, iriginite, and molybdenite. Ore minerals fill voids and fissures. Pitchblende ore exhibits streaky, cocard, mottled, breccia, cement, and massive modes of aggregation. Predominant distribution is on upper levels of the volcano-sedimentary sequence. Pitchblende ore constitutes the bulk of reserves in most deposits. Ore grades vary between low and high ranging from <0.2 to >1% U. Mo content is from 0.01 to 0.03% Mo.

- *Complex molybdenite-pitchblende ore* contains the same mineral assemblage as pitchblende ore but differs from this by a higher Mo content. Ore textures correspond to those of pitchblende ore. Predominant distribution is in upper levels of the volcano-sedimentary sequence. The Argunskoye deposit contains substantial amounts of complex U-Mo ore in xenoliths of dolomitic marble in basement granite. This ore features a dolomite content ranging from 25 to 96%, averaging 70%. Reserves are second to pitchblende ore. Ore grades range from 0.2% to >1% U. Mo content is in excess of 0.03% Mo.
- *Coffinite ore* is dominated by coffinite. Other ore minerals occur in minor amounts. Ore textures are streaky, mottled, and disseminated. Prevailing distribution is in marginal parts of deposits. Reserves are of minor order. Grades are low to average (<0.2% U). Mo content is less than 0.015% Mo.
- *Brannerite ore* essentially consists of disseminated brannerite. Other ore minerals occur in subordinate quantity. Albite seems to be a characteristic gangue mineral of granite-hosted brannerite ore. Predominant distribution is at lower levels of deposits, particularly in basement granite and in trachydacite of the basal parts of the volcano-sedimentary sequence. Reserves are of minor order. Grades are low (<0.1% U). Mo content is less than 0.015%.

Fractures, cavities, pores, and metasomatic replacement features provided space for ore deposition. In result, mineralization has most commonly vuggy-disseminated, streaky-disseminated, and brecciated textures, but also occurs locally as veinlets and massive aggregates of ore minerals, which group to veins, stockworks, or stratiform-tabular lodes.

Mineralization occurs at several stratigraphic levels of the volcanic and sedimentary units and extends into the basement. Ore-hosting caldera lithologies range from felsic, intermediate and mafic effusive and neck volcanic facies to clastic sediments. Basement host rocks are granite and xenoliths of dolomitic marble in the apex part of the granite batholith.

Basement rocks host two large deposits, Argunskoye and Antei. Seventeen deposits occur in sedimentary-volcanogenic facies, thirteen of which in stratified effusive sheets and in sedimentary rocks, and four in volcanic neck facies.

According to Ischukova (1997), the majority of the deposits are associated with 500–900 m wide meridional shear zones at their junctions with NE-SW-oriented faults such as the Argunskaya Shear Zone. Segments of steeply dipping, NW-SE-striking fractures/joints in the sedimentary-volcanogenic strata characterize these sites. The steeply dipping fractures are best developed in effusive sheets and only to a minor degree in the less brittle sedimentary rocks. Basement-hosted ore bodies are controlled by either northeasterly or northwesterly striking faults.

General Shape and Dimensions of Deposits

Original in situ resources of the Streltsovsk District are estimated at approximately 280 000 t U contained in 19 deposits. Dimensions of the deposits are given in Table 10.1.

Deposits are commonly composed of several ore bodies. Ore bodies are highly variable in shape, dimensions, internal structure, and grade. Ore bodies may extend intermittently over a vertical interval of about 800 m, a length of up to 300 m, and a width of up to 160 m. None of the ore bodies has a surface expression. Upper limit of ore lodes is between 50 m (Tulukuyevskoye) and 350 m (Antei) below surface. Most ore bodies start at a depth below 200 m.

Approximately 75% of the resources of the Streltsovsk District are at a depth interval from 200 to 600 m below surface where ore lodes are distributed at several levels in stratified sedimentary volcanogenic rocks. Largest deposits in this depth section include *Streltsovskoye*, *Tulukuyevskoye*, and *Octyabrskoye*. About 25% of the resources occur between 400 and 900 m deep. They are mainly contained in the two large and high-grade deposits *Antei* and *Argunskoye* hosted by granite and marble of the basement. Established depth of uranium ore is approximately 1 100 m but drilling intercepted also U mineralization down to a depth of 2 400 m in granitic basement.

The uranium content varies over a wide range, from the cutoff grade of 0.039% U to a few percent. [Note: 0.039% U is the normal cutoff grade used for conventional reserve estimation (i.e. non-in situ leach) in the CIS] The largest ore bodies have commonly the highest grades of up to between 0.6 and 3.0% U while most ore bodies average between 0.15 and 0.33% U. Several deposits contain additional to uranium molybdenum, while economic quantities of fluorite are rare.

Three principal configurations of ore bodies are discerned characterized by the following features:

- *Veins and veinlike* ore bodies are from several centimeters to about 25 m thick, from few meters to 700 m long, and 300 m high. Grades can be as high as 1% U. Dip is steep to shallow and may change abruptly. Greatest ore accumulations occur in highly fractured host rock intervals. Veins occur in almost all of the volcanic and sedimentary rocks and extend locally into the basement where it is heavily fractured. Veins extending into the basement are thickest near the contact to the overlying volcanics from where they rapidly thin downwards.
- *Stockwork* ore bodies are of complex linear or isometric configuration. Dimensions are on the order of up to 90 m wide, 300 long, and 600 m high. Grades can be as high as 0.6% U. Stockwork ore bodies are typically developed in favorable lithological units such as dacite and basement rocks.
- *Tabular/stratiform* ore bodies are from some tens of decimeters to a few meters thick, up to 1 400 m long and 1 000 m wide. Grades are on the order of 0.1 to several percent U. Reserves are small. Tabular ore lodes occur preferentially in cataclastic effusive sheets where these are overlain by felsite sheets and cut by both, shallow and steep dipping faults. Intercalated sandstone and conglomerate beds contain some stratiform mineralization. Minor tabular mineralization is found in sediments filling grabens peripheral to the Streltsovsk Caldera.

The bedded nature of the sedimentary-volcanogenic series and the repetition of brittle rocks at different levels caused a multi-layer distribution of ore lodes at six lithologic-structural levels: Levels 1 to 5 are in the sedimentary-volcanogenic sequence. The 6th level is in basement rocks. As a general rule, the second level contains tabular lodes composed of gently dipping, mineralized fractures at the base of felsite sheets. The third and the fourth levels host the highest-grade ore contained in stockwork- or rarely vein-type lodes in trachydacite sheets. Smaller tabular lodes occur in sandstone of the basal horizon of the caldera fill.

Major deposits are predominantly of vein or stockwork configuration while stratiform deposits are commonly of smaller magnitude. But the various styles of mineralization may occur combined in a single deposit forming a complicated system of interlinked veins, stockworks, and stratiform lenses.

Stable Isotopes and Fluid Inclusions

Temperature deduced from stable isotopes and fluid inclusions data are 230–290°C for the pre-ore quartz-carbonate-sulfide stage, 200–150°C for the uranium, 150–50°C for the post-uranium stage (Ischukova 1995).

Regional Geochronology

Geochronologic data of rocks and ore minerals of the Streltsovsk District provided by Laverov et al. (1993) read as follows:

K-Ar rock dating (Laverov et al. 1985; Andreeva et al. 1991) of monomineralic fractions and whole rock samples from dacite of the lower volcanic-sedimentary sequence to syenite-porphyries from subvolcanic stocks, yield K-Ar ages from 170 to 143 Ma. The various lithologies show a noticeable divergence in K-Ar data, except for the youngest rhyolite and syenite-porphyries, the ages of which lie within a narrow span of 149–143 Ma (±6 Ma) i.e. Upper Jurassic. The range of about 25 Ma is an approximate estimate of the duration of volcanism and the filling of the Streltsovsk depression.

K-Ar ages of mica of the pre-uranium hydromicazation phase, which affected both, volcanics of the caldera and rocks of basement, range from 144 to 129 Ma. The youngest ages were found in finely dispersed micas of cataclastic and mylonitic zones and are thought the result of a "rejuvenation" by superimposed processes. Micas outside the zones of dynamic metamorphism yield significantly narrower ranges of K-Ar ages, from 144 to 138 Ma. These values practically correspond to those of the youngest felsic volcanics. A Permian hydrothermal event is possibly indicated by K-Ar ages of 274–252 Ma obtained from biotite in granite below the caldera.

U-Pb ages of pure, massive pitchblende are within a narrow range of 136–134 Ma whereas massive pitchblende with coffinite inclusions give a 131–130 Ma age. The coffinite admixture probably causes the "rejuvenation". Regenerated pitchblende yields a U-Pb age of 18–17 Ma indicating modification processes during the Neogene.

U-Pb systematics of disseminated uraninite mineralization in basement rocks yield concordant U-Pb data of 457 and 459 Ma for pure uraninite. Uraninite crystals with coffinite in microfractures and at the margin give lower, discordant values of 448–441 Ma. Samples that contained the impure uraninite also contained later molybdenite with inclusions of spherulitic pitchblende. U-Pb ages of the molybdenite-pitchblende aggregate vary between 156 and 150 Ma, which are close to the age of the principal U mineralization at the Streltsovsk deposits.

Several pre-, syn- and post-uranium generations of galena are noticed in the Streltsovsk deposits. Circumstantial evidence based on isotope data from polymetallic Pb-Zn mineralization in the Klichkinskoye ore field in the Transbaykal region suggest a formation at 140–130 Ma (Komarov et al. 1965), which practically coincides with the pitchblende age of the Streltsovsk deposits.

Potential Sources of Uranium

A variety of potential uranium sources are proposed including a magmatic, deep-seated crustal reservoir (Ischukova 1997), basement granite (e.g. Laverov et al. 1993) and felsic volcanics (rhyolite, particularly glassy phases). Volcanics are also thought to be the source of molybdenum. U and Th background values of selected lithologies of the sedimentary-volcanic caldera fill and caldera basement, which may be considered a potential U source, are given in Table 10.2.

Table 10.2.
Streltsovsk District. Average U and Th background values of selected lithologies (Ischukova 1995)

Lithology	Number samples	U (ppm)	Th (ppm)	Th/U	Lithology	U (ppm)
Late Pz biotite granite	14	3.2	13.8	4.3	Early Pz amphibolite, amphibolite gneiss	2.1
Leucogranite	4	2.8	7.4	2.6	Quartz-mica-feldspar gneiss	4.4
Basalt	45	1.7	4.4	2.6	Granite-gneiss	3.7
Andesite-basalt	19	2.6	5.5	2.1	Porphyric granite	3.7
Trachydacite	15	7.7	22.8	3.0	Leucogranite	2.6
Trachydacite ignimbrite	39	7.2	21.6	3.0	Late Pz biotitic granite	2.8–4.46
Felsic ignimbrite	11	8.4	45.4	5.4		
Rhyolite	14	8.1	43.0	5.3		
Rhyolitic volcanic glass	14	19.0	40.2	2.1		

Granite below the caldera contains concentrations of accessorial uraninite. Isotope data indicate this uraninite as one of the potential uranium sources for the uranium ore. A pre-Mesozoic source of the uranium is indirectly also supported by radiogenic lead in jordisite enclosed in pitchblende, the $^{207}Pb/^{206}Pb$ ratios of which suggest a 270–250 Ma old source for the lead (Laverov et al. 1993).

Principal Ore Controls and Recognition Criteria

Deposits are primarily of vein and stockwork and minor tabular configuration controlled primarily by structure and subordinately by lithology within a caldera. The marked difference in host lithologies – ranging from felsic, intermediate, and mafic effusives, to clastic sediments, granite and dolomitic marble – suggests that the petrochemical composition of the rocks had no significant influence neither on the depositional site nor on the quality and quantity of the ore. Physical or rock mechanical properties amenable to brittle deformation in reaction to tectonic stress primarily controlled the development of open spaces and as such provided the sites for ore deposition.

Significant ore controlling parameters or recognition criteria governing the position of deposits and style and distribution of mineralization include:

Host Environment

- Proterozoic metamorphic basement affected repeatedly by tectonic-magmatic events including the Caledonian and Hercynian Orogeny with intrusion of granites, and the Late Mesozoic Mongolian-Priargunian tectono-volcanic event
- Caldera of Upper Jurassic–Lower Cretaceous age largely composed of mafic to felsic volcanic sheets intercalated with terrestrial sediments
- Elevated U background values in basement granite (partly contained in uraninite)
- Elevated U background values in felsic volcanics particularly in vitreous facies
- Deep reaching regional faults
- Intense faulting, fracturing, brecciation along steep and shallow dipping N-S-, NW-SE- and NE-SW-oriented faults
- Grabens filled with terrestrial sediments
- Host rocks include
  - predominantly felsic to mafic volcanics, tuffs, and intercalated clastic sediments
  - exceptionally basement granite and enclosed xenoliths of metamorphites, particularly dolomitic marble
  - mainly silica-rich (<6% carbonate) and minor carbonate dominated (>6% carbonate) lithologies

Alteration

- Intense metasomatism of basement granite by albitization, microclinization, and greisens
- Polystage Mesozoic alterations of host rocks including albitization, silicification, sulfidization, carbonatization, chloritization, hydromicazation, sericitization/beresitization, and argillization
- Vertical zoning of alteration reflected by silicification, hydromicazation prevailing on upper and intermediate levels, sericitization and albitization on lowermost levels
- Correlation of types of wall rock alteration with types of ore mineral parageneses

Mineralization

- Monometallic U (<300 ppm Mo) and polymetallic U-Mo (>300 ppm Mo) mineralization
- Principal U minerals: U-oxide and minor U-silicate and U-Ti-phases
- Principal associated minerals: sulfides of Fe, Mo, Pb, carbonates, phyllosilicates, quartz, locally albite and fluorite
- Overprint of primary mineralization by deep reaching oxidation
- Disseminated, banded, streaky, and massive texture of ores
- Irregularly shaped vein, stockwork, and tabular-stratiform ore bodies, often interlinked in complicated fashion
- Locally vertical persistence of veins into basement (Streltsovskoye-Antei, Argunskoye)
- Position and configuration of ore bodies are related to
  - intersection of faults
  - intersection of transverse faults with volcanic dikes
  - sharp changes in dip of rock contacts cut by a fault
  - heterogeneous sections of volcanic rocks
  - intercalated pyroclastic and effusive sheets, and clastic layers cut by shallow and steeply inclined faults
  - unconformities between volcanic horizons

Principal Aspects of Metallogenesis

U-Mo deposits of the Streltsovsk District are – at least spatially – related to volcanics of the Streltsovsk Caldera. Although the U-Mo mineralization formed with a time gap of about 10 Ma after the youngest volcanics, a temporal hydrothermal link between volcanism and ore formation is documented by isotope ages of kaolinite and hydromica alteration that preceded the uranium deposition.

A number of metallogenetic hypotheses have been proposed with respect to the relationship of ore formation and volcanic processes. Some authors consider the felsic volcanism instrumental for the ore formation while others favor a magmatic, deep-seated crustal source as the main root for the ore-forming fluids. The origin of the ore metals still remains dubious. Was uranium, molybdenum concentrated as residues in final magmatic solutions or leached by such fluids from granite or felsic volcanics?

Laverov et al. (1993) summarize the principal views on the metallogenesis of uranium deposits in continental volcanic belts, which were formerly described as “uranium-molybdenum” or “uranium-fluorite” formations, or as “deposits in volcanic depressions” as follows:

1. The formation of the ore deposits was related to deep magmatic processes that occurred after volcanic activity ceased, and is chronologically discrete from continental volcanic processes (Smorchkov 1966).

2. The ore deposits were formed as a result of hydrothermal activity accompanying volcanic processes and are genetically linked with them (Kotlyar 1968).
3. Ore deposits formed at the final stage of volcanic activity under anomalous conditions of thermo-artesian systems of depressions. Metalliferous fluids of magmatic and meteoric origin were involved in ore formation (Anonymous/Usloviya Obrazovaniya 1972).

A substantial key for any genetic modeling of the Streltsovsk deposits is the age correlation between volcanism and ore formation, the duration of these processes, and the sources of ore forming elements. Laverov et al. (1993) address this matter based on isotopic geochronology of rocks and ore minerals and arrive at the following result. The Streltsovsk volcanic depression evolved over a period on the order of 25–30 Ma (±5 Ma). The pre-ore and main ore stage hydrothermal processes were contiguous in time with the final phases of volcanism and lasted about 5 Ma. Later processes modified and partially redistributed the original uranium ore, at last during the late Cenozoic.

Mineralogical and geochronological evidence indicate an involvement of pre-Mesozoic uranium in the formation of the Streltsovsk deposits. Granite below the caldera contains concentrations of accessorial uraninite that had crystallized at least 100 Ma earlier than the U-Mo ore. Isotope data indicate this uraninite as one of the potential uranium sources for the uranium ore. A pre-Mesozoic source of the uranium is also supported by radiogenic lead in 135 Ma old jordisite inclusions in pitchblende. ^{207}Pb/^{206}Pb ratios suggest an age of 270–250 Ma as source for the lead. A similar age was obtained from biotite in granite below the caldera, which yield K-Ar ages from 274 to 252 Ma and as such may possibly reflect a Permian hydrothermal event that may have concentrated uranium. Consequently, Laverov et al. (1993) postulate superimposed magmatic and postmagmatic processes to have played a significant role in the genesis of the Streltsovsk uranium deposits. (See also Sect. 10.4.1.1: *Streltsovskoye-Antei* for metallogenetic data.)

Ischukova (1997) elaborates on the evolution of the Streltsovsk District as follows: The geologic-metallogenetic history of the area started with polychronic granitization during the Proterozoic (Pt_2) and Paleozoic (Pz_2). During or after granite emplacement, the granite was affected by silica-alkaline metasomatism as reflected by local zones of quartz – K-feldspar – albite metasomatite and greisens along faults.

In Late Mesozoic time, the Streltsovsk Caldera evolved during a period of regional tectonic-volcanic reactivation. Associated hydrothermal processes include pronounced acidic leaching and silica-potassic-sodic alteration, and synchronous to subsequent ore formation along reactivated fault zones within and below the caldera. Greisens developed contemporaneously in the basement rocks. These processes are attributed to a deep seated, slowly evolving magmatic chamber. The chamber provided the material for the Paleozoic granite intrusions and Mesozoic volcanic extrusions, and generated the pneumatolitic-hydrothermal systems that metasomatized and altered the magmatic rocks, and, ultimately, the low temperature hydrothermal-metallogenetic system. A recurrent link in time between magmatic differentiation and epigenetic processes is evidenced by superimposed, multi-stage alteration and mineralization imprints within the Streltsovsk Caldera and the basement.

The evolving magma chamber was capable of generating fluid flows, which introduced huge masses of ore-forming and other elements as well to form the present-day U-Mo deposits. The spatial distribution of products of magmatism and subsequent hydrothermal processes suggest a channeled fluid migration along deep-seated transcrustal faults. Steeply dipping faults that extend through basement rocks and the complete caldera fill fulfilled the channeling conditions for the percolation of the solutions.

Ischukova (1997) suggests that intersections of meridional faults and deep NE-SW faults such as the Argunskaya Shear Zone provided the main channels for magma and fluid invasion during the tectonic-volcanic event, and also acted as migration paths for the ore-forming solutions during the final period of activation.

The marked difference in host lithologies infers an only limited influence of the petrochemical composition of the rocks on the depositional site and the quality and quantity of the ore. Physical or rock mechanical properties favorable for brittle deformation in reaction to tectonic stress primarily governed the preparation of sites for ore accumulation.

Gently inclined fault/fracture zones composed of numerous gouge filled cracks exerted a screening effect on the percolation of the ore solutions. These structures are typical for the interface of the basement and overlying strata and between the Priargunskaya and Turginskaya series. These zones locally also host ore shoots. Consequently, Ischukova (1997) postulates that a combination of structural elements, that influenced, controlled and simultaneously provided the space for ore formation, combined with a few permeable faults and numerous screening fractures were the essential factor for the generation of favorable thermobaric conditions for ore deposition.

Six consecutive mineralization phases of a single hydrothermal event are documented by Ischukova (1997):

1. Argillization phase (facies of kaolinite and hydromica alteration)
2. Cryptocrystalline quartz-carbonate-sulfide phase
3. Albite-brannerite (the first ore) phase
4. Quartz-molybdenite-coffinite-pitchblende (the major ore) phase)
5. Quartz-molybdenum-sulfide phase
6. Calcite-fluorite-dickite (post-ore) phase

In summary, metal mobilization and transport are attributed to hypogene(?) hydrothermal solutions. First hydrothermal processes are assumed to be contemporaneous with the final volcanic activity in the caldera. Mineralogical and geochronological evidence attest to repeated redistribution processes, which lasted into the Late Cenozoic.

Pathways for solutions and spaces for ore accumulation were provided by permeable faults and cataclastic volcanic sheets and sediments. They resulted from intense brittle deformation by multiple fault systems that generated a subvertical and subhorizontal plumbing system for the migration of ore-forming solutions. The brittle deformation may possibly have been also instrumental in preparing source rocks for leaching of uranium and other metals. Structurally unaffected or otherwise impermeable rocks provided barriers for the fluids and as such contributed to the channeling of solutions to most favorable sites for ore deposition and enrichments.

Reducing conditions required for the reduction and arrest of uranium may have existed at sites where the host volcanics contained abundant sulfides and intercalated sediments plant remains. An additional reductant may have been ferric iron of mafic minerals as found in mafic and intermediate volcanics. Physico-chemical conditions, like effervescence with brake up of fluid components may have likewise contributed to uranium precipitation.

10.4.1.1 Streltsovskoye-Antei

The following presentation summarizes geological and metallogenetic characteristics of both, the Streltsovskoye and the Antei deposits because both are factually one deposit; Streltsovskoye is in the Mesozoic caldera-fill on top of the Paleozoic basement hosted Antei deposit.

The Streltsovskoye-Antei deposits are situated in the eastern part of the Tulukuyevsk Caldera, 18 km ESE of Krasnokamensk. Streltsovskoye, the largest deposit of the Streltsovsk U district, was discovered in 1963 and Antei in 1964. Exploitation is by underground methods and started at Streltsovskoye in 1969 and at Antei in 1976. Both deposits were in operation in 2006. Streltsovskoye had original in situ resources of 71 000 t U at an average grade of 0.185% U. Respective data for Antei are 40 000 t U and 0.2% U.

Sources of information. Andreeva et al. 1996a,b; Boitsov 1999; Boitsov et al. 1995; Chernyshev and Golubev 1996; Ischukova 1995, 1997; Laverov et al. 1992a,b; Nikolsky and Schulgin 2001; OECD-NEA/IAEA 1993–2005.

Geological Setting of Mineralization

The Streltsovskoye-Antei deposits occur at the intersection of the regional, NW-SE-oriented Argun and the N-S-trending Central fault zones in the eastern Tulukuyevsk Caldera (Fig. 10.12). The volcanic-sedimentary sequence, bipartite into the Lower Cretaceous Turgin and the Upper Jurassic Priargun series, is in the central part of the deposit up to 550 m thick and increases to 1 000 m thick in its southeastern part. Strata dip 5–10° SW. Principal lithologies are andesite-basalt lavas, dacite and rhyolite ignimbrites, trachydacite sheets, interbedded tuff, conglomerate-sandstone, cut by syenite-porphyry dikes. The caldera fill rests unconformably on Late Paleozoic basement composed of coarse-grained porphyry granite and medium-grained leucocratic biotite granite. Erosional incisions and tectonic arch-like uplifts deform the paleosurface (Fig. 10.13).

Intense tectonic activity conditioned four steeply dipping fault systems trending E-W, NE-SW, N-S, and NW-SE (from early to late). As a rule, these faults are represented by up to 12 m wide breccia and fracture zones. Although displacement of some tens of meters along major faults generated a block structure of the caldera fill, dislocations along most faults are small indicating a relative stable tectonic environment after the caldera formation. Shallow dipping faults occur intraformational within, and also separate the volcano-sedimentary suite from the basement granite.

Host Rock Alteration

Two prominent Phanerozoic alteration events, a Late Paleozoic and a Late Mesozoic, modified the host rocks at Streltsovskoye-Antei. Ischukova (1997) emphasizes the following features: Early pneumatolytic-hydrothermal activity metasomatized the ore-hosting Paleozoic granite by intense microclinization, albitization (albite-1), and greisens.

Late Mesozoic, *pre-ore*, low-temperature hydrothermal processes generated wide halos of hydromica, veinlets of quartz, siderite, and pyrite along faults. Mixed-layered hydromica-montmorillonite and chlorite occur in central parts of the halos. Fault controlled zones of early syn-ore sericitization and silicification contain polymetallic mineralization (galena with native silver, sphalerite, and molybdenite) mainly at deep levels.

Early *ore stage* phases include albite-2 veinlets, disseminated brannerite and ankerite veinlets, which prevail in the lower parts of the deposit. During the final ore stage, numerous veinlets of quartz and chlorite (chamosite-type) were formed. *Post-ore* alteration is only slightly developed in granite and restricted to faults. Veinlets of dickite, druses with quartz, calcite, pyrite, and fluorite attest to this stage.

Andreeva et al. (1996a) elaborate on the host rock alterations as summarized in the following (Fig. 10.14): *Late Paleozoic* metasomatism, dated at 250–230 Ma (Arakelyants et al. in Andreeva et al. 1996a), produced K-feldspar rocks, albitite, and greisen with fluorite, sulfides, and rare cassiterite along faults in Paleozoic granites. The K-feldspar zones expand with depth as documented by as much as 50 m long drill intersections of K-feldspar metasomatite below 1 500 m. Albitization, which is very rare at upper levels, becomes abundant below 2 100 m. Locally developed, narrow zones of fine-scaled muscovite unite to as much as several meters thick greisens with sulfide, quartz, and fluorite veinlets at a depth from 1 900 to 2 300 m. Though, no economic mineralization is associated with these processes.

Late Mesozoic tectonic and magmatic activation was associated with much more intense and widespread alteration than the Late Paleozoic process. Scope and intensity of the alteration activity can be estimated from the nearly total absence of fresh rocks within the Tulukuyevsk Caldera.

The Mesozoic hydrothermal event, which produced U(-Mo), base metals and fluorite mineralization, involves pre-, syn- and post-ore alterations with respect to the main U(-Mo) stage. The alterations imposed a differential, temperature-related vertical zoning upon the entire lithological section from the

Fig. 10.13.
Streltsovsk District, Streltsovskoye-Antei deposits, schematic geological SW-NE section across three ore zones of the two deposits. Antei is confined to Hercynian granite and contains ore primarily in en echelon arranged veins; major veins with paystreaks extend to over 1 000 m deep. Streltsovskoye ore bodies consist of anastomosing veins that grade into stockwork lodes hosted in Upper Jurassic-Lower Cretaceous volcanics and sediments. A basal conglomerate bed separates both deposits (after Krotkov et al. 1997) (see Fig. 10.11 for location)

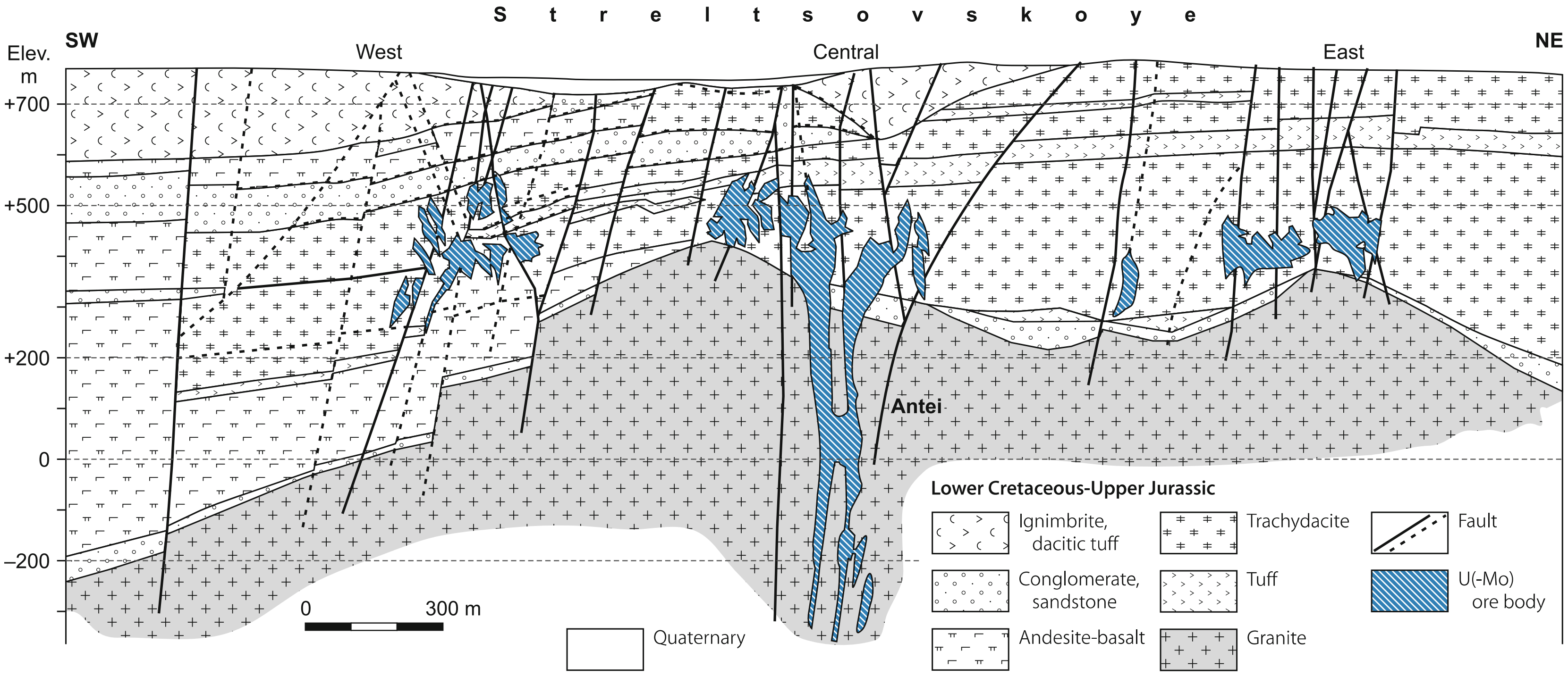
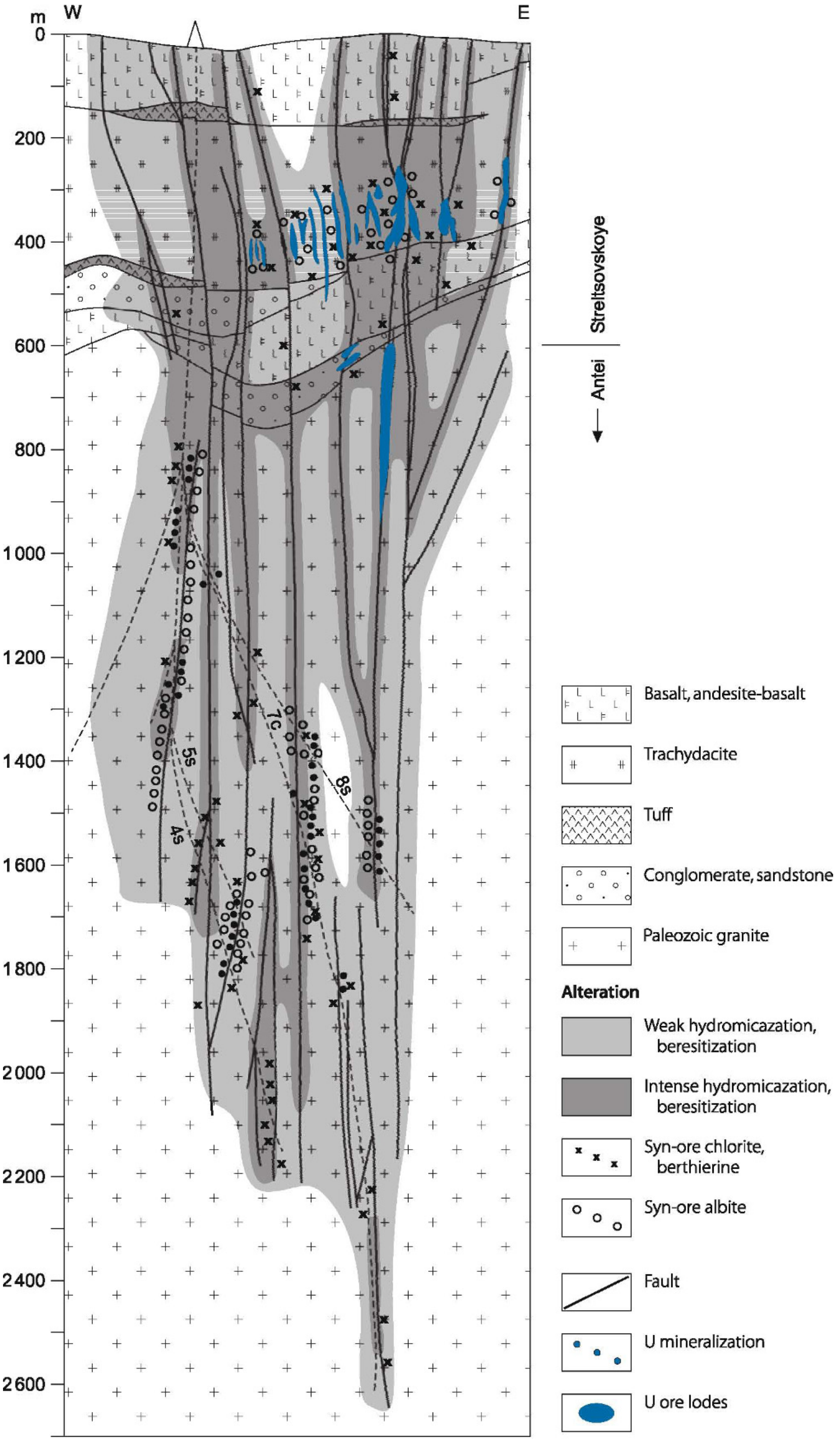


Fig. 10.14.
Streltsovsk District, Streltsovskoye (Central)-Antei, schematic W-E section with distribution of wall rock alteration features (after Andreeva et al. 1996, based on data from Ischukova, Makushin, Evstratov and others)



Streltsovskoye into the Antei deposit. Hydromicaceous facies change gradually to sericite/beresite at a depth of 1 600–1 900 m, Fe-carbonates to Mg-Ca-carbonate at approximately 1 600 m, and berthierine to ferrous chlorites within 1 600–1 900 m deep. The alteration zoning is paralleled by modifications of the ore and gangue mineral assemblages. Pitchblende gives way to brannerite and other uranium titanates at a depth of about 1 100 m, ore-related albite disappears at about 1 800 m.

Pre-ore hydrothermal activity started with *low-temperature hydromica-sericite* formation, 139–130 Ma ago. Compared with the age of 144–143 Ma for the youngest rhyolite ignimbrites of the Tulukuyevsk Caldera, the alteration began shortly after subaerial volcanism waned. Faults, cataclastic zones, lithological contacts, and permeable rocks control the hydromica-sericite distribution. Intensely hydromica altered aureoles are from several centimeters to several tens of meters wide. The alteration phenomena tend to peter out only below 2.5 km.

Mixed-layer mica-smectite and hydromica are typical above a depth of 1 600–1 900 m. They grade downward into anhydrous sericite. The sericitized rocks are similar to beresite but differ from typical beresite by the lack of pyrite. A single process apparently formed both alteration facies as indicated by the gradual transition and identical K-Ar ages of 139–133 ±5 Ma for hydromica and sericite from different hypsometric levels (160–2 160 m deep). Temperature gradation is thought to have conditioned the facies change.

Carbonate composition also tends to rely on depth. Ferrous carbonate species, essentially ankerite and occasionally breunnerite and siderite are typical for altered volcanic rocks and upper parts of granite above a depth of 1 600 m, while dolomite prevails below 2 000 m. The vertical zoning of carbonates is obscured, however, by superimposed later phase ankerite, siderite, and calcite veinlets.

Andreeva et al. (1996a) established the zonal pattern presented in Table 10.3 related to the development of hydromica and other alteration products, going from fresh rock to the core of an alteration halo (relict and neogenetic minerals listed together).

Table 10.3.
Zonal pattern related to the development of hydromica and other alteration products (Andreeva et al. 1996a)

Alteration assemblages in trachydacite	Alteration assemblages in granite
1. Slightly altered rocks: quartz, K-feldspar, plagioclase, biotite, calcite, hydromica, hematite, chlorite	1. Original granite: quartz, K-feldspar, plagioclase, biotite, titanomagnetite
2. Quartz, K-feldspar, plagioclase, hydromica, ankerite, hematite	2. Quartz, plagioclase, calcite, ankerite, chlorite, hematite, leucoxene, hydromica
3. Quartz, hydromica, ankerite, K-feldspar, siderite	3. Quartz, K-feldspar, hydromica, ankerite, hematite, siderite
4. Quartz, hydromica, ankerite	4. Quartz, K-feldspar, hydromica, leucoxene
	5. Quartz, hydromica

The main quantitative change in the authigenic mineral fraction is due to increasing hydromica and decreasing carbonate amounts in the intermediate and inner zones of the alteration aureole. Chlorite is scarce in rocks modified by the pre-ore alteration stage. On upper levels of the deposit, mafic minerals (biotite, amphibole, pyroxene) are often directly replaced by carbonate without intervening chloritization. This is notably true for trachydacite where ankerite completely pseudomorphs after biotite.

Andreeva et al. (1996a) postulate an acidic, low pH solution to have formed the beresitic-hydromicaceous alteration facies because in case of basic fluids, humbeite would have formed instead. Granite was much more altered than volcanic rocks. The discriminative alteration is attributed to more aggressive properties of the solutions presumably due to a low pH value conditioned by halide contribution, fluorine in particular, at the deep levels. Sericite and hydromica in pre-ore altered granite and volcanics contain up to 1 wt.-% fluorine, which may be regarded as indirect evidence for a fluorine involvement in early hydrothermal processes prior to the general deposition of vein fluorite.

Physico-chemical properties of the alteration minerals suggest that the thermal gradient and the total pressure hardly exceeded 100–120°C and 1 kbar, respectively, during the hydromicazation-beresitization event at the Streltsovskoye-Antei deposits. Maximum temperatures at deepest levels of the deposit were presumably in the order of 300°C as deduced from the beresite parageneses.

Hydromicazation was succeeded by the *quartz-carbonate-sulfide stage*. Thin ankerite and siderite veinlets with pyrite and arsenopyrite, and cryptocrystalline quartz with locally elevated uranium values of some tens of ppm U attest to this stage. The veinlets are usually restricted to the hydromica aureoles. They are rare in slightly altered and unaltered rocks.

The subsequent *albite-brannerite phase* produced up to 1.5 m wide zones composed of veinlets of fine-grained, untwinned albite, and disseminated brannerite and some unidentified uranium titanates. The albite contains irregularly distributed fine hematite, which imparts a pink color of varying intensity on the albitized rock. Albitization typically affected aluminous rocks, particularly granite, to a lesser extent trachydacite, scarcely basalt, and is absent in altered sediments and tuffs. A marked increase of albitization and brannerite intensity is noted around coffinite-brannerite-pitchblende ore close to the upper contact zones of granite. Veinlet albite persists over a vertical range of almost 1 600 m. It peters out at a depth of about 1 800 m and no albite is found below 1 880 m (Fig. 10.14).

Syn- to post-ore veinlets of berthierine, a ferrous chlorite-like mineral, developed simultaneously with and after the late pitchblende formation. In some volcanic rocks, for example basalt, berthierine persists beyond the hydromica aureoles.

Post-ore alteration along ore controlling faults include narrow argillization aureoles, and veins and veinlets of two fluorite generations, quartz of various habits, calcite, pyrite, marcasite, bertrandite, baryte, dickite, berthierine, zeolites, and some other minerals. Argillized aureoles are from fractions of a meter to several meters wide and appear as bleached rocks composed of smectite or smectite-kaolinite mixtures, which replace feldspar remnants or ore-related albite. Coffinite veinlets emerge where argillization overprinted rich uranium ore. The post-ore alteration minerals are typical for upper levels down to a depth of 500 m. Their intensity, particularly that of fluorite and fluorite-calcite, decreases within the 500–1 000 m depth interval. Further below, these assemblages become rare, if not absent. The deepest argillized zone composed of to sudite-kaolinite was found at a depth of 2 307 m.

Mineralization

Pitchblende is the principal uranium mineral; coffinite and U-Ti phases (brannerite) are rare. Molybdenum occurs as Fe-molybdenite or jordisite, transformed into ilsemannite in oxidized sections. Uranium locally associates with pyrite; isolated quartz veinlets, and coarse flakes of molybdenite. Some ore lodes contain noticeable quantities of beryllium in form of bertrandite. As indicated in Fig. 10.15, over 30 minerals were formed in total by hydrothermal processes.

Uranium mineralization consists of several overprinted phases starting with albite-brannerite, followed by quartz-molybdenite-pitchblende, and finally quartz-coffinite. Quantitative relations between the uranium minerals vary widely, but pitchblende is always dominant particularly in high-grade ore. Host rocks of high-grade U ore are always intensely red colored by hematitization. Molybdenum mineralization consists of jordisite/molybdenite with cryptocrystalline quartz and fine-flaked molybdenite, which may associate with pitchblende and lath-like quartz. U-Ti phases occur predominantly as dissemination in trachydacite hosted low-grade ores.

Ore fabrics include fine disseminations, vug fillings, stringers, coatings of cracks and breccia fragments, and impregnations of breccia matrix.

Chernyshev and Golubev (1996) summarize characteristics of the main ore phase, the quartz-molybdenite-pitchblende paragenesis as follows. Pitchblende is the prominent ore mineral and occurs in three generations. *Pitchblende 1* forms small spherulites, crusts, pockets, up to 5 mm thick veinlets, and coats columnar quartz and rock fragments in breccia zones. Pitchblende aggregates are often broken and recemented by pitchblende 2 or feathery quartz with Fe-molybdenite. *Pitchblende 2* occurs as less than 0.1 mm large spherulites, intergrowths, veinlets, pockets, and overgrowths of lathlike quartz crystals, and nodules and fragments of pitchblende 1 spherulites. Feathery quartz and chalcopyrite cement broken pitchblende 2. *Pitchblende 3* constitutes the bulk (ca. 90%) of the Streltsovskoye ore. Pitchblende 3 occurs as up to 10 mm large spherulites and variably shaped nodular aggregates. Pitchblende 3 in veinlets and altered wall rocks is commonly associated with chlorite and hydromica.

First generation isotropic Fe-molybdenite (Fe-molybdenite 1) fills interstices between spherulites of pitchblende 1 and 2, or cracks within broken aggregates. Pitchblende 3 corrodes and cements fragments of Fe-molybdenite 1.

Galena crystallized during several stages. Galena of the quartz-sulfide-carbonate stage contained in quartz pockets and veinlets is closely associated with sphalerite and chalcopyrite. Galena of the quartz-molybdenite-pitchblende stage occurs in thin quartz veinlets cutting pitchblende 1 and 2. In turn, this galena is corroded by pitchblende 3. Galena of a separate post-ore stage is associated with low-reflectance uranium oxides.

Redistribution of ore-forming metals is a common feature at Streltsovskoye. Redeposited coffinite and uranium oxides associated with post-ore galena occur in quartz and calcite veinlets and pockets, which cut early pitchblende. Black or dark violet, radioactive fluorite of the late quartz-fluorite-calcite phase contains minute pitchblende inclusions.

Andreeva et al. (1996a) report an alteration-related distribution of ore mineral assemblages from the Streltsovskoye into the Antei deposit (Fig. 10.16). Veins, veinlets, and disseminations of the quartz-molybdenite-pitchblende assemblage occur within and beyond the albitization zones, but they never extend beyond the boundaries of the hydromicaceous aureoles.

A vertical zoning of U mineralization is reflected by a distinct change of U mineral assemblages with depth. Pitchblende prevails on the upper levels of the deposits. It changes downward to brannerite-pitchblende and then to brannerite. Richest molybdenite-pitchblende ores with subordinate brannerite extend to a depth of 900 m. Mixed pitchblende-uranium titanate mineralization is typical for the 900–1 300 m depth interval, and uranium titanate mineralization below 1 300 m. Coffinite forming after pitchblende, and, to a lesser extent, brannerite, generally occurs on the upper levels of the Streltsovskoye-Antei deposits, although coffinite occasionally is also found at depths down to 1 200 m. Albite-brannerite ore persists to a depth of 1 880 m, and no more than a few narrow (several meters) high-radioactive zones in brecciated and fractured granite were encountered below this level (Ischukova 1995, 1997).

Shape and Dimensions of Deposits: *Streltsovskoye*

Streltsovskoye comprises six ore sectors, *Central*, *West*, *East*, *Glubinny*, *Golub*, and *Flangovy*, within a 4 km long and 2.5 km wide structural zone (Fig. 10.17). Fault zones and their intersections control their position. Mineralization occurs in the sedimentary-volcanic caldera fill over a vertical interval of 480 m. Upper limit of most ore bodies is several 10s of meters below surface. Only a single, steeply dipping uranium ore body occurs near surface, under 15 m of unconsolidated sediments. It is within the Streltsovsk fault near the same named fluorite vein. Approximately 80% of the reserves are concentrated between 300 and 550 m deep.

The *Central sector* is 2 300 m long and varies in width between 100 and 500 m; the *West sector* is 1 700 m long and 50–170 m wide; and the *East sector* 1 800 m long and 100–500 m wide. *Glubinny* is an isolated ore sector about 400 m to the NW of the Central and 500 m to the N of the West sector; ore occurs at deep levels in the lower trachydacite sheet. *Golub* is adjacent to the south of the East sector.

Sectors are composed of ore bodies of various shape ranging from variable large vein and stockwork to tabular stratiform lodes. Most ore bodies consist of a series of elongated and steeply inclined veins and stockworks in which ore occurs in contiguous, steeply dipping fractures that bifurcate from larger faults.

Fig. 10.15.

Streltsovsk District, Streltsovskoye-Antei, paragenetic scheme of ore and related minerals. The symbol size reflects the mineral abundance and time interval of deposition (after Nikolsky and Schulgin 2001)

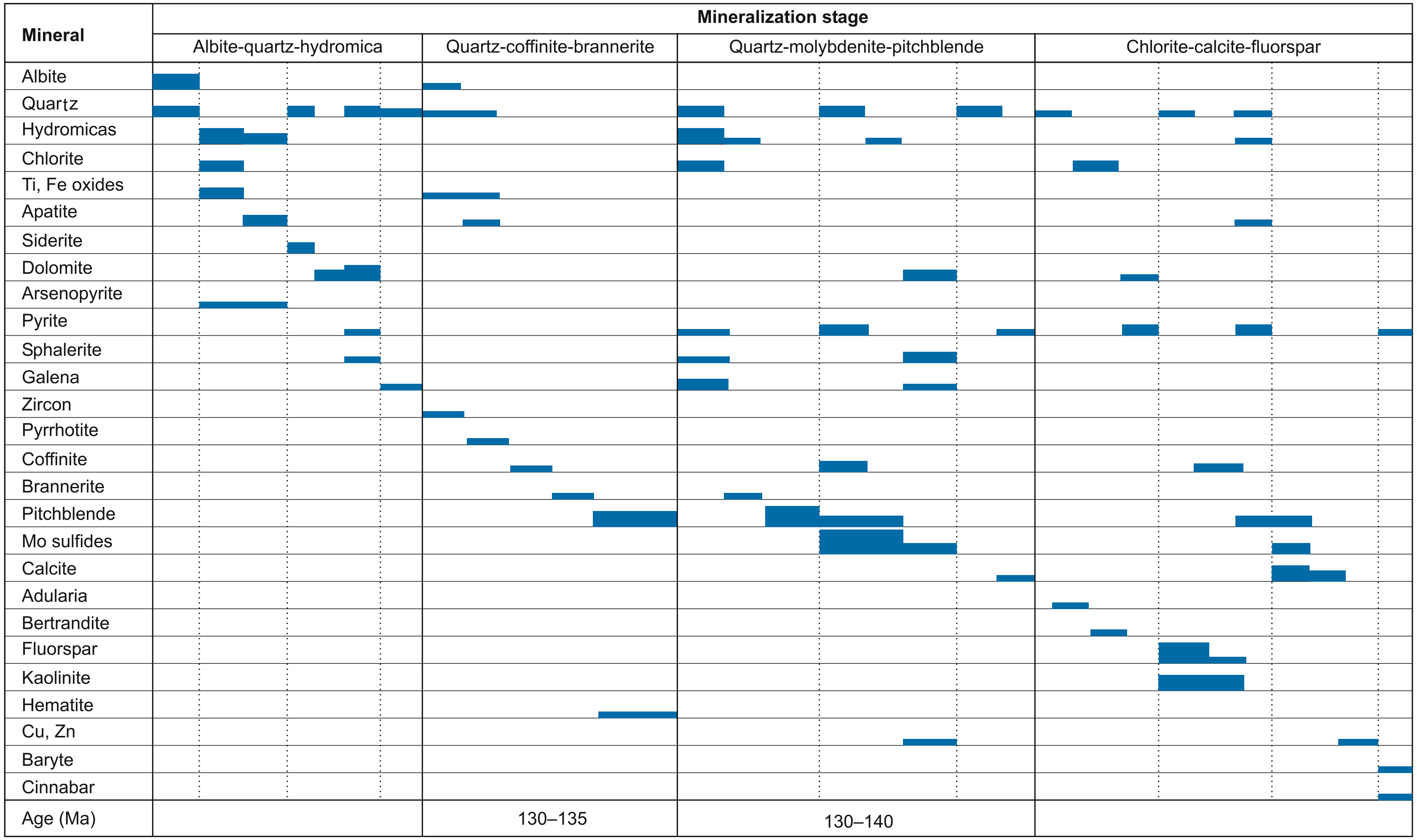
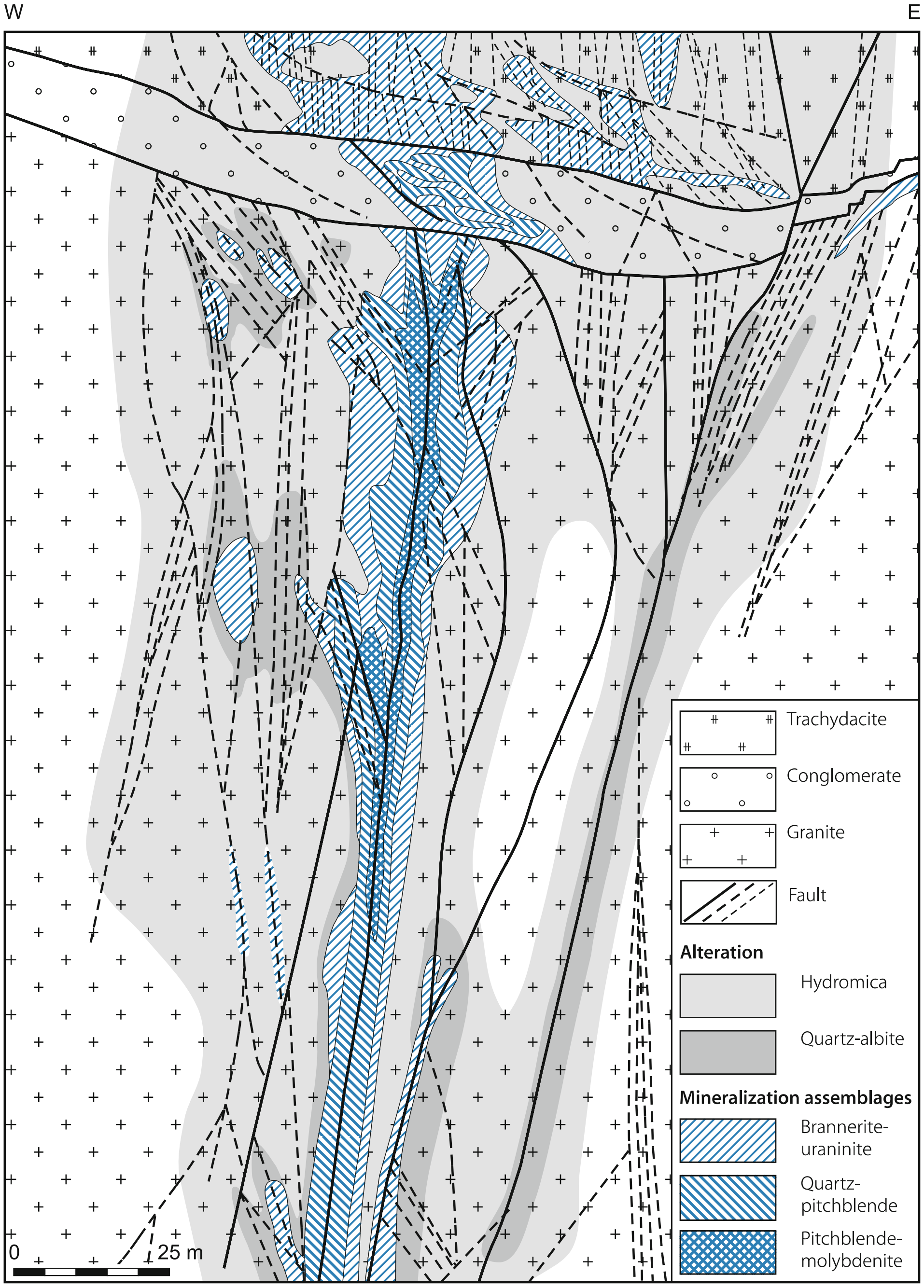


Fig. 10.16.

Streltsovsk District, Streltsovskoye-Antei, schematic W-E section with lateral and vertical distribution of uranium and molybdenum ore assemblages, and halos of major alteration facies in the basal Streltsovskoye and upper (about 200–300 m) Antei deposits (after Nikolsky and Schulgin 2001)



Stockwork lodes split at their periphery into short veins. Mineralization is distributed across all of the intersected rocks but in differential intensity. Length and width of ore bodies attains a few hundreds of meters. The vertical persistence of individual lodes commonly ranges from 30 to 90 m as a function of the thickness of the horizon cut by the ore controlling structure. Uranium grades of lodes vary between 0.15 and 0.5% U. Grades increase toward the lower or upper boundaries of ore bodies against gently dipping faults that transect tuff or conglomerate beds.

The bulk of reserves at Streltsovskoye is contained in relative narrow, 200–300 m wide, NE-SW-trending zones in the Central, West, and East sectors, which are terminated on the SE side by the NNE-SSW trending fault 13. The *Central sector* accommodates significant reserves in vein and stockwork ore lodes within the 3 km long Streltsovskaya (or N1) fault zone. The structure dips 65–80° and strikes NW-SE turning to N-S in the NW part where it joins the Central fault zone. The uranium mineralized section is 750 m long, averages 6 m thick, persists over a vertical interval of about 330 m, and averages a grade of 0.33% U.

Fig. 10.17.

Streltsovsk District, Streltsovskoye-Antei, plans and sections illustrating the shape and structural-lithological control of ore bodies. a Geological plan at level +302 m a.s.l. (ca. 400 m below surface) showing the shape of vein and stockwork ore lodes at and adjacent to the Paleozoic granite interface with overlying Late Jurassic conglomerate and trachydacite. b Geological SW-NE section (Central Zone, prospecting line 115 + 50) demonstrating the vein-stockwork system in the Streltsovskaya fault zone. Stockwork ore lodes prevail in basalt and trachydacite sheets. Their vertical extensions contract to veins particularly in conglomerate beds. c Geological SW-NE cross-section (prospecting line 113 + 50) illustrating the hanging and foot wall control of a stockwork ore body by shallow inclined faults along lithological contacts. d Geological plan at level 332 m and e W-E section (prospecting line 97) of the Glubinny sector of the Streltsovskoye deposit (after Ischukova 1997)

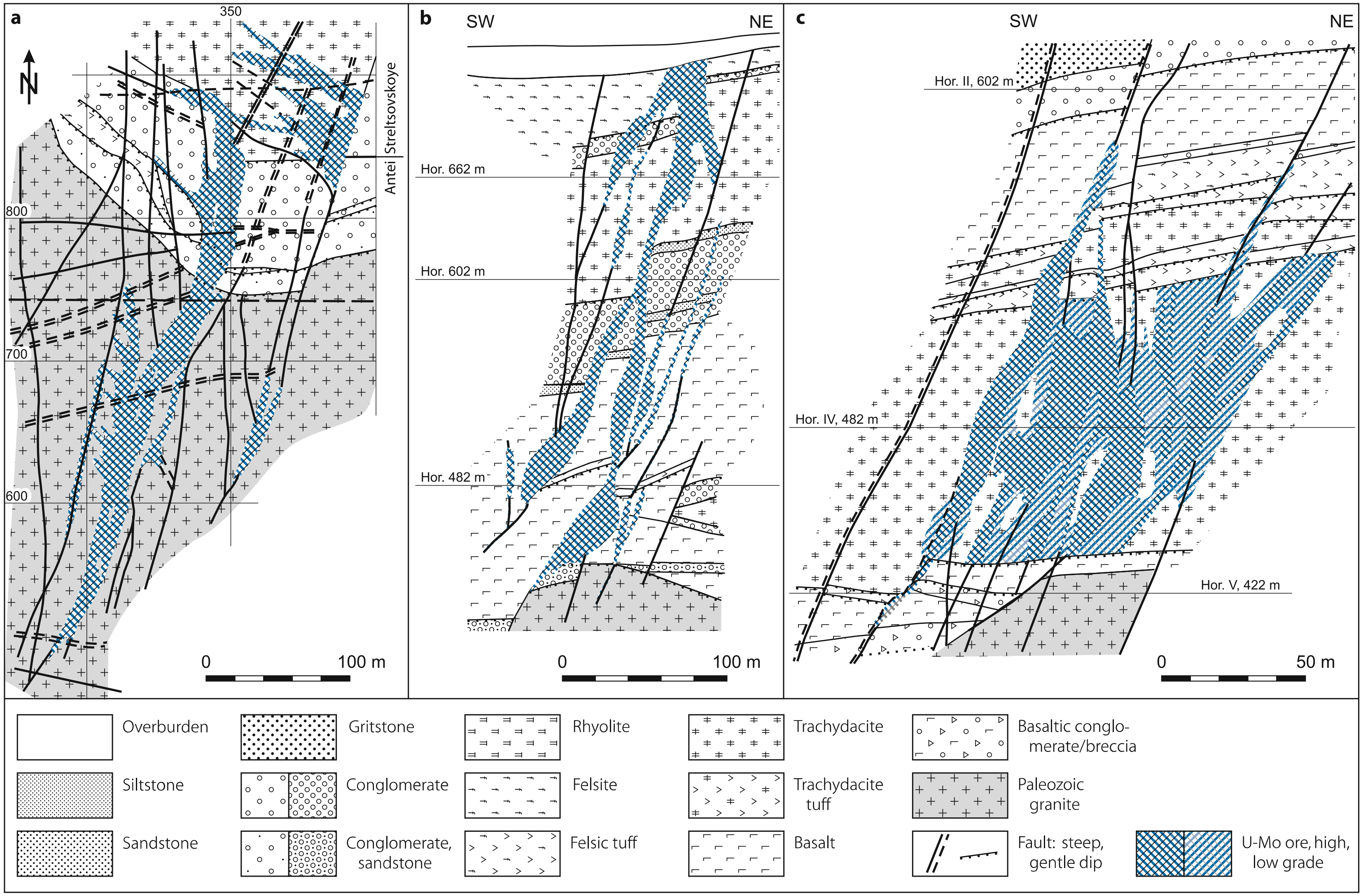
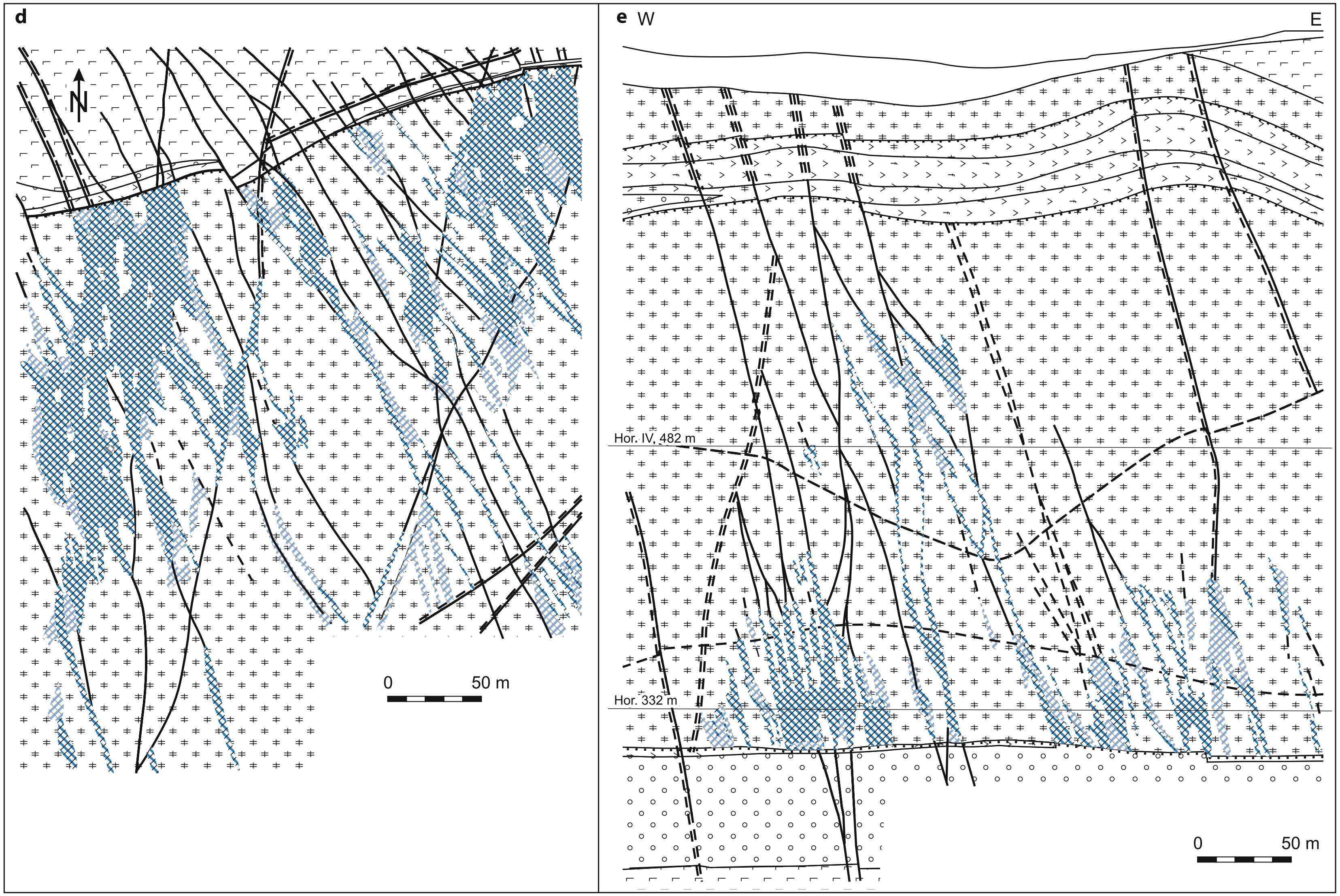


Fig. 10.17. (Continued)



The structure carries ore through all intersected lithologies, but the majority of reserves is concentrated in stockwork-like ore bodies in the lower trachydacite sheet whereas highest grades of up to 0.8% U and 0.4% Mo are restricted to basalt. 77% of the reserves occur in trachydacite, 16% in basalt, and the remainder in quartz porphyry and conglomerate. The N1 fault also contains the Streltsovskaya fluorite vein about 100 m to the NW of the uranium section.

The *Golub sector* holds in ore zone 2 the largest tabular stratiform ore body of Streltsovskoye. Ore is hosted by andesite and quartz porphyry conglobreccia (composed of almost equal amounts of pebbles and angular fragments) at the base of a felsic sheet, which is contiguous to the southern flank of the Eastern sector. The mineralized strata average 1.5 m thick, contain 0.2–0.24% U with local enrichments of as much as 2.2% U, and occur at a depth of 145–270 m below surface.

Shape and Dimensions of Deposits: *Antei*

Ore occurs over a depth interval from 350 to 1 400 m below surface, controlled by a bundle of steeply dipping, NE-SW-trending faults (Figs. 10.13, 10.16). Host rock is altered Late Paleozoic anatectic granite. Principal structures are faults number 13, 6A, 160 and 190. They control combined with a group of smaller faults the ore distribution. Most significant is the large, 30° NE-trending fault zone 6A that is between faults 13 and 160. As a function of the distance to these two faults, the width of zone 6A ranges from 10 to 50 m in the central part to 80–100 m at the flanks.

Fault 6A includes ore body 6A, which is 1 000 m long, extends 900 m down dip, has a grade of about 0.7–0.9% U locally with peaks of 4% U, and accounts for 94% of the Antei reserves. Molybdenum contents are less than 0.03%.

Ore body 6A is of complex vein-stockwork configuration. Up to 50 m wide swells with stockwork structure alternate with a few meters thick vein-like intervals. Its upper margin abuts against a gently dipping fault that follows the contact of disintegrated granite and overlying conglomerate and trachydacite. The trachydacite contains ore lodes of the Streltsovskoye deposit (Figs. 10.16, 10.17a). Most of the uranium is concentrated in the central part of the 6A body within a chimney shaped ore lode in cross-section. The lode is 200 m high, 300 m long, from 10 to 50 m thick, and averages 0.954% U (Ischukova 1997).

Geochronology

Age datings by Chernyshev and Golubev (1996) provide for massive, unaltered pitchblende concordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages within a narrow range of 136–134 Ma. Pitchblende impregnated by fine inclusions of chlorite and carbonate, and pitchblende with galena and Fe-molybdenite inclusions show a discordant age of 133 ±4 Ma, but this is within a wide range of discordant U-Pb ages obtained from pitchblende with impurities. Pitchblende with coffinite inclusions is commonly rejuvenated presumably due to a loss of radiogenic lead (131–1 30 Ma for pitchblende with coffinite, and 83–52 Ma for hydrated uranium oxides and coffinite segregations associated with primary massive pitchblende). In contrast, higher ages than those of the original pitchblende crystallization are usually obtained from pitchblende partially replaced by or intergrown with calcite or Fe-molybdenite. Massive nodular pitchblende, which is partially replaced by calcite and contains minute galena in the zones of replacement yield slightly discordant values of 142–138 Ma. Pitchblende intergrown with Fe-molybdenite shows a correlation between U-Pb age values and the content of Fe-molybdenite reflected by a roughly proportional increase of radiogenic ages of samples with an increase in Fe-molybdenite content, up to a geologically unrealistic value of 179–177 Ma.

K-Ar ages of mixed-layer micas formed during a pre-uranium hydromicazation process fall within a range of 144–129 Ma. Most samples of hydromica from altered granite yield Rb-Sr ages of 134±1 to 131±2 Ma, and K-Ar ages of 133 to 135±5 Ma. Chernyshev and Golubev (1996) calculated an average Rb-Sr age of 133±2 and a K-Ar age of 135±3 Ma for these pairs and consequently propose a period between 139 and 131 Ma as a best estimate for the hydromicazation event, i.e. a time span, which only slightly exceeds that of the main ore-forming process of 135–133 Ma.

Monomineralic fractions and some whole rock samples of the volcanic-sedimentary suite, from trachydacite of the early lava unit to the youngest porphyritic syenite, give K-Ar ages from 166 to 142 Ma, and a Rb-Sr age of 139 Ma for the late porphyritic syenite and rhyolite.

Sources of Uranium

Various lithologies provide potential source rocks for the U deposits in the Streltsovsk District. Table 10.2 furnishes average U and Th background data for these and other rocks.

Circumstantial evidence based on isotope systematics provided by Chernyshev and Golubev (1996) indicates two discrete potential uranium sources in the basement of the Tulukuyevsk Caldera. Fe-molybdenite in a pitchblende-molybdenite ore sample contains 260–250 Ma old radiogenic lead. It is thought that the lead and presumably also uranium have originated from a Permian uranium protore in a 258–248 Ma old porphyry granite (biotite and K-Na feldspar dated by K-Ar method).

Another, still older uranium source is testified by dispersed uraninite mineralization in a granite-hosted Precambrian amphibolite xenolith. The uraninite yields an Ordovician U-Pb age of 459–457 Ma. The sample containing the uraninite also includes molybdenite crystals with small pitchblende spherulites. The pitchblende gives discordant U-Pb ages of 156 and 150 Ma, which point to a Mesozoic hydrothermal event that affected the Precambrian rocks below the caldera. The discordant U-Pb ages of pitchblende and their difference with the U-Pb ages of the Streltsovskoye ores proper may be caused by the significant amount of common lead in the sample (ca. 1.2% ^{204}Pb) and the excessive radiogenic lead mobilized by the alteration of the Ordovician uraninite.

A similar age as that of the afore mentioned uraninite is provided by isotopic data of common lead from galena of the Streltsovskoye deposit. The lead consists of a two-component mixture of lead with a model age of 460 Ma and lead similar in composition to radiogenic lead from the uranium ore.

Metallogenetic Aspects

The Streltsovskoye-Antei deposits originated in a relatively stable tectonic environment as indicated by only minor displacements along most faults. This and also the limited post-ore processes favored the conservation of the ore and pre-ore alteration assemblages.

Chernyshev and Golubev (1996) arrive at a metallogenetic model for the Streltsovskoye deposit that involves several hydrothermal events including two separate major phases of mineralization that formed uranium and fluorite ore. Strong hydromicazation and relatively scarce quartzification-sulfidization preceded the uranium deposition. The bulk of uranium was deposited during the quartz-molybdenite-pitchblende stage, in which three generations of pitchblende are the predominant constituents. U-Pb ages of these three generations indicate that the principal ore-forming event took place 135–133 Ma ago, i.e. during the Hauterivian/Cretaceous and lasted less than 3 Ma. This episode coincides approximately with the age of 138–136 Ma for uranium deposition in the Dornod volcano-tectonic structure in eastern Mongolia, which is also within the Mongolian-Argun volcanic belt. The wide range of discordant U-Pb ages obtained from pitchblende with impurities is interpreted to testify to telescoping hydrothermal processes and related pitchblende modifications.

Chernyshev and Golubev (1996) also address the age relationship between volcanic rock and uranium ore formation. Compared with the 135–133 Ma ages of pitchblende, there is a formal time gap of 4 Ma between the intrusion of porphyritic syenite dikes, the latest magmatic facies at Streltsovskoye, and the principal uranium introduction. By including the pre-uranium hydrothermal event of hydromica formation, the time gap reduces to 3 Ma. Analytical error values and likewise the dispersion of ages signal an uncertainty of some 3–4 Ma, however, and thus the time gap could have been as long as a fraction of a million to several million years. The authors interpret the interval as the time it took for the major magma chamber, which existed below the Streltsovsk Caldera for a long time during the Late Jurassic and participated in the formation of the Tulukuyevsk volcanic-tectonic structure, to cool to the point at which the mineralizing hydrothermal system began functioning that provoked the U-Mo ore formation. Consequently, they stipulate a contiguity of the final volcanic phases and the ore-forming process. The established hydromica ages, which overlap with those of the ore, are thought an additional argument to support the contiguity concept.

The metallogenesis of the large Streltsovskoye ore lodes involved repeated concentration processes that overlapped in time and space. Although a volcanogenic proper source of the uranium cannot be excluded, isotopic evidence attests to a uranium source in the basement granite. Excessive radiogenic lead, present in Fe-molybdenite and galena of the Streltsovskoye deposit and in the ore province as a whole, implies a contribution of lead and presumably uranium from precursor mineralization in basement rocks that had formed in at least two periods 460–450 and 260–250 Ma ago and was related to the granitization and granite emplacement processes.

The conclusions drawn by Chernyshev and Golubev (1996) with respect to the granitic uranium source are relativized by findings of Andreeva et al. (1996a,b) who studied the redistribution of elements associated with the hydrothermal host rock alteration and who arrive at the following results: An increase of chalcophile elements (Li, Sb, Mo, Au, Zn, and Hg) in the volcanic and sedimentary rocks of the Tulukuyevsk Caldera at the upper levels of ore bodies and superjacent zones was already earlier established by Kozhevnikov (in Andreeva et al. 1996).

Average background values of trace elements in unaltered granite at Streltsovskoye-Antei are compared with those in hydromica/sericite-altered granite in ➲ Table 10.4. The calculated average of all analyzed samples yield a net gain of elements, such as Co, Mg, and Th in hydromica altered granite and a net loss for Mo, U, Pb, and other elements. Although the data in ➲ Table 10.4 provide a general picture of the geochemical (re-)distribution of trace elements, the factual situation is more complex. Altered granite and trachydacite display alternating gain and loss sections and a differentiated intensity of loss and gain patterns along the vertical profile. The intensity of the loss aureoles decreases towards the surface, while the gain aureoles become more pronounced.

In the granite, the loss of a number of components, including U, Mo, and Pb, is most pronounced in the lower, beresitized part

Table 10.4.

Streltsovsk District, Antei deposit. Average background values of trace elements and their ratios in hydromica altered and unaltered granites (Andreeva et al. 1996)

Element	Average content (ppm) Granite		Ratio 1/2
	Hydromicaceous (1)	Unaltered (2)	
Co+	4.6	4.1	1.121
Ti	1 958	1 805	1.085
Mg+	0.35	0.33	1.083
V	25	24	1.075
Th+	20	19	1.059
Mn	918	870	1.055
Sr	203	193	1.055
Fe	1.8	1.7	1.044
Be	4.4	4.3	1.030
Zn	62	60	1.029
P	326	318	1.022
Cr	53	52	1.014
Ba	734	729	1.006
Zr	145	149	0.978
Nb	9.5	9.7	0.977
La	56	58	0.967
Ni	22	23	0.960
Ga+	24	26	0.944
Cu	12	13	0.944
Y+	33	35	0.930
Yb+	3.3	3.7	0.913
Sc+	4.1	4.5	0.912
Sn+	3.8	4.1	0.910
Ca+	1.3	1.5	0.870
Pb+	24	28	0.861
U+	5.1	6.0	0.853
Mo+	6.2	8.2	0.750

Amount of samples: hydromicaceous granite: *N* = 100, unaltered granite *N* = 136; "+" marks the elements with significantly different average contents in the hydromicaceous and unaltered granites.

of the explored section. Other elements such as Co, Mg, and Th were accumulated at these levels, but a great number of the elements extracted at the lower levels (Yb, Mo, Sr, Y, Ni, Cr, Zr, Be, Nb, Mg, Fe, etc.) were transported to and redeposited at upper levels.

Hydromicazation caused practically no loss of uranium from trachydacite, while the average uranium tenor of granite was reduced from 6.0 to 5.1 ppm but not in a uniform manner. A genuine U loss is documented for beresitized granite at deep levels below 1 500 m, whereas the upper, hydromica-altered levels show both, intervals of loss and partial gain of uranium as well, which, in sum, yielded a gain within the hydromica zone. Andreeva et al. (1996a) conclude from these data that the liberation of many elements, including uranium to some extent, from the basement granite in result of beresitization and hydromicazation does not provide sufficient evidence to define the granite as a viable source for the uranium in the Streltsovsk deposits. The authors rather assume that the uranium leached during the pre-ore alteration was redeposited in subeconomic concentrations in cryptocrystalline quartz and siderite veinlets of the quartz-carbonate-sulfide assemblage.

10.4.1.2 Tulukuyevskoye

Tulukuyevskoye is a polymetallic U-Mo deposit in the central-western part of the Streltsovsk District, about 15 km SE of Krasnokamensk. Original in situ resources were some 37 000 t U. Ore averaged a grade of 0.24% U. The deposit also contained molybdenum ore with grades of 0.2% Mo. Molybdenum concentrate had an average rhenium content of 146 ppm. Mining was largely by open pit operation and lasted for almost 30 years from 1968 to 1998. The deposit is depleted.

Source of information. The subsequent description is summarized from Ischukova (1997) unless otherwise stated.

Geology, Alteration and Mineralization

Tulukuyevskoye is positioned at the intersection of the NW-SE-striking Tulukuyevskaya with the NE-SW-trending Argunskaya shear zone. Principal host rocks are stratified volcanics, predominantly Lower Cretaceous felsite/rhyolite and subjacent felsic tuff, and minor Upper Jurassic trachydacite and basalt (Figs. 10.12, 10.18a,b).

Wall rock alteration is well developed and includes hydromicazation, carbonatization, silicification, hematitization, and chloritization. Banded silicification and chloritization are confined to large faults. Andreeva et al. (1996a) state, that, in contrast to the Streltsovskoye-Antei deposits, albitization is absent at Tulukuyevskoye.

Principal U mineral is pitchblende. Coffinite occurs in subordinate quantities and associates with pitchblende. Uraninite and U-Ti phases are rare. Molybdenite is present as finely flaked and cryptocrystalline (jordisite) varieties. Pyrite and loellingite occur locally. Trace amounts of beryllium, lead, and rhenium are associated with the U-Mo ore. Ore has disseminated and banded textures.

Shape and Dimension of Deposits

The deposit is 1 300 m long and up to 250 m wide. Ore starts 30–50 m below surface from where it extends for 180–270 m downward. The deposit includes several ore bodies of complex configuration composed of a series of contiguous, steeply dipping veins, stockworks, and gently pitching lodes (Figs. 10.18a,b).

Ore zone # 5 is the richest and largest ore zone. It persists for 400 m long and contains between 60 and 70% of the total Tulukuyevskoye reserves in ore bodies that are up to 60 m thick. Ore grades range from the cutoff grade to 7% U, and average in excess of 0.4% U. Some segments have grades of 30–40% U over a thickness of 5 m. Ore lodes of zone 5 are controlled by NW-SE-trending structures (Fig. 10.18c). Most favored host rocks are felsite, felsic lava breccias and tuffaceous sediments. Some lower grade ore is in underlying basalt and trachydacite.

Ore zone # 2 constitutes the central part of the deposit. Steeply dipping, N-S and NE-SW faults control the ore lodes; they are limited by NW-SE faults. Ore is particularly concentrated at fault junctions. Grades average about 0.3% U. A gently dipping tabular ore body occurs within a tuff-sandstone horizon below a felsite sheet. It averages 0.2% U. Where the tuffaceous horizon is intersected by steeply dipping faults, grades increase up to 10% U.

Recoverable molybdenum at Tulukuyevskoye is mainly concentrated in the lower part of rich uranium ore bodies. The average content is 0.2% Mo, but grades vary highly in different ore bodies, from a few hundreds ppm to 12% Mo. Highest Mo grades occur in basalt and felsite tuffs. Mo ore contains rhenium, which averages 146 ppm in molybdenum concentrate.

10.4.1.3 Argunskoye

Argunskoye is a polymetallic U-Mo deposit in the SW part of the Streltsovsk District, some 13 km SE of Krasnokamensk. It was discovered in 1979 and had original in situ resources in excess of 30 000 t U and 10 000 t Mo. Ore grades average 0.17% U and 0.18% Mo. The deposit is explored by underground methods (Mine 6).

Source of information. The subsequent description is largely derived from Ischukova (1995, 1997) amended by data from Nikolsky and Schulgin (2001).

Geology and Alteration

Argunskoye is confined to the interjunction of NE-SW-, NW-SE-, and N-S-oriented deep shear zones intersecting the northern limb of an anticline of metamorphic basement rocks composed of steeply dipping, up to 200 m thick dolomitic marble with thin intercalations of quartz-mica-andalusite schist, and biotite-amphibole gneiss intruded by mafic magmatites (diabase, diorite) metamorphosed to amphibolite. The core and the southern limb of the anticline are composed of multiply metasomatized granite. A 140–300 m thick sequence of basalt and trachydacite sheets rests upon the basement. A volcanic neck occurs adjacent to the south of the deposit (Figs. 10.19a,b).

Pre-ore metasomatism produced microcline, albite, and phlogopite facies, skarn, and greisen. They tend to be particularly abundant within and near ore bodies. Low-temperature

Fig. 10.18.
Streltsovsk District, Tulukuyevskoye, a geological plan at level +600 m a.s.l.; b SW-NE section displaying the complex configuration of vein-stockwork-style U(-Mo) mineralization largely hosted in Lower Cretaceous felsite sheets and controlled by steeply dipping, NW-SE-trending structures. Shallow inclined faults act as ore boundaries; c grade distribution of uranium of a deposit segment at level 640 m a.s.l (after a, b Ischukova 1997; c Laverov et al. 1992b) (legend for a and b see Fig. 10.17)

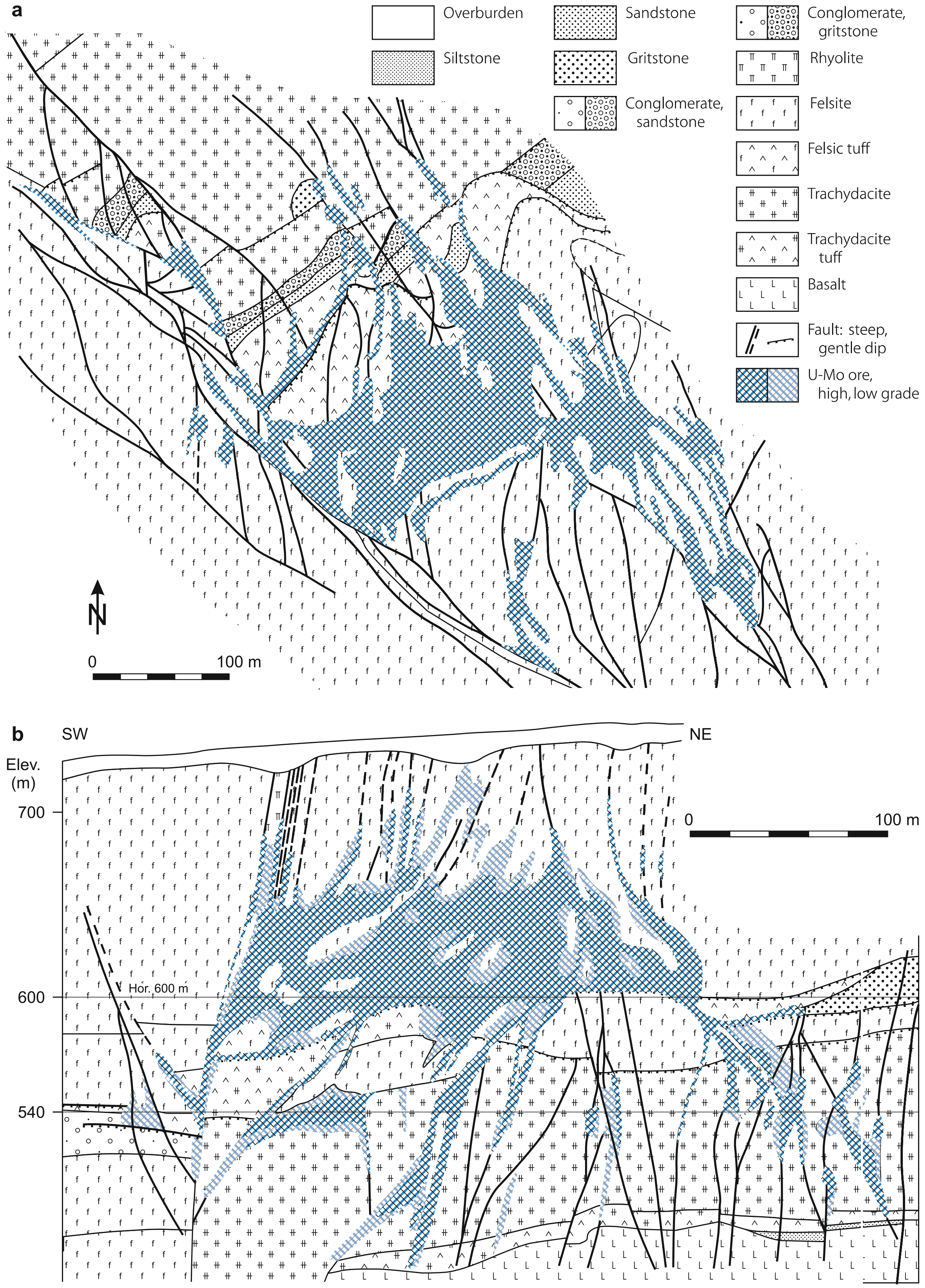
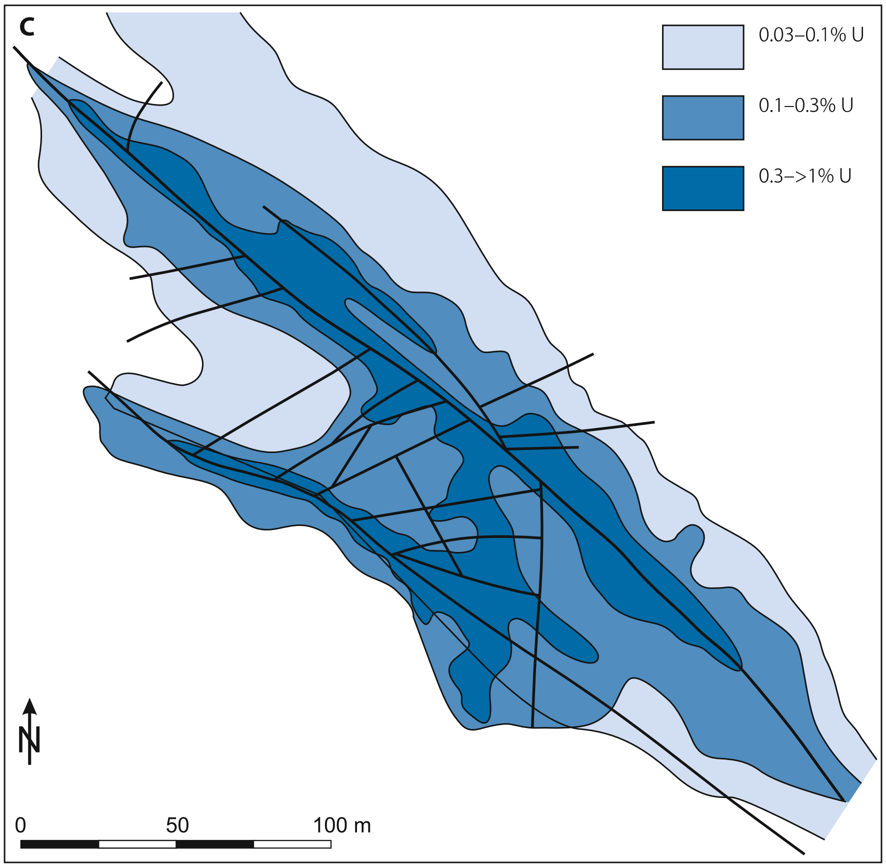


Fig. 10.18. (Continued)



alteration includes argillization and silicification. Argillization displays a zoned pattern. Kaolinite prevails at upper levels. It is downwards replaced by montmorillonite and chlorite and, below 700 m, by hydromica. Chlorite and chlorite-montmorillonite assemblages, related to the post-uranium fluorite process, occur along faults to a drill intercepted depth of 2 500 m. Andreeva et al. (1996a) clarify, that in contrast to the Streltsovskoye-Antei deposits, albitization-2 is absent at Argunskoye.

Mineralization, Shape and Dimensions of Deposits

Principal U mineral is pitchblende. Coffinite occurs in minor amounts. Mo is present as coarse-flaked molybdenite and jordisite, associated with fluorite and sulfide-bearing quartz. The ore minerals form veinlets, fill cracks and cavities, and impregnate breccia cement and wall rocks. Three ore varieties are discerned, uranium and molybdenum proper, and a mixed U-Mo ore. Most of the ore is in the dolomitic marble unit. Some ore is in granite below the marble (Figs. 10.19a,b).

Ore lodes are controlled by N-S-, NW-SE-, E-W- and, to a minor degree, NE-SW-trending structures. A 50–100 m thick breccia zone in the basal part of the marble horizon hosts the main ore lodes. The breccia body is isometric in plan view and has a steep dip conformable with the bedding.

Ore bodies consist of irregularly distributed mineralization contained in vertically elongated stockworks with apophyses, and veinlike lodes. Ore lodes are 200–300 m long, 16–70 m thick, and occur over a vertical interval of more than 1 000 m. Uppermost ore is 140 m below surface. A fault contact between basement and overlying volcanics governs the upper boundary of the ore. Grades are highly variable ranging from the cutoff grade (0.039% U) to 3.5% U. Carbonatic ore contains about 0.15% Mo, and alumosilicate (granite hosted) ore up to 0.26% Mo. Mo ore veins in syenite-porphyry contain between a few percent and 51% CaF_2, and average 12.6% CaF_2 present as violet fluorite that fills veins and impregnates breccia cement.

Approximately one third of the reserves are concentrated in ore shoots of enlarged thickness and grade with more than 0.3% U.

10.4.2 Vitim District, Asian Russia

The Vitim (Vitimsky, also referred to as Khiagda) District is some 140 km north of the town of Chita at the upper course of the Vitim River on the Amalat Plateau in the Buryate Autonomous Republic (Fig. 10.10). Although Vitim is located within the central Transbaykal subregion, it is treated separately due to its economic potential.

The district contains basal-channel sandstone-type U deposits; eight are grouped around the Khiagda ore field and form the Vitim District sensu stricto. In addition, several isolated deposits occur in some other fluvial systems in the Vitim area (Fig. 10.20). Explored resources are estimated at 52 000 t U and total resources are speculated to be on the order of 100 000 t U (Naumov et al. (2005).

Sources of information. Boitsov 1999; Laverov et al. 1992b, c, 2000; Krotkov et al. 1997; Loutchinin 1995a; Naumov 1999; Naumov et al. 2005; Pelmenev 1995.

Regional Geological Setting of Mineralization

Paleoproterozoic metamorphic rocks (schist, gneiss, migmatite) intruded by Middle to Lower Paleozoic granite constitute the basement of the Vitim District. The old peneplain was deeply weathered during a semiarid to arid climate and incised by a paleodrainage system. The system consists of tributary channels dewatering to two major ancestral rivers trending NE-SW at the margins of the Buysiuchan plain.

Up to 50 m thick or more Pliocene to Oligocene sediments predominantly of colluvial and, along thalwegs, of alluvial provenance fill the paleochannels. The sediments consist of grey and multicolored carbonaceous clay-siltstone, sandstone,

Fig. 10.19.

Streltsovsk District, Argunskoye, a geological plan at level +374 m a.s.l. and b SW-NE section illustrating the litho-stratigraphic position of ore lodes with U and/or Mo mineralization and related alteration aureoles in Proterozoic dolomitic marble xenolith in Late Paleozoic granite below a basalt sheet of the Tulukuyevsk Caldera (after Nikolsky and Schulgin 2001)

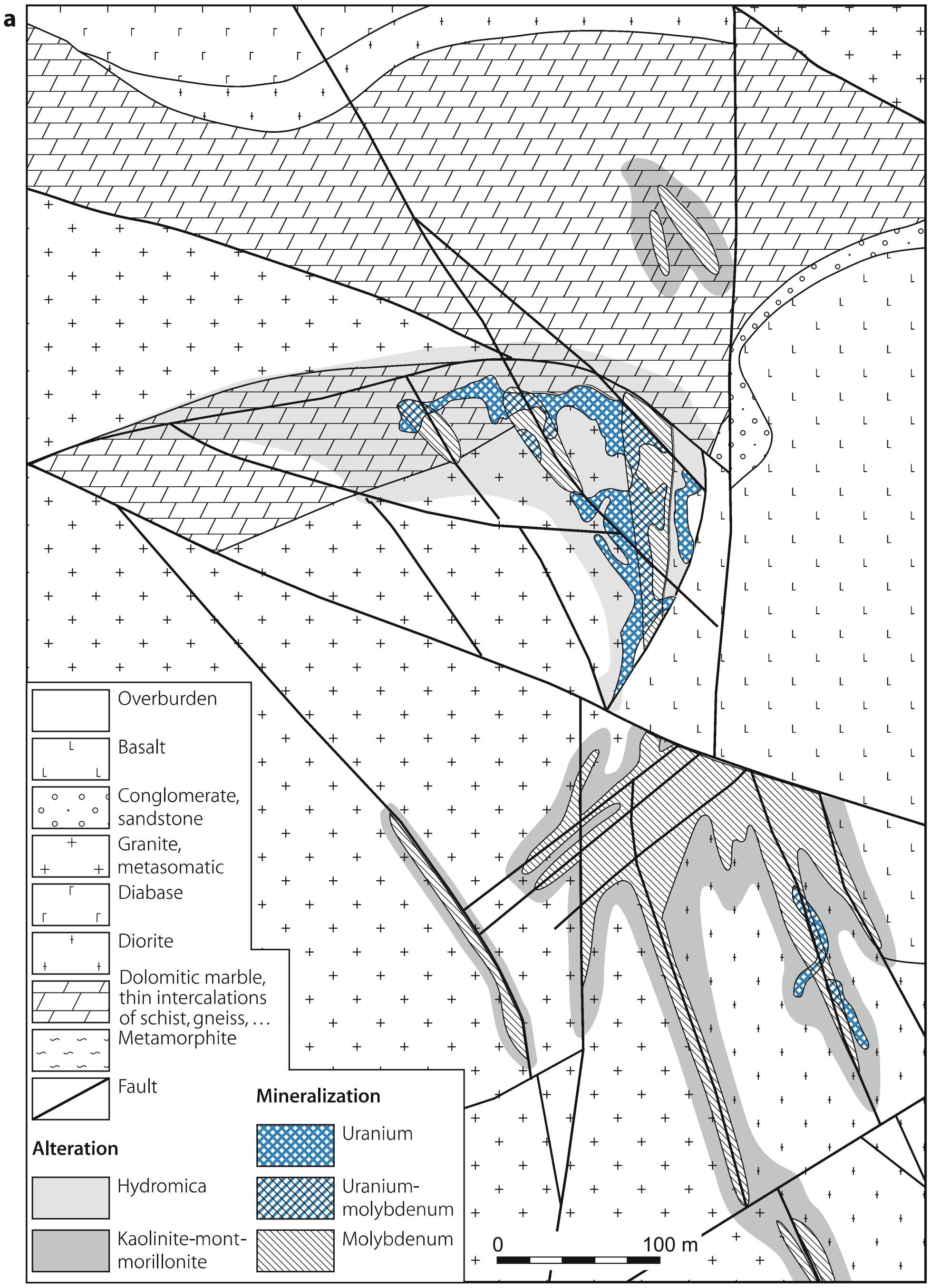
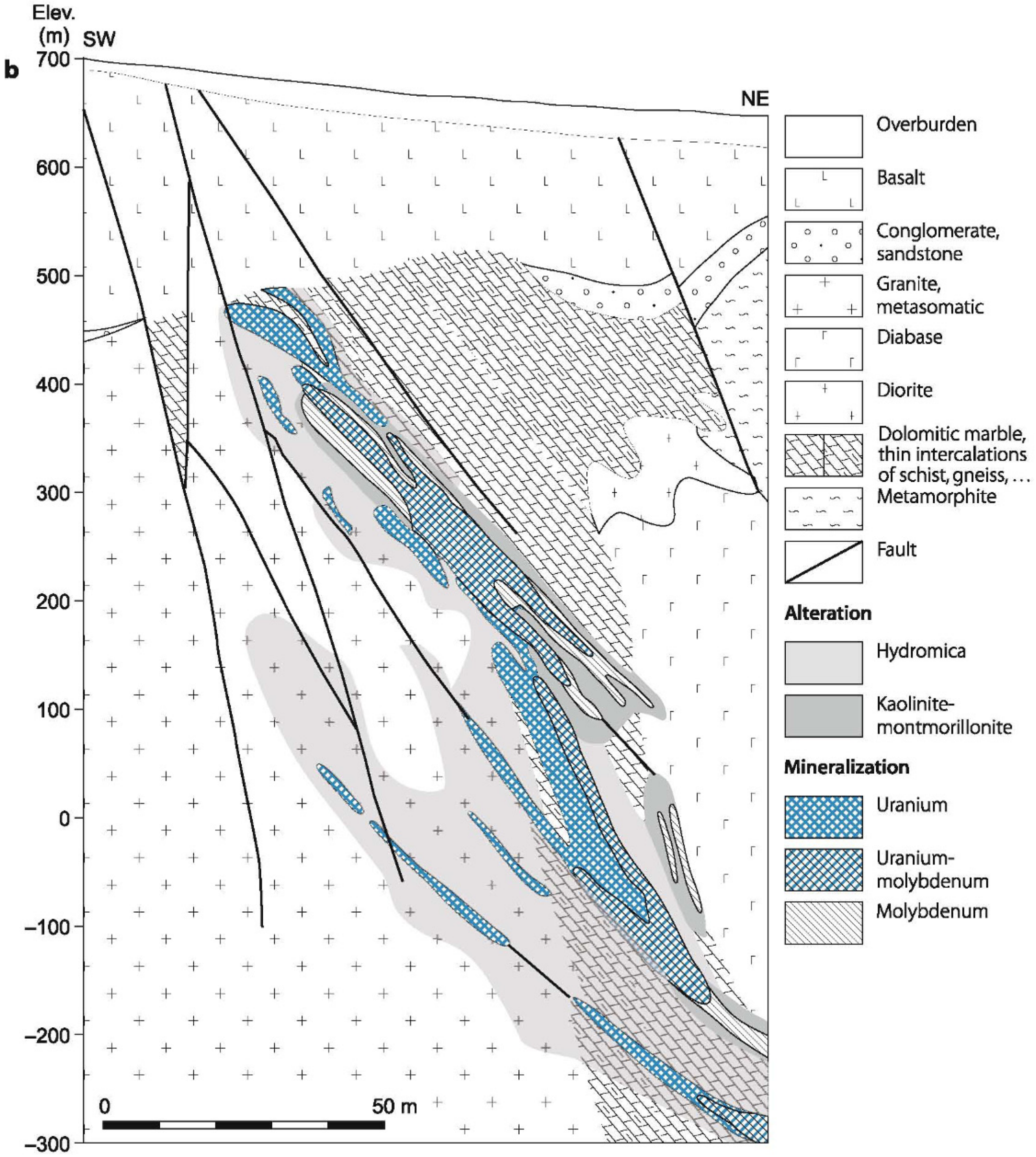


Fig. 10.19. (Continued)



conglomerate, and tuff with some intercalated lignite seams. Grey facies contain pyrite and are enriched in plant debris. Carbon content averages about 0.8% C_{org}. A cover of 10–30 m, locally up to 250 m thick Quaternary-Neogene tuff-bearing sand and gravel intercalated with or overlain by basalt lenses or sheets rests on the older rocks.

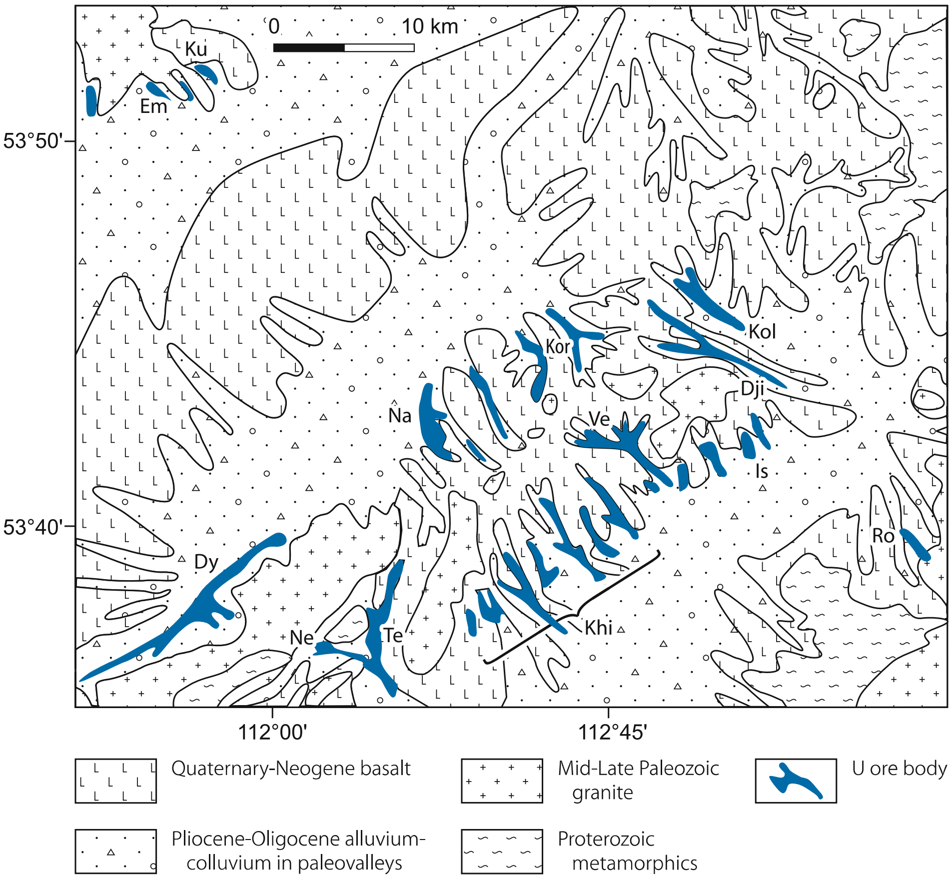
Principal Host Rock Alteration and Characteristics of Mineralization

Originally grey host rocks are oxidized to multicolored facies in which pyrite, siderite, and organic matter are replaced by Fe-hydroxides. The oxidation front developed from the sides of the paleovalleys. Bleaching produced a whitish facies along the interface of grey and multicolored rocks.

Principal U minerals are U-oxides and coffinite, and rare ningyoite. Uranium is also adsorbed on carbonaceous and clay matter. Associated minerals include arsenopyrite, galena, marcasite, pyrite, sphalerite, and hematite. In addition, the ore has elevated contents of Co, Cu, Mo, Sc, Y, Zn, and Zr. Their tenor ranges from 5 to 400 times of the Clarke figures. Dating of U minerals yields ages ranging from 25 Ma to Recent. The ore minerals occur finely dispersed mostly in sandstone and conglomerate in basal parts of paleochannels.

Uranium deposits are restricted to channel sections underlain by granite. Channels in metamorphic terrane are barren of

Fig. 10.20.
Vitim area, geological map with surface projected U deposits in contributory paleochannels filled with Oligocene-Pliocene alluvial-colluvial sediments. Quaternary plateau basalt sheets (not shown) cover most of the area (courtesy AV Boitsov based on Russian literature). U deposits: *Dji* Djilindinskoye, *Dy* Dybryn, *Em* Emkerse, *Is* Istochnoye, *Khi* Khiagdinskoye, *Kol* Kolichikan, *Kor* Koretkoide, *Ku* Kularinta, *Na* Namaru, *Ne* Nevskoye, *Ro* Rodionovskoye, *Te* Tetrakhskoye, *Ve* Vershinnoye



uranium but may contain gold. Ore minerals occur disseminated along the interfaces.

General Shape and Dimensions of Deposits

Mineralized paleochannels range commonly from 1 to 10 km in length and 0.5–1.5 km in width (Fig. 10.20). Individual deposits contain several hundreds to more than 5 000 t U. They consist of ore bodies, which are in plan view of ribbonlike configuration trending along channel axes, and in sections of elongated roll or lens shape (Figs. 10.21, 10.22). Ore bodies are up to 3 km long, 150–400 m wide, and from less than 1 m to a maximum of 23 m thick. They occur at a depth of 60–240 m. Grades range from 0.01 to 0.5% U.

Potential Sources of Uranium

Paleozoic granite exposed in the basement is favored as the most likely source of uranium. Granitic facies contain uraninite and have elevated uranium background values reportedly of up to 80 ppm U. Another uranium source is possibly provided by the tuffaceous constituents of the cover sediments.

Principal Ore Controls and Recognition Criteria

Mineralization is primarily of lithological and geochemical control. Significant ore controlling parameters or recognition criteria of deposits include:

Host Environment

- Basement of Proterozoic metamorphics intruded by Paleozoic granite
- Paleosurface deeply weathered during semiarid climate
- Old peneplain incised by Tertiary rivers
- Valleys filled with Tertiary continental clastic sediments
- Cover of Quaternary tuffaceous sediments and basalts providing protection against erosion of ore hosts
- Host rocks are characterized by
  - up to 50 m thick alluvial and proluvial sediments composed of sandstone, siltstone, and conglomerate of Oligocene-Miocene age
  - reduced facies of grey color and characterized by pyrite and high content of carbonaceous matter (1–8% C_{org})

  - oxidized facies of multicolor containing Fe-hydroxides
  - good permeability of ore hosting facies
- Potential U sources are primarily provided by granite

Alteration

- Oxidation with formation of redox fronts by vadose waters migrating downward from channel margins
- Re-reduction(?)-related bleaching along reduced and oxidized facies
- Reduction potential provided by organic matter and sulfide

Mineralization

- U-oxides and coffinite
- Large number of associated elements
- Disseminated texture of mineralization
- Ore bodies are
  - lens- and roll-shaped and elongated along channel axes
  - mostly in sandstone and conglomerate in the basal section of channels controlled by redox boundaries
  - restricted to channel sections underlain by granite
- Locally mineralization is in the weathering crust of granite

Principal Aspects of Metallogenesis

Uranium ore formation is considered of epigenetic origin resulting from the infiltration of oxygenated, U-bearing vadose water. The porous, predominantly sandstone channel facies served as conduits through which the fluids migrated. Precipitation of uranium occurred where the pregnant solutions encountered sufficiently high carbonaceous matter to establish a redox front along which the dissolved hexavalent uranium was reduced and deposited. The ribbonlike configuration of ore bodies stretching along the axis of valleys suggests that the mineralizing fluids entered the valleys from their flanks.

Circumstantial evidence suggests that the uranium originated from basement granite. This hypothesis is supported by the fact that all deposits are restricted to channel sections underlain by granite and that oldest U minerals yield ages of 25 Ma i.e. they must have been formed prior to the deposition of the Quaternary tuffaceous cover rocks. The latter may perhaps have contributed uranium at a later stage.

Description of Selected Deposits in the Vitim District

10.4.2.1 Vitim District/Khiagda Ore Field

Eight basal-channel-type U deposits occur in several paleochannels, from 1.5 to 6 km apart, in a 250 km^2 large area: *Khiagda* (or *Khiagdinskoye*), *Tetrakhskoye*, *Vershinnoye*, *Dybryn*, *Istochnoye*, *Kolichikan*, *Koretkondinskoye*, and *Namaru* (Fig. 10.21). Distance between deposits varies between 1.5 and 6 km. Explored resources are estimated at 52 000 t U. Deposits consist partly of

Fig. 10.21.
Vitim District, geological subsurface map showing the location of ore bodies of the Khiagdinskoye (# 1–7) and other deposits. Oligocene-Pliocene colluvial sediments (conglomerate, sand silt, clay, mud, tuff) in contributory paleochannels incised into granite are the principal host to ore bodies. (Quaternary basalt sheets not shown) (after Loutchinin 1995a). U deposits: *Dji* Djilindinskoye, *Dy* Dybryn, *Is* Istochnoye, *Khi* Khiagdinskoye, *Kol* Kolichikan, *Kor* Koretkoide, *Na* Namaru, *Ne* Nevskoye, *Te* Tetrakhskoye, *Ve* Vershinnoye

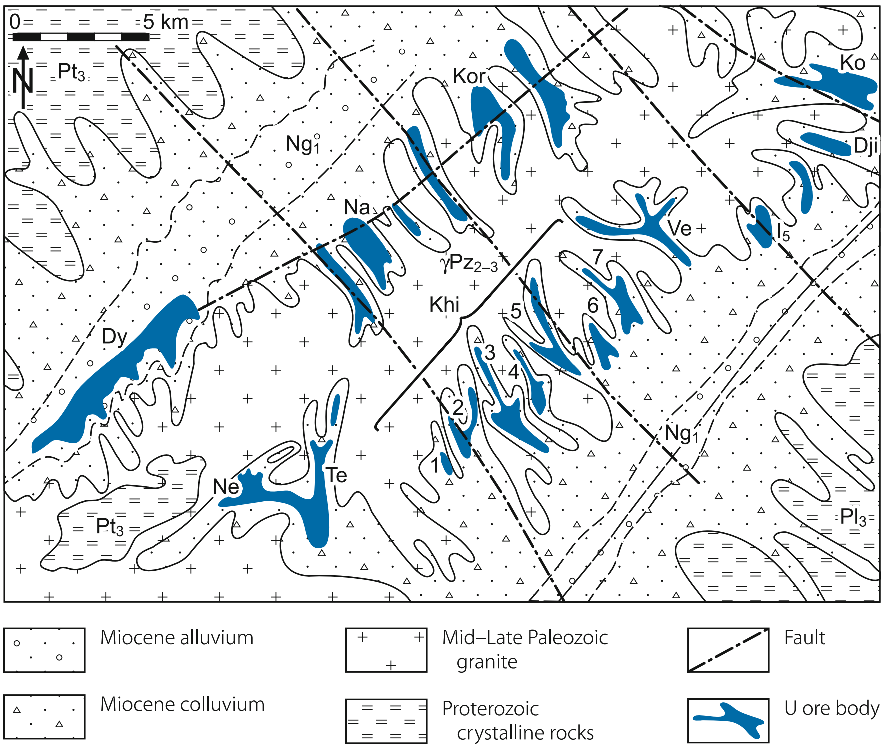
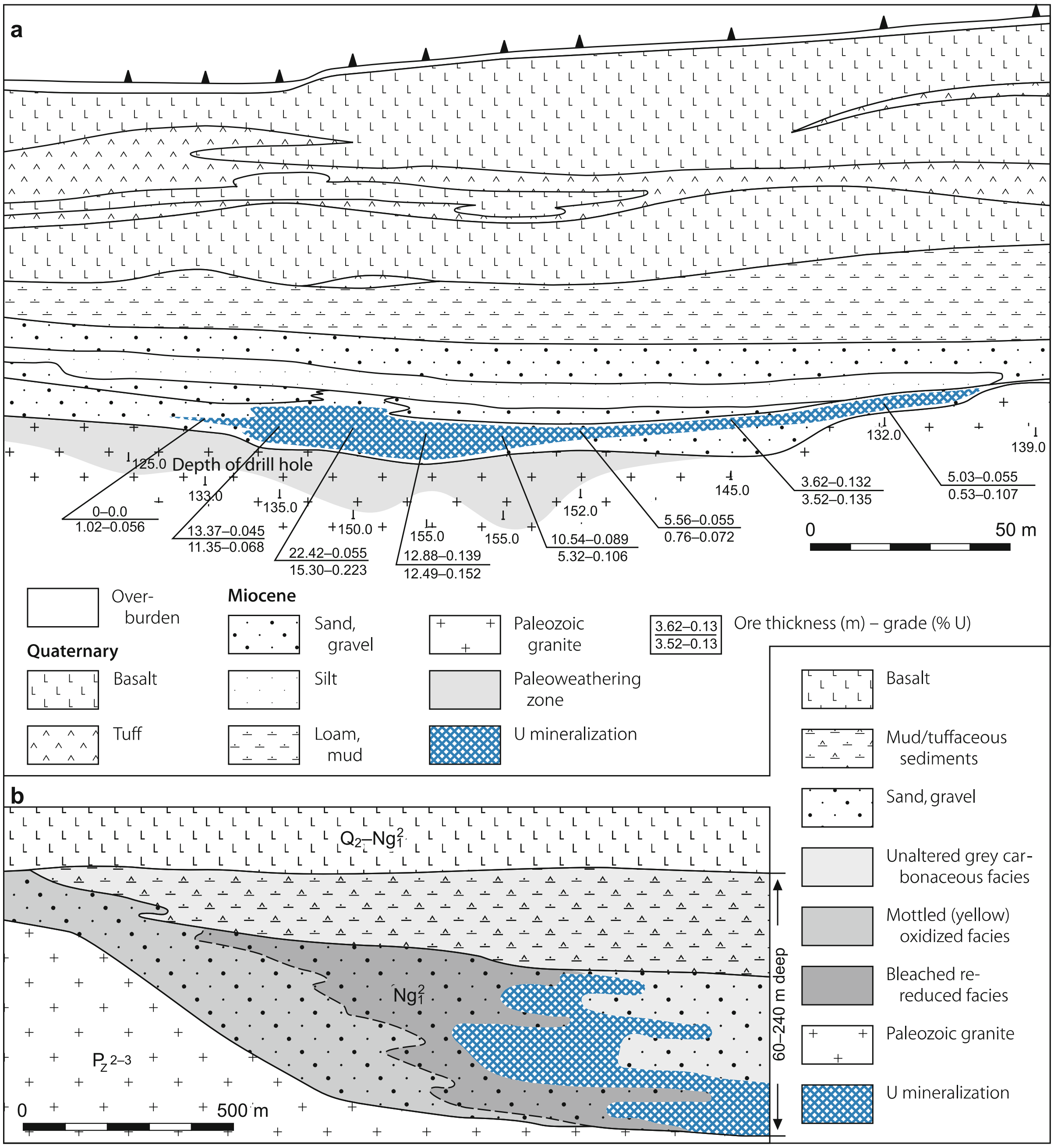


Fig. 10.22.
Vitim District, Khiagdinskoye (ore body VI?). a Geological SW-NE cross-section showing U mineralization along the upper contact of an oxidation zone, which has developed along the sediment-basement interface of a paleochannel incised into Paleozoic granite. Drill intercepted U grades are shown below the drill holes. (courtesy AV Boitsov based on Russian literature). b Schematic geological cross-section exhibiting alteration features associated with a roll-shaped U ore body in Miocene carbonaceous gravel and sand (after Boitsov and Nikolsky 2001; Loutchinin 1995a)



several ore bodies; their grades average between less than 0.05 and 0.3% U.

Khiagda is with 15 500 t U the largest deposit. This figure includes 6 900 t U RAR and 4 380 t U EAR-I in the <$40 per kg U cost category (OECD-NEA/IAEA 2005). Average ore grade is 0.05% U. Resources of Tetrakhskoye are in excess of 5 000 t U, and of the others between 1 500 and 5 000 t U each. Khiagda is in the planning stage for exploitation by ISL methods at a nominal production capacity of 1 000 t U yr^{-1} (since 1999). Operator is JSC "Khiagda".

Khiagda includes eight ore bodies in five neighboring paleochannels, which are incised into Paleozoic granite. The channels range from 5 to 7 km in length and from 0.5 to 1.5 km in width (Fig. 10.21), and are filled with slightly consolidated, from a few meters to 120 m thick, Neogene fluvial-colluvial sediments upon which Neogene to Quaternary basalt rests.

Host rocks contain abundant coaly debris and Fe-sulfides, and exhibit older sheet and soil-type oxidation zones from channel heads and from the slopes downward. In these oxidized zones pyrite, siderite, and coaly material are replaced by Fe-hydroxides that impose beige to tan hues on the sediments. A zone of secondary reduction reflected by lighter color and absence of Fe-hydroxides and coaly matter intervenes between oxidized and unaltered rocks.

Mineralization consists of finely dispersed pitchblende, coffinite, and sooty pitchblende. Ore bodies extend lenticular or ribbonlike along paleochannels and exhibit geological and alteration features as illustrated in ❯ Fig. 10.22. Individual ore lenses are 800–4 100 m long, 15–800 m wide, and tens of centimeters to 26 m thick, and occur at a depth of 60–240 m.

10.4.2.2 Other Deposits in the Vitim Area

Zheglovskoye was discovered in 1998 in the Eravninsky area of the Buryatia A.R., some 100 km N of Chita. Total in situ resources amount to 7 900 t U contained within two tributary channels of the Khushida paleovalley. The channels are filled with 120–150 m and locally up to 250 m thick Neogene effusive-sedimentary rocks, from top to bottom composed of an as much as 170 m thick basalt sheet, which covers the commonly 5–20 m and locally up to 120 m thick, U-bearing horizon of badly sorted sand, gravel, and silt. A conglomerate horizon forms the basal channel unit.

The two channels contain lenticular ore bodies in two ore zones. Ore zone one is in the northern channel and ore zone two in a parallel channel 1.5 km to the south. Ore zone one is 5.8 km long, 70–300 m wide, averages 3.23 m thick, and occurs between 8 and 180 m deep. Ore zone two is 3.6 km long, 100–300 m wide, averages 3.4 m thick, and 10–180 m deep. Grades in both zones average 0.062% U.

Radinovskoye and *Vitlandskoye* are located in the Ingur and Kholoi areas, respectively. Both deposits occur in paleovalleys. Mineralization is in the permafrost zone and exposed on surface. Prognosticated resources of Radinovskoye amount to 5 300 t U and of Vitlandskoye to 8 980 t U.

Emkerse and *Kularinta* are small basal-channel U occurrences in another Tertiary fluvial system located about 30 km NW of the main part of the Vitim District.

10.4.3 Central Transbaykal Subregion, Asian Russia

The central Transbaykal subregion encompasses nine uranium areas distributed over an area extending for some 500 km from the northeast to the southwest of the town of Chita in central Transbaykalia, Buryatia Autonomous Republic. Each ore field contains several uranium deposits but none was mined to date (status 2006). Permafrost constitutes to some extent an obstacle to uranium recovery by ISL methods. ❯ Figure 10.10 shows the distribution of uranium areas in the central Transbaykal subregion and a summary of available data of U deposits is given at the end of this chapter.

Deposits include volcanic vein-stockwork (referred to as Streltsovsk-type) and volcanic stratiform, sandstone, and granite-related vein types. Most deposits are small with resources of some hundreds to several thousands tonnes of uranium except for Olovskoye and Imskoye (see below). Ore grades generally average less than 0.1% U.

Total resources of the Central Transbaykal subregion are estimated at 40 000 t U, 24 000 t U of which are classified as RAR + EAR-I and 16 000 t U as EAR-II. All resources belong to the $80–130 per kg U cost category (Laverov et al. 1992c).

Sources of information. Kislyakov and Shumilin 1996; Laverov et al. 1992b,c; Pelmenev 1995; Vizhnyakov 1995a–c.

General Geological Features and Metallogenetic Aspects of the Central Transbaykal Subregion

The central Transbaykal subregion covers part of the Mongolian-Okhotsk zone. The zone is situated at the boundary between Caledonian and Hercynian orogenic terrane and evolved by tectonic-magmatic reactivation in Mesozoic time during which Early Jurassic granite and volcanics were emplaced into crystalline rocks of Precambrian to Paleozoic age. Repeated tectonic events downfaulted NE-SW-oriented basins and grabens, which were filled with Middle to Upper Jurassic and Lower to Upper Cretaceous terrestrial carbonaceous sediments and mafic to felsic volcanics. Additional depressions filled with terrestrial sediments and basalt formed during the Quaternary.

Two significant metallogenetic episodes affected the Transbaykal subregion during the Late Jurassic and the Cretaceous. The former is the principal ore-forming event of U deposits associated with Jurassic calderas and the latter generated U mineralization in Lower Cretaceous depressions but also left traces in the volcanic-hosted deposits.

The Cretaceous event took place at the terminal stage of the Mesozoic tectonic-magmatic activation, independently of the Jurassic metallogenetic epoch from which it is separated by a substantial time span documented by the formation of grabens and deposition of the Lower Cretaceous coal-bearing sediments and intervening basalt flows.

More equivocal is the age relation of uranium deposits in the substantially sedimentary sequences of Middle-Late Jurassic depressions. Some of them, for instance, the Ozernoye deposit in the Zyulzya Depression, are close in age to the Olov and Ima deposits. Others, which probably include the Slantsevoye and Zhuravlinoye deposits of the western Transbaykal region, may be related to the Late Jurassic ore forming epoch (Kislyakov and Shumilin 1996).

In summary, uranium mineralization in the Mesozoic depressions of the central Transbaykal subregion is essentially related to three ore-forming processes and events:

1. Hydrothermal low- and medium-temperature processes of Late Jurassic age determined the formation of vein-stockwork and stratiform deposits in the Late Jurassic volcanogenic

structures of the Streltsovsk District and other districts as, for example, Dornod in Mongolia.

2. Hydrothermal low-temperature processes of Cretaceous age were pronounced in the Early Cretaceous coal-bearing graben-syncline type depressions (Stepnoye, Kuka, Meridionalnoye, Sirotininsk deposits) and also in Jurassic volcanogenic-sedimentary depressions (deposits of the Olovsky area).
3. Exogenic-epigenetic processes of Cretaceous age generated the ore-controlling oxidation zones in the Ima deposit and also, evidently, the pink coloration of Upper Jurassic and Lower Cretaceous coarse-clastic rocks in substantially grey-colored sequences (including coal-bearing strata). This event took place at the waning stage of block movements and related termination of sedimentation, and synchronous with the aridization of the climate during the Late Cretaceous. In result, the hydrodynamic regime of groundwater was changed from the former ascendant regime, determined by the squeezing of interstitial water, to the influx of oxygenated meteoric water.

10.4.3.1 Olovsky(-Mogochinsky) Area, Olovskoye Deposit

The Olovsky(-Mogochinsky) area is situated some 200 km to the NE of Chita. It includes the *Ozernoye* (also called *Zyulzinskoye*) and the large Olovskoye (or Olov) deposit described in the next chapter. Additionally, more than fifteen, generally small and low grade, volcanic/sandstone-type U occurrences are established in the ore field. They are shown in Fig. 10.23.

Sources of information. Kislyakov and Shchetochkin 2000; Kislyakov and Shumilin 1996; Vizhnyakov 1995a; unless otherwise stated.

General Features of Geology

The Olov ore field covers two adjacent depressions filled with up to 3 000 m thick, subhorizontally dipping volcanic and sedimentary rocks of Middle Jurassic to Lower Cretaceous age. The basement consists of Paleozoic granite and Precambrian gneiss, and has a marked relief, which determines the thickness of the Jurassic deposits. The stratigraphic sequence includes from top to bottom (Fig. 10.24):

- *Soktui Formation*, Lower Cretaceous, <800 m thick: Slightly indurated claystone, siltstone overlying sandstone, and sandy conglomerate, with intercalated lignite seams, and basalt flows.
- >Unconformity<
- *Ukurai Formation*, Upper Jurassic, <700 m thick: An upper, as much as 500 m thick, alternating sequence of claystone, siltstone, sandstone and minor alluvial-deltaic conglomerate

Fig. 10.23.

Central Transbaykalia, Olovsky (Olov) ore field, generalized geological map with location of U deposits and occurrences in Cretaceous-Jurassic volcanic-sedimentary depressions (after Kislyakov and Shumilin 1996). *Depressions*: *I* Zyulzya, *II* Southern Zyulzya, *III* Kangil, *IV* Olov, *V* Utan. *U deposits*: *1* Olovskoye (Olov), *2* Ozernoye. *U occurrences*: *3* Olekan, *4* Zyulzya, *5* Poiskovoye, *6* Severnoye, *7* Kalanga, *8* West Lukdun, *9* Novoe Olov, *10* Areda, *11* Staroe Olov, *12* Komsomolsk, *13* Aleur, *14* North Gaur, *15* West Gaur, *16* Gaur, *17* Shevya

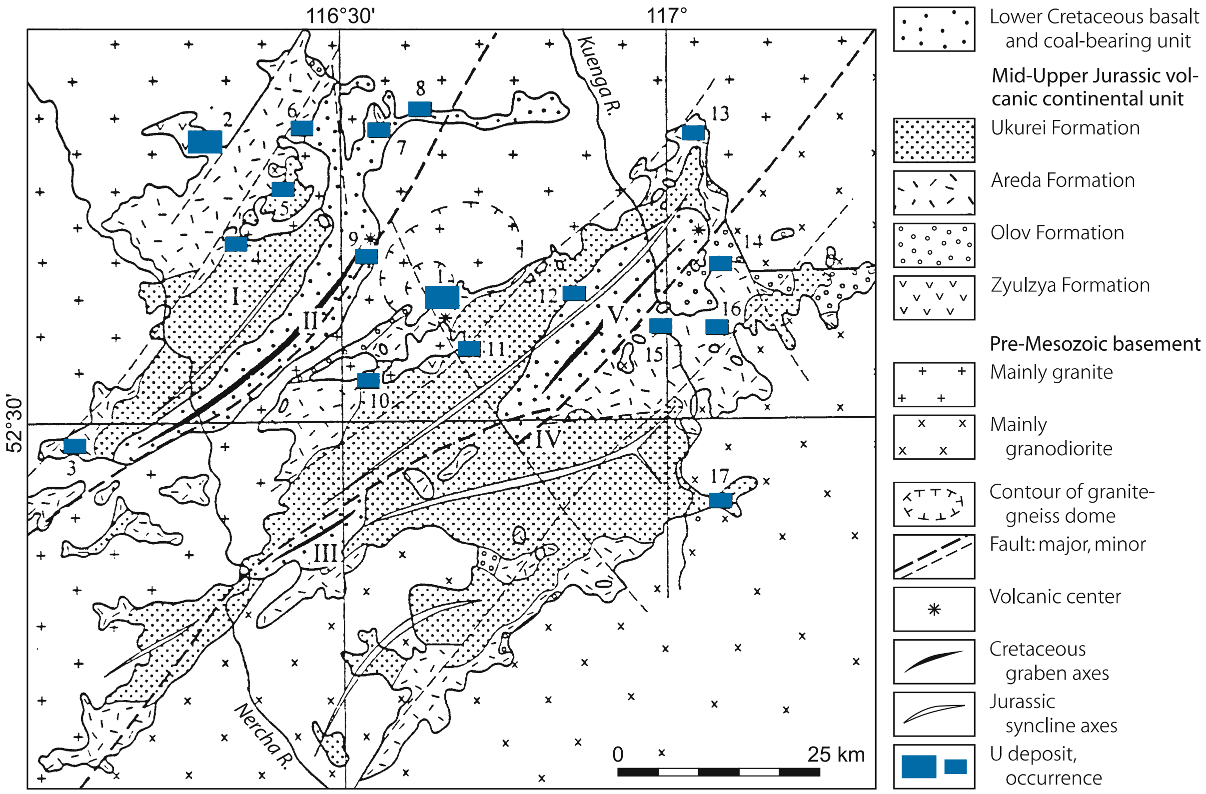
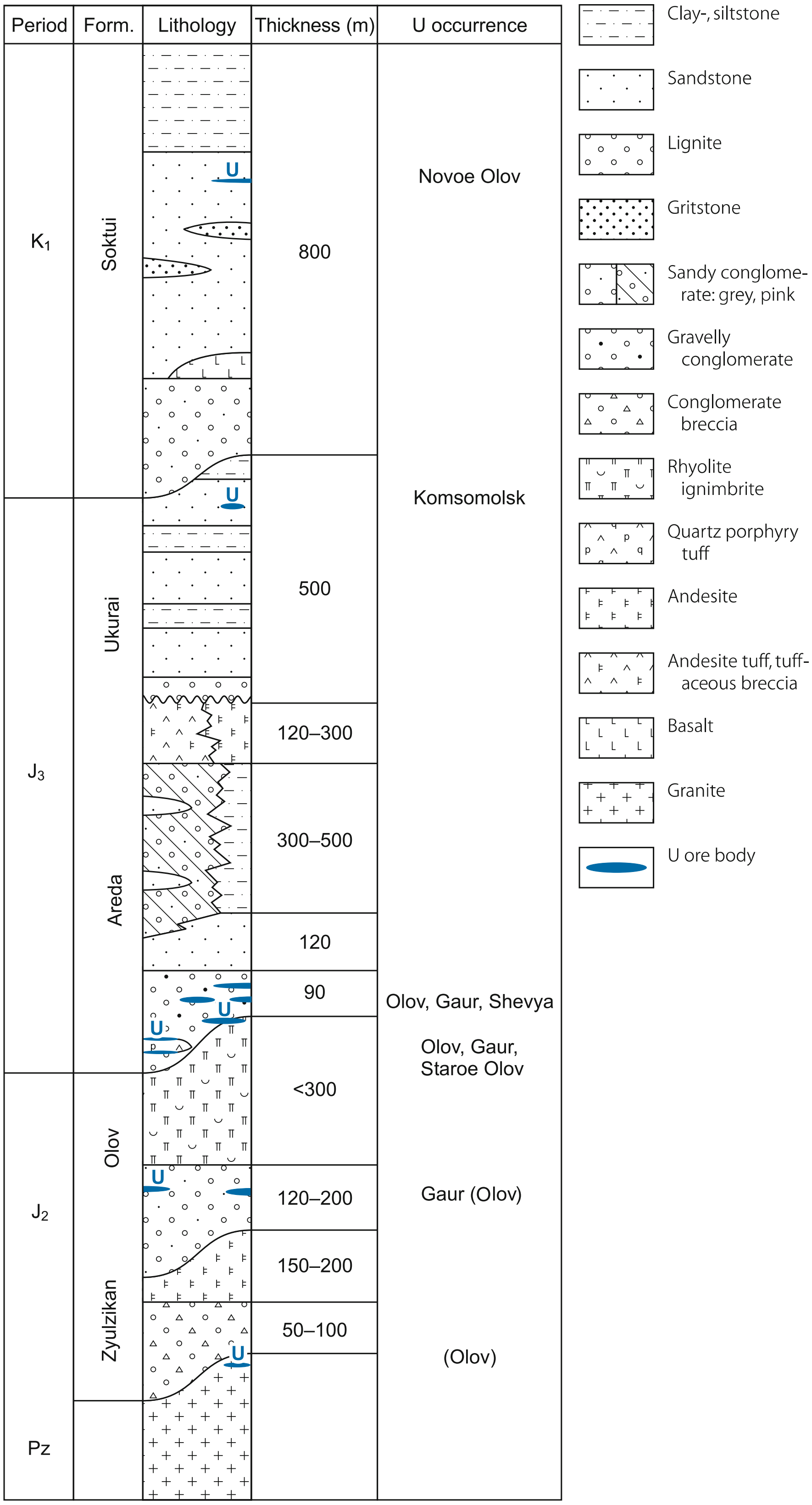


Fig. 10.24.

Central Transbaykalia, Olovsky ore field, litho-stratigraphic column of the Lower Cretaceous to Middle Jurassic volcanic-sedimentary sequence in the Olov area with stratigraphic position of U ore bodies (after Kislyakov and Shumilin 1996)



overlies a 120–300 m thick unit of andesite, basaltic andesite, and tuffaceous breccia with interbedded conglomerate, sandstone, and siltstone.

- *Areda Formation*, Upper Jurassic, 500–700 m thick: The upper, 120 m thick member consists of lacustrine, grey claystone, siltstone and sandstone, which grade laterally into up to 500 thick, deltaic and proluvial, pink conglomerate with intercalated grey sand- and siltstone beds. The middle member is as much as 120 m thick and composed of alluvial gritstone, sandstone, siltstone, and tuffite. The lower, up to 90 m thick member consists of proluvial, grey conglomerate with intercalated sandstone and deluvial breccia lenses, and, in the basal part, a single bed of quartz porphyry tuff.
- >Unconformity<
- *Olov Formation*, presumably Middle Jurassic, <500 m thick: An upper, up to 300 m thick suite of rhyolitic ignimbrite with black volcanic glass sheets rests upon an 120–200 m thick suite of gritstone with sandstone and carbonaceous shale interlayers, and a basal grey conglomerate of granitic and andesitic provenance.
- >Unconformity<
- *Zyulzikan Formation*, presumably Middle Jurassic, <250 m thick: Two units are distinguished, an upper, 150–200 m thick andesite unit that rests on 50–100 thick conglomerate and conglomeratic breccia with granite and gneiss fragments.

Deposition of the various sedimentary formations was preceded by general uplifts, followed by subsidence and erosion. Early sediments accumulated along the axial zone of the paleovalleys and abut against the granitic sidewalls. Major, NE-SW-oriented dislocation zones in the basement control the paleovalleys. Tectonic features are reflected by about NE-SW-, NW-SE- and E-W-trending, steeply dipping faults and closely spaced fractures, and by gently inclined faults. Mafic dike swarms follow the fault systems.

Host rock alteration features at U occurrences in the Zyulzya Depression include kaolinitization, hydromicazation, carbonatization (calcite veinlets), and, locally, silicification (dark grey and pink cryptocrystalline quartz veinlets). Hydrobiotitization is related to the ore-forming process (for alteration features in the Olov Depression see Sect. *Olovskoye*).

Principal Characteristics of Mineralization

Mineralization of U occurrences in the Zyulzya Depression consists of disseminated sooty pitchblende and other U-oxides associated with metacolloid and crystalline pyrite. U occurrences in the Olov Depression may additionally contain pitchblende and native arsenic (see Sect. *Olovskoye*).

Uranium deposits/occurrences of the Olovsky ore field are structurally controlled and hosted by terrestrial, grey, carbonaceous sandstone and siltstone predominantly of the Areda and Olov Formations, and to a minor degree of the Soktui and Ukurai Formations. Only a few occurrences are in rhyolitic volcanics of the upper Olov Formation and the granitic basement. Ore bodies are controlled by shallow dipping, intraformational faults and occur most commonly at or adjacent to the intersection of these structures with steep faults.

General Shape and Dimensions of Deposits

U occurrences of the Zyulzya Depression consist of stratiform, up to 0.5 m thick lenses. The lenses are conformable with the bedding and display irregularly shaped tabular and curvilinear bandlike configurations in plan view. Lateral dimensions of ore bodies range from less than 100 m wide and long to 1 000–1 500 long and 200–400 m wide. Ore grades average 0.05–0.08% U. Grades increase up to 0.2% U close to steep faults and granitic channel walls.

Olovskoye

Olovskoye (or Olov) was discovered in the central-north part of the Olovsky area in 1957. In situ resources are estimated at some 15 000 t U. at a grade of less than 0.1% U.

Sources of information. The subsequent description is summarized from Kislyakov and Shumilin (1996) and Vizhnyakov (1995a).

Geology and Alteration

The Olov deposit is on the northwestern flank of the Olov Depression (Fig. 10.23). Middle(?) and Upper Jurassic sediments and volcanics of several paleovalleys fill the depression. The channels are incised into a basement of Paleozoic granite. Proterozoic gneiss forms the basement to the south. Andesite and microdiorite dikes and sills cut the sedimentary-volcanic sequence. Host strata dip 10–12° SE. Structures include shallow inclined faults, and steeply dipping, NE-SW-, NW-SE- and E-W-trending faults (Fig. 10.25).

Alteration phenomena include argillization, carbonatization, silicification, sulfidization, and hematitization. *Pre-ore alteration* is represented by clay minerals (kaolinite after feldspar), carbonate (ankerite), and sulfide (pyrite) the distribution of which is controlled by the original rock permeability. These alteration products encompass the entire uranium mineralized litho-stratigraphic segment and display their strongest development within the uranium dispersion halo. Hematitization is presumably also a pre-ore process. Hematitization postdates argillization and is best developed in some parts of the deposit in unmineralized, basal conglomerate and subjacent granite imposing a dark red color on the rocks over up to 30 m thick intervals. Other parts of the Olov deposit display less pronounced hematitization, which is thought the result of a partial reduction of hematitized rocks. *Syn-ore alteration* is reflected by hydrobiotite and restricted to ore bodies, where it imposed a dark green color upon the host rocks. *Post-ore alteration* produced fissure fillings of dickite, realgar, and orpiment over a large vertical extent.

Mineralization – Shape and Dimensions of Deposits

The ore is monometallic. Uranium minerals include finely dispersed pitchblende, sooty pitchblende, and minor hydro-pitchblende and coffinite. Associated minerals are cryptocrystalline pyrite and native arsenic.

Uranium mineralization extends bandlike for more than 10 km in curvilinear E-W direction along the main paleochannel trend with diversions into tributary valleys. The band is composed of numerous, mostly ribbonlike ore bodies of low grade (<0.1% U) stacked along intraformational inhomogeneities. Better grade ore occurs as pockets characterized by grades of 0.1–1% U and a dark green color due to abundant hydrobiotite along steeply and gently dipping fractures filled with post-ore dickite. Position, size and shape of ore bodies are controlled by shallow inclined, often strata-peneconcordant faults composed of densely spaced fracture systems, and particularly at their intersection with steeply dipping NE-SW, NW-SE and E-W faults (Fig. 10.25).

Paleovalleys filled with the Upper Jurassic Areda Formation provide the preferential host sites. Some mineralization occurs in the Middle Jurassic Olov Formation and in granite. Mineralized horizons occur at several litho-stratigraphic levels. *Ore horizons 1 and 2* are confined to thin carbonaceous silt- and sandstone beds of the gritstone member of the Olov Formation. The Areda Formation contains *ore horizons 3 and 3a* in both tuff and grey sediments at the base and top, respectively, of the quartz porphyry tuff intercalation within the basal gritstone-conglomerate member, and *ore horizons 4, 4a, and 4b* in the upper part of the same gritstone-conglomerate member. Most extensive ribbonlike ore bodies are found in ore horizons 3 and 3a. Largest ore bodies in horizons 4, 4a, and 4b occur as up to 30 m thick, elongated lenses in tributaries to the main paleovalley on the northern flank of the Olov deposit. Ore lenses may laterally cross litho-stratigraphic contacts of overlapping channels, and may also persist into granite.

In a general way, ore bodies are preferentially localized in the basal part of the volcanogenic-sedimentary sequence close to the granitic basement. Ore bodies are enveloped and interconnected by an up to 100 m thick halo of elevated uranium tenors; the lower boundary of which largely coincides with the basal volcanogenic-sedimentary contact but locally also penetrates into the underlying granite. The upper limit corresponds to the roof of the gritstone-conglomerate member of the Areda Formation. Arsenic, mainly as realgar and orpiment, forms an even larger aureole than the uranium.

Metallogenetic Aspects

Both hydrothermal and exogenic-epigenetic ore-forming processes of Cretaceous age left their prints in the Olov deposit. The leading role is attributed to the hydrothermal activity.

Kislyakov and Shumilin (1996) suggest a hydrothermal model for the origin for the Olov deposit, which includes four mineral stages:

Fig. 10.25.
Central Transbaykalia, Olovskoye (Olov) deposit. a Generalized structural map outlining the distribution of U lenses in the Olov and basal Areda Formations, and granite; b schematic geological NW-SE cross-section at the western flank and c at the northern appendix of the deposit. The latter exhibits the spatial relationship between hematitized and U mineralized zones. U mineralization (Fig. a) extends over a NW-SE width of several 100s of meters and is hosted in grit of the Orlov Formation (# 1 and 2 Fig. b), and in quartz porphyry tuff (# 3, 3a) and grit-conglomerate (# 4, 4a, 4b) of the Areda Formation (after Kislyakov and Shumilin 1996)

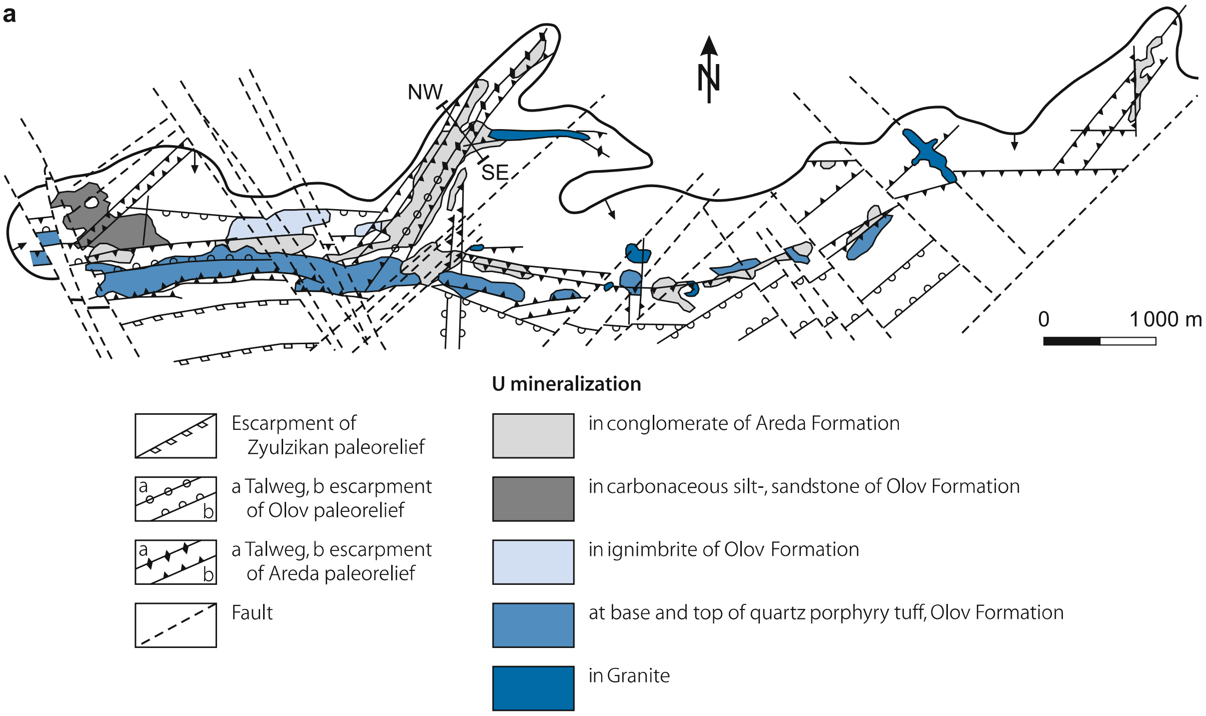
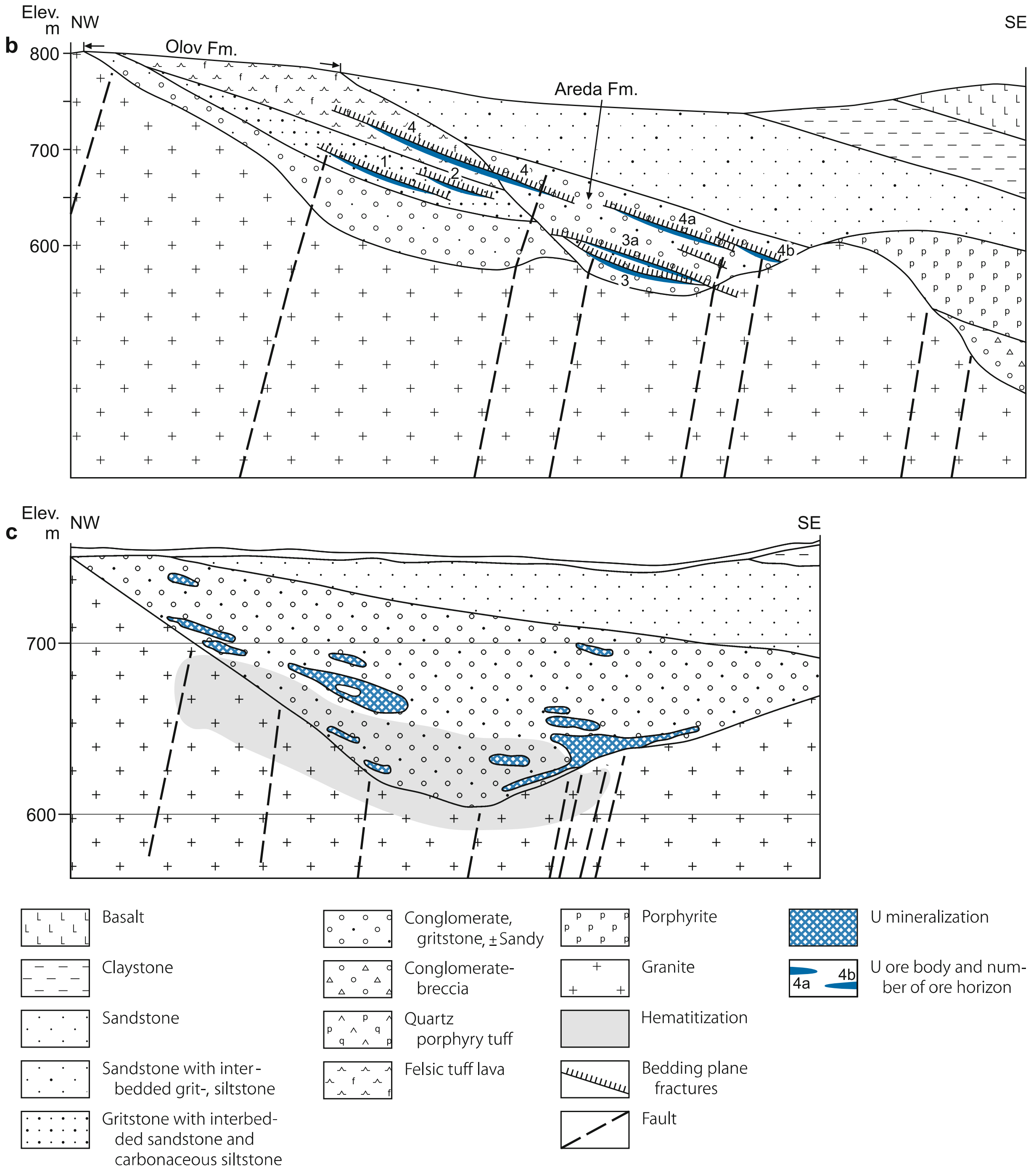


Fig. 10.25. (Continued)



1. pre-ore acidic leaching stage reflected by argillic, siliceous, and carbonate alterations
2. pre-ore carbonate-sulfide (ankerite, pyrite) stage
3. ore stage represented by disseminated U minerals, native As, pyrite, and hydrobiotite; and
4. post-ore stage marked by fissures filled with dickite, realgar, and orpiment

Radiometric datings yield ages of 110–100 Ma for the ore formation (Rozentsvit in Kislyakov and Shumilin 1996).

A hydrothermal origin of the Olov deposit is favored due to circumstantial evidence provided by the

a spatial relationship with vein-stockwork uranium mineralization in claystone of the Ukurei Formation at the Komsomolsk occurrence southeast of the Olov deposit and that in granitoids of the Mayak, Korolevsk, and Chasovoye deposits southeast of the Olov ore field,
b localization of the U mineralization mostly near the contact to the basement granitoid,

c predominance of stratiform ore bodies,
d structural features of ore localization, and
e wide development of hydrothermal low-temperature ferromagnesian alteration and hematitization.

The low grade of the Olov ore can be partially explained by a low uranium concentration in the granitoid basement.

10.4.3.2 Amalat Area, Imskoye Deposit

The Amalat area is some 300 km N of Chita in the northern Buryatia A.R. It includes with the 1964 discovered Imskoye (or Ima) deposit a large but low-grade tabular sandstone-type uranium deposit in the western section of the Malaya Amalat Depression (Fig. 10.26). Kislyakov and Shumilin (1996) report that Ima is larger in size than Olov (= 15 000 t U). Ore grades are low, ranging between 0.01–0.1% U.

Source of information: Kislyakov and Shumilin 1996 unless otherwise stated.

Geological Setting of Mineralization

The Malaya Amalat Depression is a graben structure downfaulted along NE-SW and NW-SE faults into Precambrian and Early Paleozoic metamorphites intruded by Proterozoic, Paleozoic, and Mesozoic granitoids. Sediments of the Lower Cretaceous Gusinoe Ozero Series fill the graben. There are three deepened segments within the depression, one of which, the Ima "syneclise", hosts the Ima deposit.

The Gusinoe Ozero Series is partitioned into three lithostratigraphic formations; only the lower of which, the 1 500–1 800 m thick Ima Formation, occupies the area of the Ima deposit. The Ima Formation is dominated by polymictic, unsorted clastic sediments and proluvial conglomerate alternating, in the mineralized upper section, with sandstone, gritstone, siltstone, and single claystone and lignite beds. Granite-derived clastic material with elevated uranium tenors of 5–20 ppm U constitutes a large fraction of the rocks at the deposit. Basal, coarser clastic facies of the Ima Formation are pink colored, while the upper, U mineralized part consists of alternating grey and pink beds. Host rocks dip 20–25° NNW. Transverse strike-slip faults separate the deposit area into several blocks while linear normal faults generated numerous slices (Figs. 10.26, 10.27).

Alteration

Host rock alteration phenomena include argillization, carbonatization, sulfidization, silicification, chloritization, sericitization, zeolitization, and oxidation and reduction processes. Argillic alteration distribution is controlled by structures and elevated permeability of slightly lithified sediments and shows zoning as exemplified from the eastern flank of the Ima deposit where mineralization occurs in the lower part of the grey unit near the interface with pink sediments:

Fig. 10.26.
Central Transbaykalia, Malyi Amalat area, generalized geological map of the Lower Cretaceous Malo Amalat Basin with delineation of the Ima (or Imskoye) deposit (after Kislyakov and Shumilin 1996 based on Korobenko, Ilichev, and others)

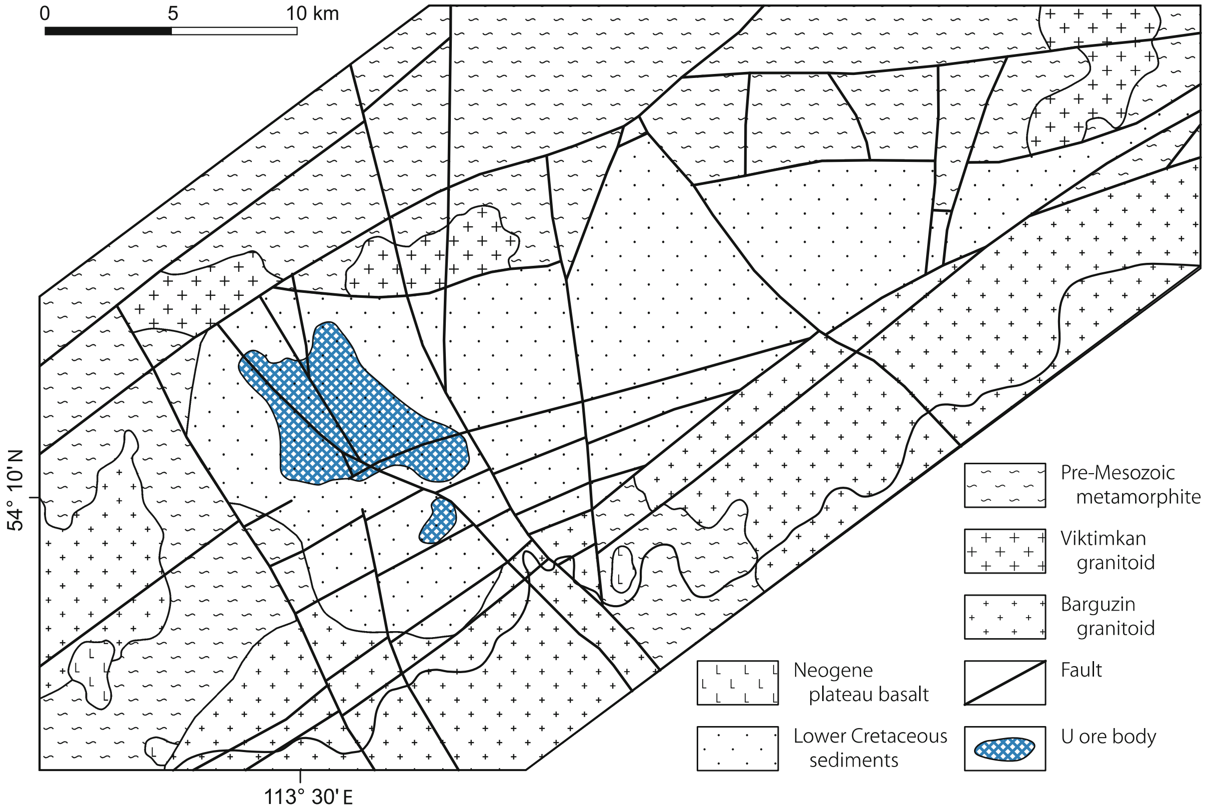


Fig. 10.27.
Central Transbaykalia, Ima deposit. a NNW-SSE cross-section through part of the sandstone-type deposit showing the superjacently stacked U lenses in the Lower Cretaceous Ima Formation/Gusinoye Ozero Series; b schematic W-E section illustrating alteration features of the mineralized segment; c sketch of a drift wall demonstrating the relationship of oxidized pink, reduced grey and bleached alluvial facies, humic accumulations, and U mineralization (after Kislyakov and Shumilin 1996)

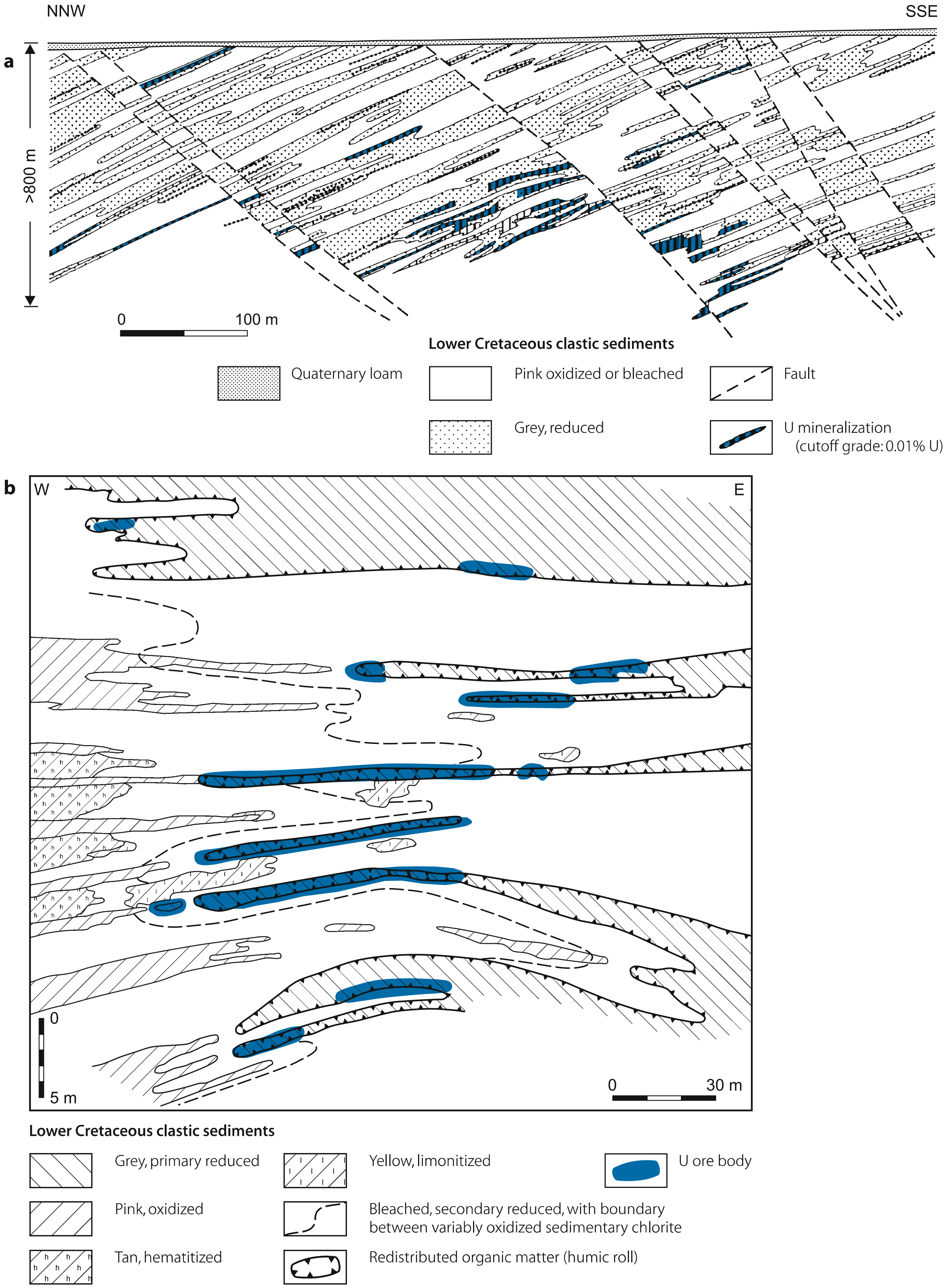
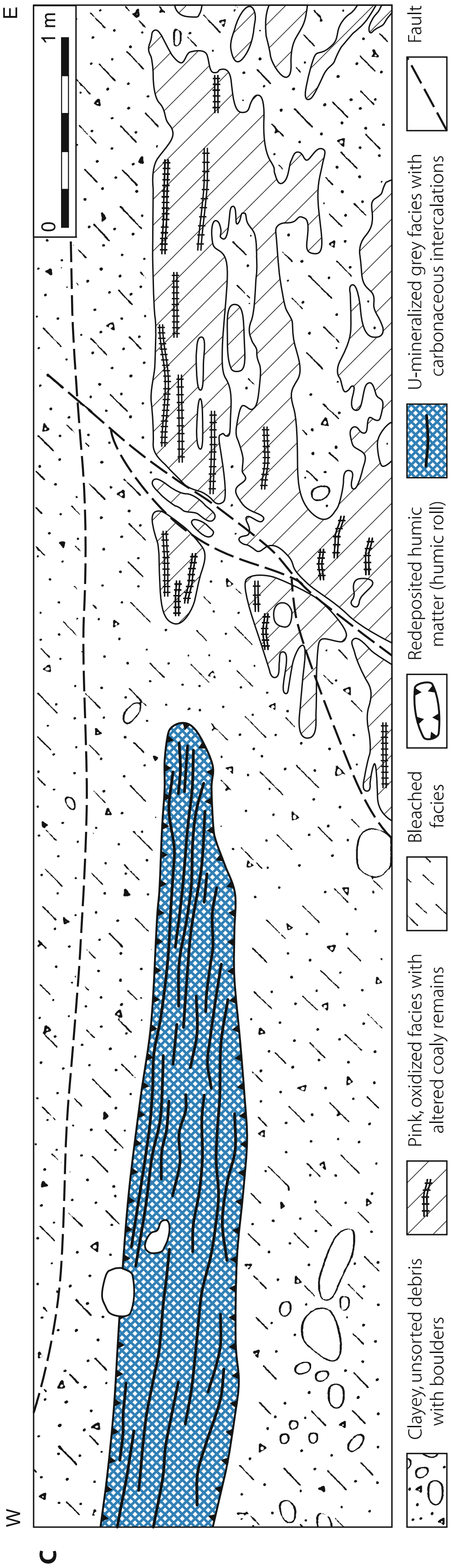


Fig. 10.27. (Continued)



Outer, uppermost zone, divided into two subzones: *(a)* a kaolinite-carbonate subzone where kaolinite replaces the ground mass and clastic plagioclase, and carbonate biotite; and *(b)* a carbonate-quartz-pyrite subzone where authigenic kaolinite is replaced by carbonate, biotite by both carbonate and pyrite; and cryptocrystalline quartz has formed.

Inner hydromicaceous-chlorite zone: hydromicas replace plagioclase, orthoclase, biotite, newly formed kaolinite, and carbonate. Chlorite replaces biotite. Sericite and adular replace orthoclase. Zeolites developed locally.

Ore zone: composed of complex mineral associations including organic matter (rich in U, Mo, As, and, less commonly, Pb and Cu), pyrite, chlorite, hydromicas, and cryptocrystalline quartz.

Vein carbonate is widespread in the outer and inner zones but almost absent in the ore zone. Siderite is typical for the inner and ore zones, dolomite and calcite in the outer zone.

The hydrodynamic regime, which was from west to east during the oxidation event, later reversed its direction and redox potential. Mild reducing conditions evolved and generated in the formerly pink facies an irregular dimensioned bleached zone. The zone is up to several hundreds of meters wide in permeable rocks and narrows to fractions of a meter in impermeable beds. Traces of former oxidation are retained in bleached rocks as relic pink patches in clayey nests and lenses and in the interior of boulders and pebbles, and as pink speckled argillized feldspar due to Fe-hydroxides pigmentation. The bleaching of oxidized rocks was accompanied by a partial Fe loss, and Fe redeposition in pink facies. In the latter, the total iron content makes up 1.5–2 wt.-% whereas in bleached rocks it does commonly not exceed 0.4 wt.-%. The adjacent grey rocks also show low iron contents (0.3–1%) suggesting a Fe loss due to carbonate solution.

During a later event, bleached rocks near the contact with pink facies experienced locally a re-introduction of iron of up to 0.4–0.6 wt.-% associated with a pink re-coloration. There are also local areas of manganese and calcite accumulation with the formation of a coarse-grained poikilitic rock matrix. Calcite veinlets occur locally. Calcite contains fluid-gas inclusions with a homogenization temperature of 200 °C.

An unusual feature of redox activity is reflected by a narrow, 1–20 cm thick zone of redeposited organic matter (humic roll), whose appearance is related not only to the abundance of organic matter in primary grey rocks (3–5% C_{org}), but, evidently, also to the elevated alkalinity of the stratum waters. In mineralized horizons, the humic roll is universally traced along the boundary between primarily grey and bleached rocks. The humic roll does generally not differ in uranium content and radioactivity from uraniferous but ore-free grey rocks. Despite the influence of later reducing processes, the rear segment of the humic roll still reveals subzones of both weak oxidation with relics of coalified debris and more intense rock transformations up to complete oxidation of chlorites and ferruginous hydromicas. At some distance from the humic roll, the green color of clayey layers in bleached facies turns to pale.

A late yellowish limonitization is essentially confined to the present-day surface and probably originated during the Neogene-Quaternary prior to the development of permafrost. Permafrost persists to a depth of 120 m. At deep levels, limonitized rocks are partially reduced presumably by reaction with locally formed oxygen-free carbonic acid waters.

Mineralization

Principal uranium minerals are pitchblende and coffinite, and subordinate hydrous pitchblende and ningyoite. The uranium minerals associate with carbonaceous debris, redeposited humate, globular pyrite, and jordisite (Kochenov et al. 1995).

Most ore samples yield a radiometric age of 80–50 Ma, i.e., they formed not earlier than the Late Cretaceous whereas low-grade mineralization distant from stratum oxidation zones gives an age of 130 Ma (Malyshev in Kislyakov and Shumilin 1996).

U mineralization is controlled by an asymmetric, strata intersecting redox zoning. Four zones are distinguished: (1) primarily grey, intensely argillized host rocks with an elevated uranium content of several 100 ppm U; (2) rocks with redeposited organic matter (humic roll); (3) bleached reduced rocks with relics of preceding oxidation; and (4) pink oxidized rocks with pseudomorphoses of Fe-hydroxides after coalified remains, pyrite, and siderite. Ore occurs primarily in the grey facies and, to a lesser extent, in humic rolls and adjacent bleached rocks.

Ore lodes are essentially arrested at the interface of oxidized and reduced facies, and they are noticeably associated with zones of spatially continuous pink oxidized facies, which are typical for weakly permeable horizons. Within these zones, ore bodies are commonly confined to intervening grey rocks, which are marked by a bleached aureole. Some ore bodies occupy the hanging and footwall of ancient stratum oxidation zones whereas a few others show in cross section a reversed roll shape.

In the heavily disrupted SW segment of the deposit, numerous pink oxidation tongues penetrate permeable sand-gravel horizons from E to W and control the ore locus. Pseudomorphoses of Fe-hydroxides after abundant coaly debris and, less commonly, pyrite and siderite imposed the pink hue. The tongues join in the westernmost part of the deposit to a single, thick, pink unit.

Shape and Dimensions of Deposits

The Ima deposit consists of numerous, commonly tabular uranium lodes. Ore lodes are defined by a cutoff grade of 0.01% U. Ore lodes are from 0.2 to 12 m thick, tens of meters wide, and hundreds of meters long, and occur multiply stacked over a vertical range of more than 800 m. In the northern flank of the deposit, as much as 60 ore bodies were intercepted by deep drilling.

Conterminous, but fault separated blocks and beds differ, in spite of equal lithology with ore-hosting rocks and apparent uniform epigenetic alterations, in grade and size of ore lodes.

The difference is tentatively explained by a screen provided by gouge filled faults during ore formation.

Metallogenetic Aspects

The origin of the Ima deposit is debatable; a favored concept involves a multistage provenance during Cretaceous time. In a *first* stage, permeable granitoid clastic material with elevated uranium contents was accumulated. The *second* stage involves a low-temperature hydrothermal event that resulted in carbonatic-argillaceous alteration, chloritization, and zeolitization of the sediments, and an additional uranium influx into grey rock facies. During the subsequent *third* stage, exogenic-epigenetic processes produced the ancient (Late Cretaceous?) stratum oxidation tongues and related ore bodies at their basinward interfaces.

It is assumed that the hydrothermal and exogenic-epigenetic events most likely occurred during the terminal phase of the Malyi Amalat Basin development and prior to a denudation period, which eroded substantial parts of the Ima deposit. Some uranium was redistributed by Cenozoic redox processes, which produced young "augen" ores composed of round aggregates of finely dispersed coffinite fringed by light rims within limonitized rocks.

10.4.3.3 Other Uranium Deposits/Occurrences in the Central Transbaykal Subregion

The Korolevo-Chasovo ore field is to the north of Chita and contains the vein-type *Crystalnoye, Chasovoye,* and *Korolevskoye* occurrences (each <5 000 t U, <0.1% U) in Middle-Upper Paleozoic granites (Vizhnyakov 1995b).

Chikoisky-Yuzhno-Daursky ore field, situated to the south of Chita, contains a number of U occurrences of various type, all of them are of low grade. Reported occurrences include: *Gornoye* (>5 000 t U): vein-type hexavalent U mineralization in highly radioactive Mesozoic granite; *Berezovoye* (>500 t U): vein-type hexavalent U mineralization in Mesozoic highly radioactive granite; *Akhutinskoye*; *Barun-Ulacha;* and *Vostochnoye* (Vizhnyakov 1995c).

Khiloksky area, close to SW of Chita, includes the *Stepnoye* deposit in the Beklemishev Depression/Graben structure. Stepnoye has estimated resources in excess of >5 000 t U at ore grades of <0.1% U, contained in tabular, basal channel sandstone-type ore bodies. Host rocks are Lower Cretaceous lignite-bearing sandstone and conglomerate altered by argillization and intense zeolitization (Pelmenev 1995).

Mensensky area in the southern Transbaykal region contains the *Yugalskoye* vein-type deposit in highly radioactive granite (>1 500 t U, approximately 0.2% U).

Tunguisky area in the southwestern Transbaykal region hosts the tabular *Zhuravlinoye* F-Mo-U deposit (>5 000 t U, <0.1% U) in Lower Cretaceous pyroclastics and clastic sediments.

Urulyunguevsky depression (overlaps the north part of the Streltsovsk/Tulukuyevsk Caldera) includes the *Meridionalnoye* and *Sirotininsk* deposits (each <5 000 t U, <0.1% U) with stratiform U mineralization in Lower Cretaceous argillized arenaceous sediments.

10.5 Aldan Shield Region

The Aldan Shield is an Archean-Lower Proterozoic crystalline massif in the Aldan River region in southern Yakutiya. Major towns are Aldan and Tommot. The massif is known for gold and uranium deposits. Gold is mined from recent placers and stratiform concentrations in basal Jurassic? beds. Uranium was explored in the Elkon District, an uplifted basement block in the central part of the Aldan Shield. Boitsov and Nikolsky (1997) in agreement with Naumov and Shumilin (1994) consider the uranium potential of the shield as the largest in Russia.

10.5.1 Elkon District

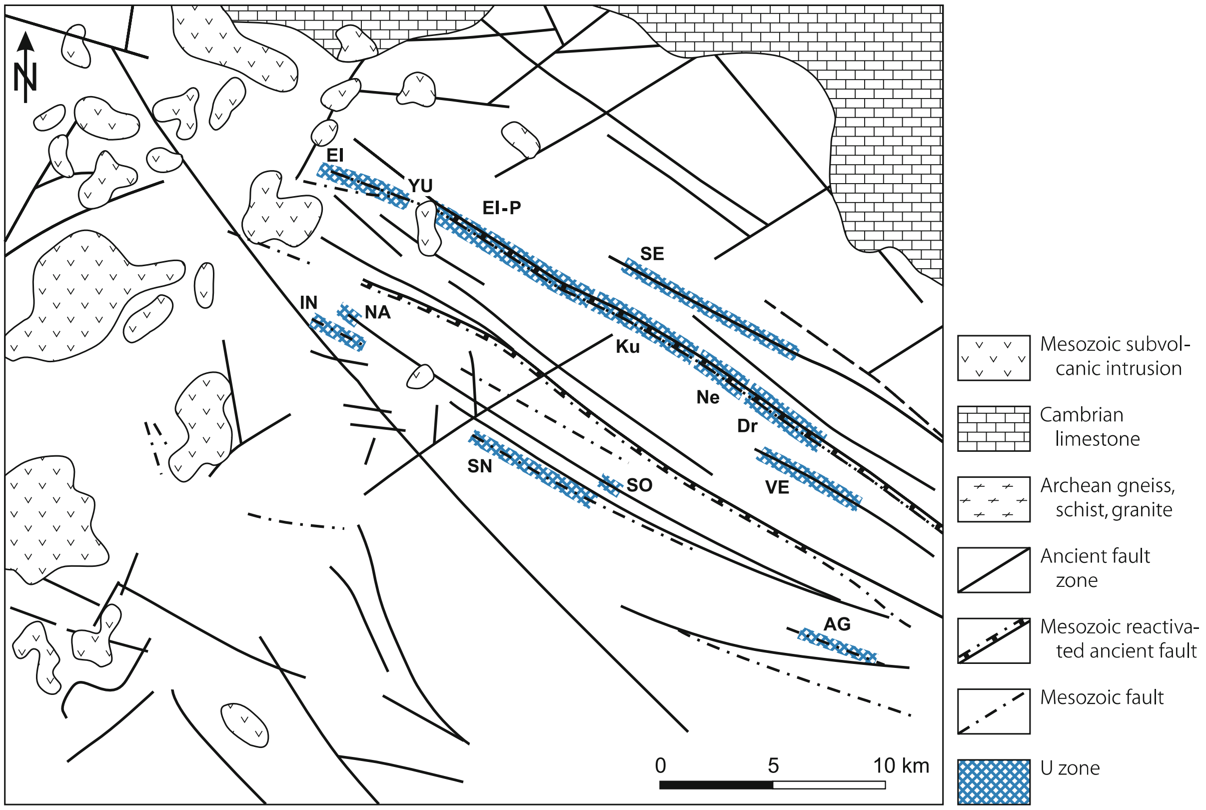
This district is located some 100 km ENE of the town of Aldan in the Sakha Republic, eastern Asian Russia. After the discovery of the first uranium occurrence in the early 1960s, about eighty more Au-U(-Ag)-bearing occurrences including nine deposits of vein-stockwork-type were found along distinct structural zones. Most significant deposits were identified along the Yuzhnaya structure. ➲ Figure 10.28 shows the location of major ore zones and deposits.

Four deposits were investigated by underground workings and five by drill holes to a depth of 2 000 m from the 1960s to the early 1980s. Some uranium was presumably produced during the underground investigations.

Total resources of the Elkon District are estimated in excess of 200 000 t U in the high cost category. Ore grades average 0.1–0.15% U while gold values range from less than 1 ppm to several ppm. (According to a press release of the Russian Natural Resources Ministry in 2006, "proven" resources amount to 342 000 t U; planned production capacity is 3 000 t U yr^{-1} in ten years time.)

Sources of information. Birka et al. 2005; Boitsov and Nikolsky 1997; Boitsov 1989, 1996; Boitsov and Pilipenko 1998; Gotman et al. 1979; Kazansky 1995; Kazansky and Laverov 1977; Kazansky and Maksimov 2000; Kirillov and Berdinkov 1998; Kochetkov et al. 1986; Korolev et al. 1979; Miguta 1997; Miguta and Modnikov 1993; Naumov and Shumilin 1994. Miguta (1997) provides a comprehensive synopsis of alteration and ore-related mineralogical and geochemical features while Boitsov and Pilipenko (1998) address the typical geological settings of deposits and ore types.

Fig. 10.28.
Aldan region, Elkon District, generalized geological map with location of principal U zones and deposits. Small intrusive bodies and dikes (not shown) of Mesozoic age are particularly abundant in the western part of the region (after Boitsov AV and Nikolsky 2001 based on Akhapkin EV). *Au-brannerite zones:* *AG* Agdinskaya (Agda), *SE* Severnoye, *SN* Snezhnoye, *SO* Sokhsolookhsk, *VE* Vesennyaya, *YU* Yuzhnaya; *deposits:* *Dr* Druzhnoye(-Mineyevsky), *El* Elkon, *El-P* Elkon Plateau, *Ku* Kurung, *Ne* Neprokhodimoye. Au-uraninite zones/ deposits: *IN* Interesnaya, *NA* Nadezhda



Regional Geological Setting of Mineralization

The core of the Aldan Shield consists of an Archean-Lower Proterozoic crystalline basement, which is exposed in several uplifts including the Au and U-bearing Elkon Horst. As much as 700 m thick, subhorizontally bedded Vendian-Lower Cambrian limestone and dolomite cover the basement to the north while Lower Jurassic coal-bearing continental sediments and pyroclastics fill grabens.

The Elkon Horst is a NW-SE-elongated, 60 km long and up to 40 km wide uplift in the central Aldan Shield. Principal lithologies are Archean granulite, amphibolite, gneiss, schist, quartzite, and marble. Intense Late Archean-Early Proterozoic granitization generated leucocratic biotite-microcline granite and migmatite. Only remnants of gneiss and schist are found in the granitized rocks.

Small laccolithic bodies, stocks, sills, and dikes of alkaline and calc-alkaline rocks of the Aldan volcano-plutonic complex were intruded into the afore mentioned units during three periods in the Jurassic and Cretaceous. Their abundance is most prominent in the western part of the Elkon Horst.

Brittle deformation affected repeatedly the region, particularly during the Early Proterozoic and Mesozoic and resulted in three prominent fault sets: *ancient*, NW-SE- and NW-SE-trending faults formed during the Early Proterozoic, ancient faults *reactivated* during the Mesozoic, and *neotectonic* NW-SE and submeridional oriented faults of Mesozoic age. The latter caused block movements and resulted in horst and graben structures.

Principal Host Rock Alterations

Several kinds of alteration are documented by Miguta (1997). They include from oldest to youngest:

Post-granitization potassium-siliceous metasomatism is developed in zonal distribution in the Early Proterozoic granitoids. These metasomatites contain local concentrations of disseminated uraninite, cleveite, bröggerite, orthite, thorite, malacon, and sphene.

Multistage Mesozoic, *pre-uranium* (brannerite) alteration is reflected by various mineral assemblages (➔ Table 10.5), which are superimposed on each other in ore-bearing zones. All of them are controlled by Mesozoic neotectonic and reactivated ancient fault zones. Oldest is an *albite-sericite-chlorite* facies that zonally overprinted former rock constituents and formed microveinlets for up to a few tens of meters from faults. In the *outer*

Table 10.5.
Aldan region, Elkon District. Mineral assemblages of uranium-bearing zones (Miguta 1997)

Mineral assemblage	Minerals	Mode of occurrence
Albite-sericite-chlorite	Actinolite-tremolite, biotite, talc, chlorite, epidote, sericite, albite, calcite, magnetite. hematite, rutile, leucoxene	Metasomatite replacement, microveinlets
Pyrite-carbonate-K-feldspar	Pyrite, marcasite, calcite. dolomite, ankerite, brown K-feldspar, adularia, sericite, sphene, apatite, fluorite, and dispersed gold	Metasomatite replacement, microveinlets
Pyrite-carbonate	Pyrite. marcasite, dolomite. calcite, dispersed gold	Veinlets, breccia cement
Baryte-quartz	Quartz, baryte, tennantite, pyrite, chalcopyrite, enargite, sphalerite, galena	Veins, veinlets
Brannerite	Brannerite, pyrite, marcasite	Microveinlets, breccia cement
Micrograined quartz	Quartz, sagenite, recrystallized brannerite	Metasomatic replacement
Brookite-molybdenite	Finely dispersed molybdenite, brookite, uranium oxide	Veinlets, gouge
Coffinite-carbonate	Dolomite, ankerite, pyrite, marcasite, coffinite, hematite, anatase, gold	Metasomatic replacement
Fluorite-quartz-carbonate	Quartz. carbonate, baryte, fluorite, pyrite, marcasite, galena, sphalerite	Veinlets
Oxidized phases	Fe and Mn hydroxides, clay minerals, opal, chrysocolla, malachite, azurite, jarosite, carbonates, products of brannerite decomposition, utanyl minerals	Crusts, films, dispersed inclusions

zone, only mafic minerals were replaced by actinolite, tremolite, and talk imposing a greenish color on the rocks. An *intermediate zone* is characterized by chlorite development and locally hematite giving a green or pinkish-green color to the rocks. An *inner zone* is only locally developed. Where present, all leucocratic minerals were replaced by albite or albite-oligoclase, and mafic minerals by hematite and chlorite, which imposed a greenish-pink or reddish color on the rocks. Sericite and carbonates occur in the latter two zones. The process is considered of Mesozoic age since it affected Jurassic minette dikes.

A younger and the most prominent pre-uranium alteration assemblage consists of *pyrite-carbonate-potassium feldspar* with dispersed gold. It is of tan, greenish-brown, or dark grey color and surrounds all ore-bearing structures. This facies overprinted particularly the albite-sericite-chlorite aureoles, and formed micro-veinlets for several hundreds of meters along strike and dip of reactivated ancient faults and commonly persists for 6–10 m and locally up to 20 m into the wall rocks. A vague zoning is reflected by an outer halo of *pyrite-carbonate-sericite* that developed along fractures and an inner zone where *pyrite-carbonate-orthoclase* with *adularia* subzones overprinted brecciated rocks. In the *outer zone*, mafic minerals are completely substituted by dolomite, ankerite, pyrite, and marcasite while plagioclase is replaced by sericite and carbonate, magnetite by pyrite, and quartz by calcite. Proportions of carbonate and pyrite are highly variable. Carbonate can amount to 50% as found in the Yuzhnaya zone. The *inner halo* is characterized, besides the above mentioned replacements, by a markedly increased K-feldspar content. Microgranular orthoclase formed first and was subsequently more or less recrystallized to translucent adularia over tens of centimeters to few meters thick intervals. In result, a dense, dark grey, fine-grained alteration facies evolved composed of 40–75% K-feldspar, 35–50% carbonate, 5–15% pyrite and minor sericite, sphene, and apatite. Pyrite concentrates carry as much as 80 g t^{-1} of gold.

Boitsov VE and Pilipenko (1998) consider the pyrite-carbonate-feldspar alteration facies to have originated from three sequential mineral formations: (1) pyrite-ankerite-orthoclase, (2) pyrite-dolomite-orthoclase, and (3) calcite-adularia. Pyrite of the first and second assemblages contains significant amounts of gold and silver.

Subsequent to brecciation, a *pyrite-carbonate* assemblage developed within the older pyrite-carbonate-orthoclase/adularia facies. Dolomite is the prevailing mineral associated with subordinate calcite, pyrite, and marcasite. The assemblage cements breccias and forms up to 0.5 cm thick veinlets. Pyrite contains dispersed gold with values of up to 4.5 g t^{-1} Au in pyrite concentrate.

A *baryte-quartz* assemblage associated with minor Fe-, Cu-, Zn-, and Pb-sulfides is restricted to the Druzhnoye deposit in the Yuzhnaya zone where these minerals form up to 2 m thick and 30 m long and deep veins. Quartz occurs in several generations.

Late and post-ore alteration includes carbonatization, silicification, fluoritization, sulfidization, and oxidation. The post-ore emplacement of Mesozoic alkaline intrusions caused fenitization of earlier facies.

Geochemical changes by the alteration processes include removal and introduction of elements. Desilicification is documented by replacement of quartz by calcite and the destruction of mafic minerals both causing removal of SiO_2 from the altered zones. The SiO_2 content of quartz-rich gneissic granite and massive granite was depleted by about 40% while gneiss and schist lost on the order of 12% SiO_2. Redeposition of the liberated SiO_2 occurred as quartz along structurally prepared sites in form of segregations, stockworks of thin veinlets, up to 3 cm thick veins, and cement of breccias. Quartz was preferentially deposited at the upper levels of deposits where it formed "quartz caps".

Removal of alumina is typical for wall rocks in the vicinity of mineralized zones. Al_2O_3 depletion is strongest in extremely altered rocks immediately adjacent to ore veins where the original alumina content decreased by up to 25%.

Ca, Mg, Mn, P, and Ti were dissolved and redeposited over the whole section as constituents of authigenic mafic minerals, apatite, carbonates, rutile, sphene, and other minerals.

Potassium was introduced and sodium removed during the pyrite-carbonate-potassium feldspar alteration process. Altered rocks show an addition on the order of 10–20% K_2O and a loss of 80–90% Na_2O.

Addition of carbon dioxide and sulfur occurred all along the metallogenetic evolution. It was distinctively intense during the pre-ore stage when calcite replaced quartz while ankerite, dolomite, marcasite, and pyrite substituted mafic minerals. In addition, carbonates and sulfides developed as disseminations along fissures, and in the matrix of breccias. Carbonates also constitute late stage gangue minerals. Miguta (1997) estimates that during the alteration processes about 130 kg of CO_2 and 60 kg sulfidic sulfur per m^3 was added to the precursor rocks.

Fluorine was locally introduced into peripheral parts of alteration zones where it occurs as fluorite veinlets and matrix constituents of breccias. The fluorine grade increases here up to 0.6% as compared with background values of 0.05–0.1 wt.-% F.

Principal Characteristics of Mineralization

The only *primary uranium mineral* is a medium to low temperature U-Ti-phase defined as brannerite-A by Korolev et al. (1979). It commonly occurs in massive, colloform aggregates that enclose small fragments of host rocks, and more rarely as up to 0.08 mm high prismatic crystals. *Associated minerals* are pyrite and marcasite. They largely predate brannerite. Only a small fraction of them is contemporaneous with brannerite. Alteration products of brannerite include secondary brannerite, more or less uraniferous TiO_2-phases, U-oxides and, in oxidized intervals, hexavalent U minerals, which formed after renewed deformation interludes.

Gold is a common constituent of most of the ores but it tends to be not syngenetically related to U. Au mineralization predates and postdates the brannerite formation.

Brannerite was significantly decomposed during a carbonatization event to amorphous TiO_2-phases containing variable amounts of uranium and admixtures of Nb, W, and Zr. A part of the liberated uranium migrated into the host metasomatites where it recrystallized as coffinite during a silicification event that generated microgranular quartz in up to a few meters wide, lenticular, brecciated intervals. Corroded primary brannerite survived as relics in the quartz mass and as recrystallized prismatic crystals. Titanium was redeposited as acicular rutile crystals. Coffinite typically replaces pyritized mafic minerals, and coats Fe-sulfides contained in fissures and voids. This silicification affected all deposits where it prevails in the upper sections and decreases with depth.

Aggregates of subhedral to rounded uraninite and Ti-oxide phases with or without brannerite occur in the vicinity of Mesozoic magmatic intrusions in the NW segment of the Elkon District. Their generation is attributed to the destruction of brannerite by contactmetamorphism.

Fenitization related to Mesozoic alkaline intrusions caused alteration of brannerite and its decay products up to a complete replacement of the uranium ore by biotite, aegirine, and albite.

At the Druzhnoye deposit and adjacent sections of the Yuzhnaya zone, a brookite-molybdenite assemblage with a uranium mineral that was tentatively defined as a uranium oxide was found. The minerals form a few centimeters to 2.5 m wide, flattened stockworks of veinlets, and black earthy masses, crusts, and coatings in breccias.

Post-ore breccias are cemented by dolomite and ankerite with disseminated marcasite, pyrite, rare anatase, and native gold. Rock fragments contain intensely corroded brannerite. Small grains and rare veinlets of coffinite, which always associate with pyrite or marcasite, occur in the breccia matrix. Up to 36 µm large grains and leaflets of native gold are enclosed in fine-grained carbonates. The gold accumulates in pockets, which locally can contain up to 100 g t^{-1} Au.

A final generation of endogenic mineralization consists of dark veinlets of calcite, dolomite, fluorite, marcasite, pyrite, quartz, and minor baryte, chalcopyrite, galena, and sphalerite.

Oxidation of primary ore persists to a depth of some tens of meters below the current surface in most deposits of the Elkon District but may extend to 600 m deep in some ore-bearing structures. Characteristic minerals include Fe- and Mn-hydroxides, azurite, carbonates, chrysocolla, clay minerals, jarosite, malachite, opal, various products of decomposed brannerite, uranyl-phosphates, and U adsorbed by Fe-hydroxides and other minerals.

Textures of uraniferous mineralization are dominated by fine- to microclastic breccia and veinlet-breccia. Stringer and dissemination textures are less frequent.

Breccia-type ore includes the primary brannerite-pyrite-marcasite paragenesis and occurs along mylonites, quartz vein contacts and similar structural elements within deformed pyrite-carbonate-potassium feldspar altered rocks. Primary brannerite, pyrite, and marcasite occur as up to 3 mm thick and several centimeters long veinlets and disseminated grains or aggregates within the matrix of breccias. Both textural varieties coexist commonly and constitute together with their alteration products the bulk of the veinlet-breccia-type uranium ore.

Miguta (1997) reports as major *geochemical ore components* 1.5–10 wt.-% CO_2 and 1–4 wt.-% sulfidic sulfur, and distinguishes four characteristic geochemical groups of minor elements in the various ore zones (in wt.-%):

Group 1 elements are 0.1–0.3% As, 0.01–0.1% Tl, 1–10 ppm Ag, and 0.2–2 ppm Au, which are concentrated in finely dispersed pyrite of pre-ore potassium metasomatite. The host pyrite replaced mafic minerals or occurs in the matrix of pyrite-carbonate breccias.

Group 2 elements are As, Bi, Cd, Cu, Ge, Pb, Sb, Sn, Tl, and Zn. They typically occur in chalcopyrite, fahlore, sphalerite, and other sulfides associated with pre-ore quartz-baryte veins.

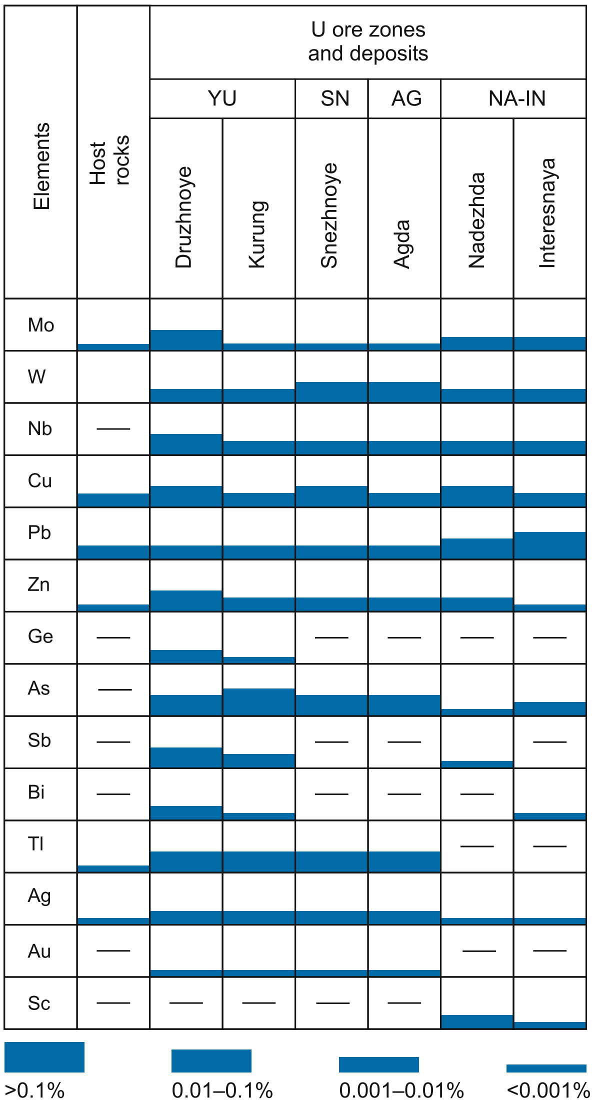
Group 3 is composed of minor constituents of brannerite and includes Nb, W, Zr, radiogenic Pb, and some REE. Their tenor in ore correlates well with that of uranium.

Group 4 includes Ag, As, Hg, Pb, and Tl that occur with finely dispersed molybdenite. The abundance of the various elements in selected deposits is shown in Fig. 10.29.

Boitsov VE and Pilipenko (1998) distinguish three *uranium ore varieties*: gold-brannerite, gold-uraninite, and brannerite-silver-gold mineralization, and, additionally, three gold ore types, which may or may not contain minor uranium.

Gold-brannerite mineralization is typical for deposits at the Yuzhnaya, Severnoye, Sokhsolookhsk, Pologaya, Vesennyaya, and Agdinsk zones. Ore control is by reactivated ancient and neotectonic NW-SE-oriented and steeply SW dipping faults of Mesozoic age and by pyrite-carbonate-potassium feldspar altered rocks. Mineralized zones are traced by blastomylonites imposed on Early Proterozoic metadiorite dikes. Country rocks are Archean-Early Proterozoic ultrametamorphic lithologies. Gold-brannerite mineralization is of veinlet-disseminated-type and commonly located within gold-bearing pyrite-carbonate-potassium feldspar altered zones. Brannerite is the only primary U mineral. Appreciable amounts of gold and silver are bound in two, pre-brannerite pyrite generations of the pyrite-carbonate-potassium feldspar facies. Pyrite I occurs as 0.001–0.1 mm large grains and contains most of the gold but only minor silver, thallium, vanadium, and, more rarely, arsenic. Together with ankerite, pyrite I profoundly replaced magnetite and femic minerals. It constitutes up to 20 vol-.% of altered mafic and 0.5–7 vol-.% of other host rocks. Monomineralic concentrates of pyrite I yield 60–90 ppm of gold. Pyrite II occurs as 0.01–0.15 mm large grains. Contents of pyrite II in altered rocks compare with those in pyrite I, but pyrite II contains much less gold (2–5 ppm in concentrate) whereas it is enriched in arsenic (up to 0.5 wt.-%), silver, vanadium, lead, and zinc. Native gold occurs locally and is associated with the calcite-adularia alteration facies.

Fig. 10.29.
Aldan region, Elkon District, abundance of minor and trace metallic elements in selected U deposits and host rocks (after Miguta 1997). *U ore zones: AG* Agdinskaya, *NA-IN* Nadezhda-Interesnaya, *SN* Snezhnoye, *YU* Yuzhnaya



Gold-uraninite mineralization is known from the Nadezhda and Interesnaya zones in the northwestern sector of the Elkon District where Mesozoic stocks and dikes are abundant (Tables 10.6, 10.7). Ore control and geological setting are similar to those of the gold-brannerite deposits except that the uraninite is restricted to zones of thermal metamorphism. In contrast to the gold-brannerite assemblage, the gold-uraninite mineralization has higher uranium grades. Early pyrite tends to be the essential host of native gold. Concentrates of the early pyrite have contents from 9.1 to 24.5 ppm Au.

Brannerite-silver-gold mineralization is reported from the Fedorov, Marsovaya, Mramornaya, and Zvezdnaya zones in the southwestern Elkon District. Ore control and geological setting are similar to those of the gold-brannerite deposits. Ore lodes consist of gold-bearing metasomatic rocks intersected by thin brannerite stringers and a younger generation of small quartz and carbonate veinlets with acanthite, native gold, native silver, and pyrite (for ore grades see next section).

General Shape and Dimensions of Deposits

Location, shape, dimensions, and internal structure of uranium-gold and uranium-gold-silver deposits are primarily controlled by NW-SE-oriented and steeply SW dipping faults (Fig. 10.30).

Deposits consist of one or several intermittently distributed ore bodies composed of veinlike or columnar ore lodes with an internal stockwork or network structure of closely spaced brannerite stringers and impregnations (Fig. 10.31). Ore shoots within these lodes may carry also gold, silver, and locally molybdenum in variable amounts (Fig. 10.32). Ore lodes are usually 0.2–5 m wide in neotectonic Mesozoic faults but achieve a width of up to 10 m in rejuvenated Proterozoic faults. Lodes group to

Table 10.6.
Aldan Shield, Elkon District. Types of Mesozoic gold-uranium and gold mineralization (Boitsov and Pilipenko 1998)

Ore zone/deposit	Ore types	U phases	Au and Ag phases	Geological setting	Ore-controlling structures	Morphology of ore bodies	Average mineral composition of ore (vol.-%)				Average content (ppm)	
							F	Q	C	S	Au	Ag
Yuzhnaya, Sokhsolookhsk, Pologaya, Vesennyaya, Agdinsk zones	Au-brannerite	Brannerite	Au-bearing pyrite, native Au	Crystalline basement	Reactivated old faults, Mesozoic fracures	Large lodes	65	10	20	5	1–2	8–15
Interesnaya, Nadezhda zones	Au-uraninite	Uraninite	Native Au	Crystalline basement	Mesozoic fractures	En echelon lenses	60	15	15	10	0.5–1	10–20
Fedorovsk, Zvezdnaya, Marsovaya zones	Brannerite Ag-Au	Brannerite	Native Au, Ag, Au-Ag-bearing pyrite, acanthite	Crystalline basement	Reactivated old faults, Mesozoic fractures	En echelon veins	50	10	30	10	3–10	15–200
Ryabinovsk, Novoye deposits	Porphyry Au	–	Native Au, Au-Ag-bearing pyrite	Crystalline basement	Mesozoic intrusions contact zones of intrusive phases	Linear, ring, and pipe-like	75	5	10	10	2–5	2–10
Lebedinsk, Koltykon, Samodumovsk deposits	Au-sulfide	–	Native Au and Ag, Au-Ag-bearing sulfides	At base of platform cover	Bedding-plane and cross-cutting fractures	Ribbon-shaped lodes and veins	5	10	10	75	10–80	20–90
Bokovoye, Delbe, Centralnoye, Porfirovoye, Severnoye deposits; Nizhne-Yakokit ore field	Au redeposited in karst	Uraninite	Native Au, Au-bearing pyrite	At contact of platform carbonate rocks with Jurassic terrestrial sediments	Linear karst zones	Ribbon- and lens-shaped	5	80	5	10	2–10	2–10

F feldspar, *Q* quartz, *C* carbonate, *S* sulfide. *Note*: For the mineralization type of redeposited gold, the table shows an average mineral composition of primary ores.

Table 10.7.
Aldan region, Elkon District. Characteristics and dimensions of uraniferous zones (Miguta 1997)

Ore zone	Structural characteristics						Ore bodies	
	Type of zone	Length (km)	Width (m)	Strike and dip	Inherited older structural elements	Mesozoic structure	Shape and size	Depth extension
Yuzhnaya, Sokhsolookhst	Rejuvenated ancient regional faults	Sev.10	Sev. 100	300–330°, 65–90° SE	Ancient structural elements: orthotectonite, metamorphosed dikes, blasto- and ultramylonite	Elongated subparallel cataclastic and breccia zones, <10 m wide, commonly in the footwall of ancient faults	Large tabular bodies, 1.5–10 m thick, sev. 100s m long along strike and dip	~2 km
Pologaya, Fedorov, Centralnaya, Nevskaya	Large fault zones of relative simple structure	2–15	2–10	280–330°, 45–80° SE	Some, extended intervals at contacts of metamorphosed rocks and dikes	Extended cataclastic and breccia zones, 1–3 m wide	Elongated, flat lensoid bodies, 1–2 m thick, several 10s to sev. 100s m long, elongated along dip	1–1.2 km
Agda, Veselaya, Marsovaya, Kurumkan	Variably oriented, complex fault zones	1–8	2–3, in bulges 10–15	Variable strike and dip with 65–80°	–	En echelon cataclastic and breccia zones, sev. 10s cm to 3 m wide, at fault junctions <15 m wide	Flat lensoid bodies, sev. 10s cm to 2 m thick, sev. 10s to sev. 100s m long, complex bodies at fault junctions	700 m
Interesnava, Udachnaya	Fault zones at contact with Mesozoic dikes	0.3–2	1–5	280–310°, 65–80° SE	Contact of pre-ore dikes	Cataclastic zones with breccias at contact with dikes	Small individual lodes with complex morphology, sev.m long along strike and dip	100–300 m

Fig. 10.30.
Aldan region, Elkon District, geological sections across deposits in the four principal U zones (after Miguta 1997)

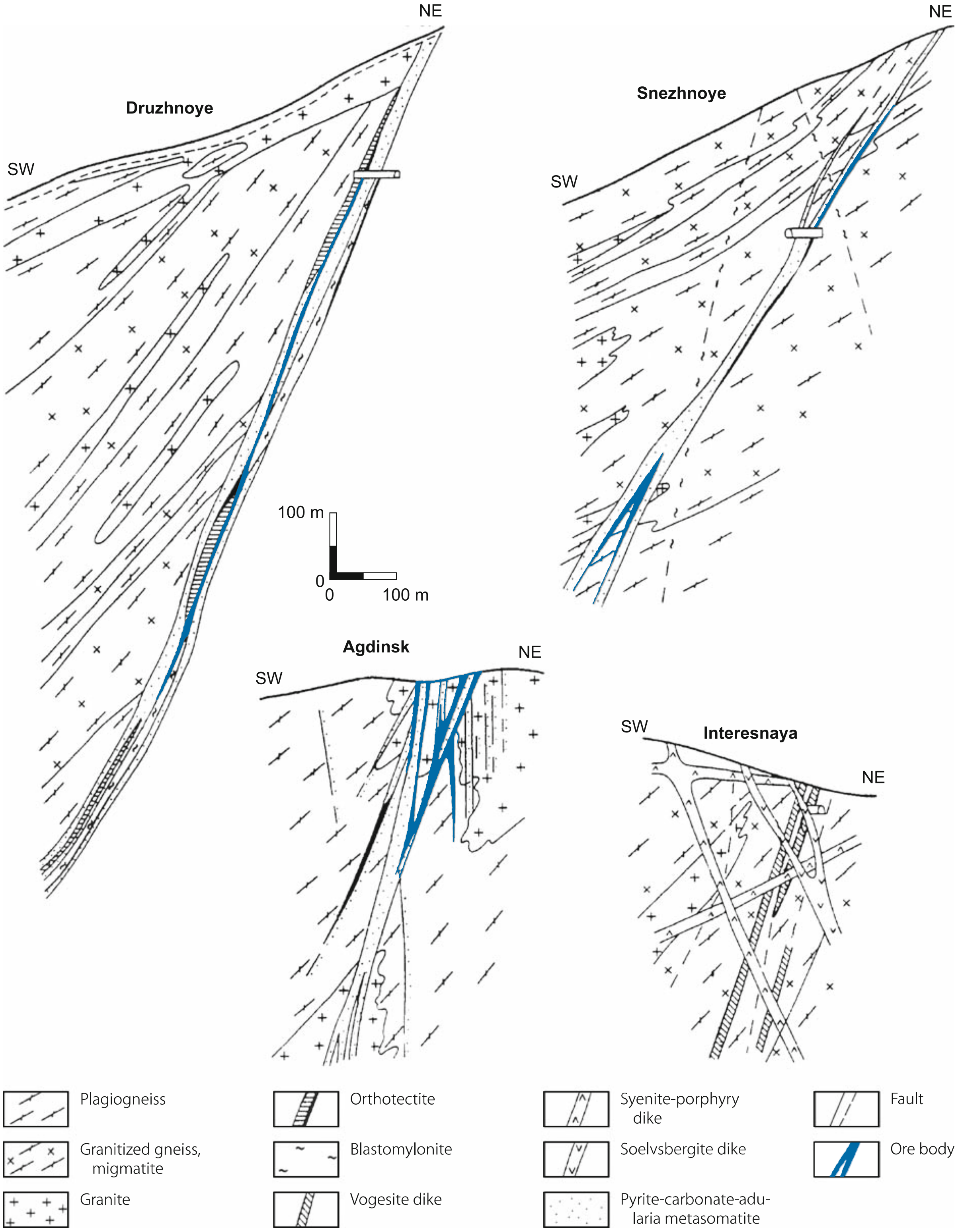
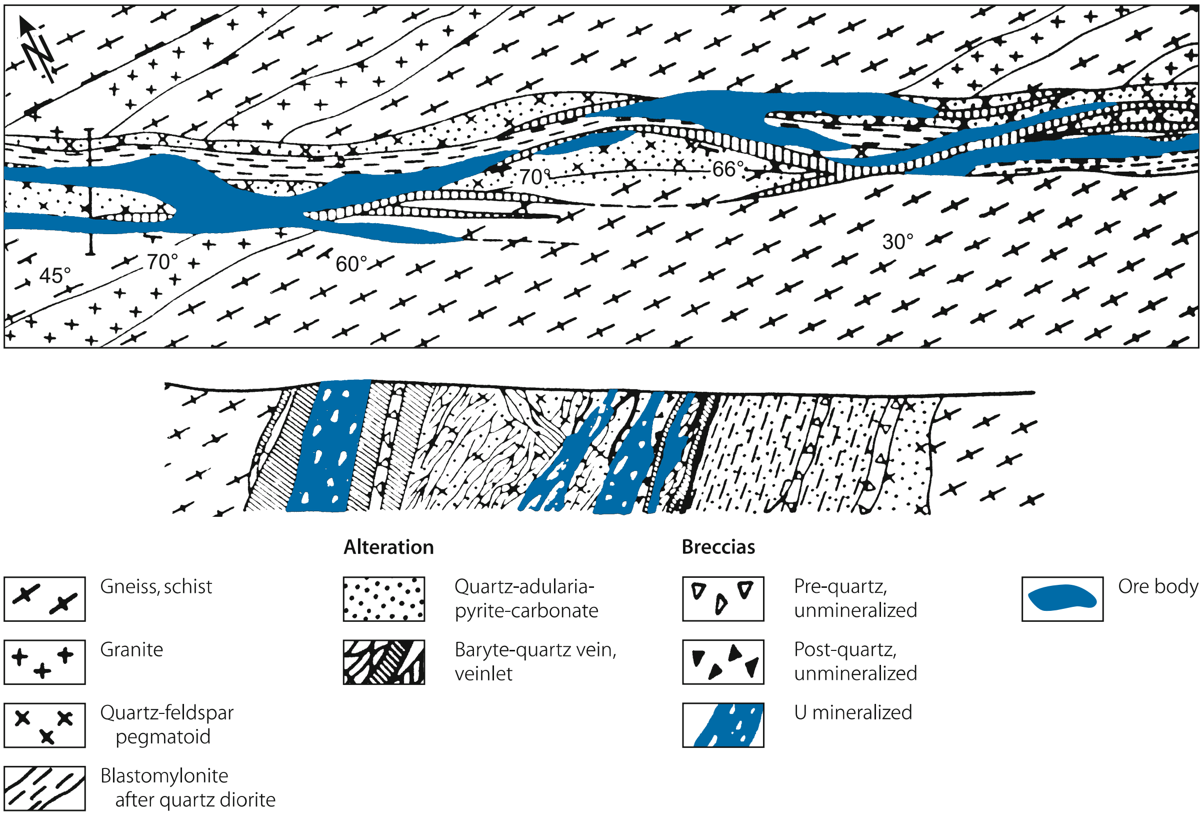


Fig. 10.31.
Aldan region, Elkon District, a Plan and b SW-NE cross-section across a U mineralized structure illustrating the distribution of alteration zones and U mineralization along rejuvenated blastomylonite intervals (after Kazansky and Laverov 1977 based on Krupenikov et al. 1968)



en echelon arranged, linear, 500–700 m long and 0.5 to more than 10 m wide ore bodies. Ore bodies are separated by barren or erratically mineralized ground composed of variably mineralized fractures, joints, and disseminations, the distribution, intensity, and dimensions of which are a function of the brecciation degree of the host rock.

Ore bodies are rarely exposed on surface. Upper limit of most ore bodies is at a depth below 200 m. Ore was drill intercepted to a depth of 2 000 m. No depth-related change in ore mineralogy was noticed over the whole vertical interval suggesting that mineralization probably continues into greater depth.

Brannerite-gold ore has uranium contents ranging from 0.02% to 0.2% U and more, and averages about 0.1–0.15% U. Gold tenors average 1–2 g t^{-1}, silver 8–15 g t^{-1}. Molybdenum grades vary between 0.01 and 0.1%. *Uraninite-gold ore* averages 0.5–1 g t^{-1} Au, 10–20 g t^{-1} Ag and has U contents exceeding that of the brannerite-gold ore. *Brannerite-gold-silver ore* has average tenors of 3–10 g t^{-1} Au and 15–200 g t^{-1} Ag but locally the Au and Ag grades can be substantially higher. U grades are between 0.02 and 0.2% but can exceed 0.5% U. The carbonate content of ore varies between 1.5 wt.-% in silicified ore and 10 wt.-% in other ore types, and the sulfidic sulfur content between 1 and 4 wt.-% but can be up to 20% S and more. For more details see Sect. *Description of Individual Ore Zones*.

Stable Isotopes and Fluid Inclusions

Fluid inclusion studies suggest the following approximate crystallization temperatures (Miguta 1997): Calcite formed at the end of the albite-sericite-chlorite alteration stage: 250 °C, pre-ore quartz of quartz-baryte veins: 230–290 °C, post-ore quartz: 160–200 °C, and late post-ore fluorite: 115–140 °C.

Decrepitation tests on pyrite of the main pyrite-carbonate-potassium feldspar, pre-ore alteration stage indicate a formational temperature of about 300 °C. Circumstantial evidence provided by adularia recrystallization suggests that subsequently the temperature dropped markedly since adularia typically crystallizes at temperatures of 150–200 °C.

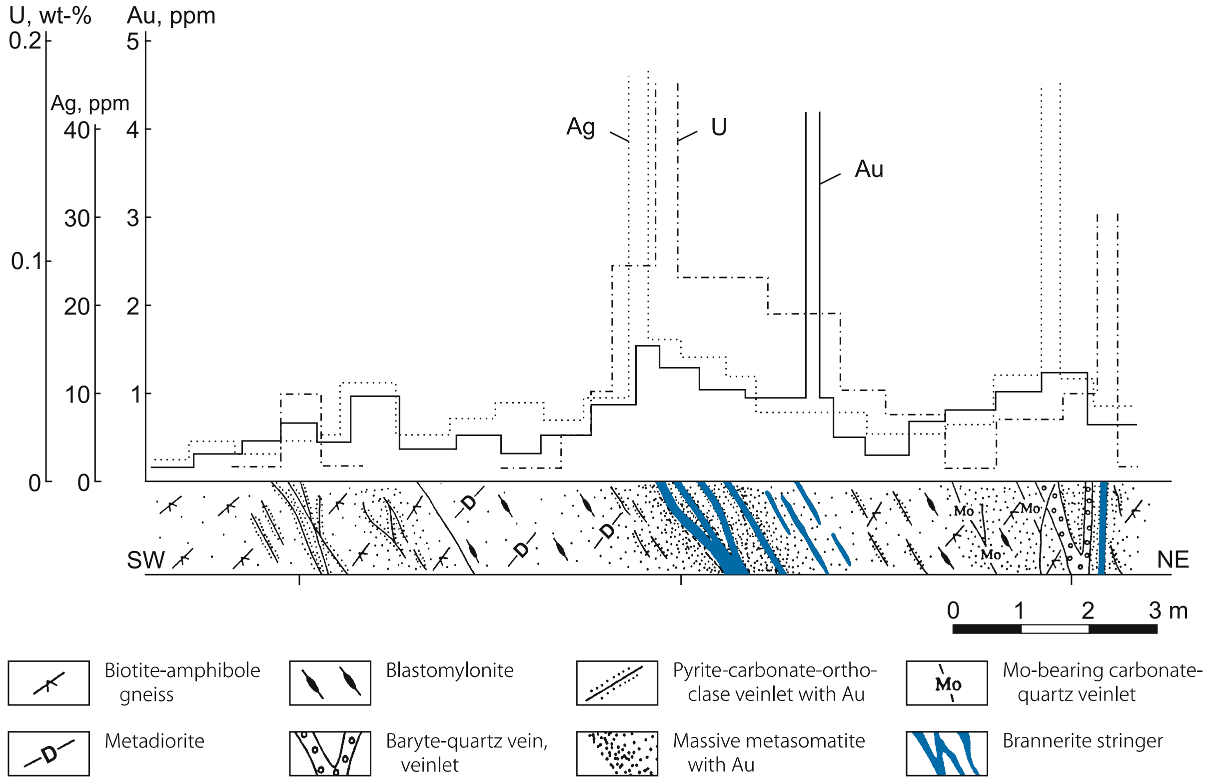
Thermobarometric studies indicate pronounced variations of temperatures during the entire metallogenetic evolution of the Elkon ores and its individual stages. Successive mineral stages started constantly with higher temperatures than those at the end of the previous stage suggesting a multiphase influx of ore-forming fluids.

Regional Geochronology

Three major episodes of Mesozoic magmatism are recorded: Syeno-diorite porphyry, minette, bostonite, kersantite, and

Fig. 10.32.

Aldan region, Elkon District, schematic section of a trench floor across a blastomylonite interval with vein and disseminated gold, silver, and brannerite mineralization (after Boitsov VE and Pilipenko 1998)



calcalkaline rocks yield a *Middle Jurassic* age of 188–158 Ma; monzonite, nepheline syenite etc. an *Early Cretaceous* age of 140–130 Ma; and aegirine granite, sölvsbergite, tinguaite a *Middle Cretaceous* age of 120–107 Ma.

U/Pb isotope dating gives an age of 135–130 Ma for primary brannerite, which correlates with the emplacement of the Early Cretaceous intrusions (Boitsov VE and Pilipenko 1998).

Potential Sources of Uranium and Gold

Archean-Lower Proterozoic granitized rocks are considered the most likely source of uranium. Miguta (1997) reports the following uranium contents of these rocks from the Druzhnoye deposit. Unaltered granite contains 10 ppm U, pyrite-carbonate altered apo-granite 270 ppm U, and pyrite-carbonate-potassium feldspar metasomatite 1980 ppm U. At the Agda deposit, granitized plagiogneiss contains less than 2 ppm U, metasomatized apo-gneiss <620 ppm U, and ore-bearing breccia of altered apo-gneiss <3 800 ppm U (Table 10.8).

The assumption of uranium derivation from Archean-Lower Proterozoic granitoids is supported by Tugarinov's studies (in Miguta 1997), which identified a lead isotope composition in galena associated with uranium ore similar to that of galena in Archean rocks.

The pre-uranium gold is considered to have a source related to Mesozoic magmatic chambers of mantle material while the post-uranium gold and silver, and the porphyry gold derived from shallower magmatic chambers (Boitsov VE and Pilipenko 1998).

Principal Ore Controls and Recognition Criteria

Location, shape, and dimensions of uranium-gold and uranium-gold-silver deposits are primarily controlled by reactivated ancient and neotectonic NW-SE-oriented and steeply SW dipping faults of Mesozoic age and surrounding pyrite-carbonate-potassium feldspar alteration zones. Significant ore-controlling parameters or recognition criteria of the major deposits in the Elkon District include:

Host Environment

- Archean-Early Proterozoic metamorphic and granitoid lithologies
- Granitoids with elevated uranium background
- Reactivated ancient and neotectonic NW-SE-oriented, steeply SW dipping faults of Mesozoic age

Alteration

- Pre-uranium multistage Mesozoic alteration processes are dominated by silicification, carbonatization, desilicification, feldspathization, and sulfidization and include from oldest to youngest:
  - Albite-sericite-chlorite
  - Pyrite-carbonate-potassium feldspar with dispersed gold

Table 10.8.

Aldan region, Agda deposit. Minor and trace element tenors in % of unaltered plagiogneiss, metasomatite, and ore-bearing breccias of apogneiss metasomatite (Miguta 1997)

Component	Granitized plagiogneiss	Apogneiss metasomatite	Ore-bearing breccia	Component	Granitized plagiogneiss	Apogneiss metasomatite	Ore-bearing breccia
U	<0.0002	0.062	0.38	FeO	4.15	2.04	1.33
TiO_2	0.90	1.02	1.27	Fe_2O_3	2.81	4.95	5.23
Pb	Traces	<0.01	<0.01	S_{total}	0.26	–	–
V_2O_5	0.02	0.07	0.06	SO_3	–	0.24	0.43
Nb_2O_5	n.d.	0.005	0.011	S_{sulf}	–	2.48	3.36
ZrO_2	0.01	0.01	0.02	F	0.16	0.08	0.06
As	<0.005	0.03	0.051	CO_2	1.37	5.34	5.56
W	n.d.	n.d.	<0.04	P_2O_5	0.44	0.53	0.43

  - Locally baryte-quartz with minor Fe-, Cu-, Zn- and Pb-sulfides
- Late and post-ore alteration includes carbonatization, silicification, fluoritization, sulfidization, and oxidation
- Fenitization related to Mesozoic alkaline intrusions

Mineralization

- Principal ore assemblages are gold-brannerite, gold-uraninite and brannerite-silver-gold
- Early gold is dispersed in pyrite of the pyrite-carbonate-potassium feldspar alteration facies
- Brannerite, the only primary U mineral, is superimposed on earlier gold mineralization
- Uraninite substituted brannerite in contact-metamorphic aureoles
- Late veinlets of native gold and silver overprint locally earlier mineralization
- U ore is restricted to pyrite-carbonate-potassium feldspar alteration zones intersected by NW-SE-oriented, steeply SW dipping faults
- Location, shape, dimensions of deposits is largely defined by brecciated intervals of faults
- Deposits consist of intermittently distributed ore bodies separated by barren or erratically mineralized ground
- Distribution, dimensions, and internal structure of ore bodies is defined by the brecciation degree of the host rock
- Ore bodies are of veinlike or columnar shape
- Internal structure of ore bodies is of stockwork or network nature composed of variably mineralized breccias, fractures, joints, and disseminations

Metallogenetic Concepts

A multistage metallogenetic evolution for the gold-uranium deposits of the Elkon District may be deduced from the work of Miguta (1997), Boitsov VE and Pilipenko (1998), and other authors.

The ore-forming process started with the gold-bearing pyrite-carbonate-orthoclase alteration event with most of the gold contained in pyrite. Subsequently, uranium was introduced into the previously altered rocks by hydrothermal fluids. Both processes occurred during the Mesozoic tectono-magmatic activation of the Aldan Shield. Uranium was deposited as brannerite under medium to low temperature conditions at medium to shallow depth and formed structurally controlled deposits in rejuvenated ancient and neotectonic Mesozoic fault zones. Due to the association of deposits and intrusions in space and time, it can be assumed that the hydrothermal process was initiated by the Mesozoic magmatic activity. Uranium probably derived from the Archean granitized rocks, which have an elevated uranium content. Uranium dissolution resulted from the interaction of ascending medium temperature, sulfide-carbonate-bearing solutions with granitized rocks. Posterior, the Au-Ag mineralization with native gold and silver minerals developed in some of the formerly generated U-Au zones in areas with Mesozoic intrusions as exemplified by the Fedorov zone.

It is noteworthy that there is no vertical zoning in the uranium zones of the Elkon District except for an immense quartz accumulation in the upper parts of the deposits. Mineralogical and chemical composition of ores are rather uniform over the drill intercepted interval, in the Yuzhnaya zone down to about 2000 m, which indicates relative stable conditions of ore deposition over a large vertical section presumably due to a homogenous environment.

Thermobarometric studies indicate pronounced variations of temperatures during the entire metallogenetic evolution of the Elkon ores and its individual stages as well. Successive mineral stages started constantly with higher temperatures than those at the end of the previous stage suggesting a multiphase influx of ore-forming fluids.

Where thermal metamorphism related to Mesozoic magmatic intrusions affected the brannerite mineralization, uraninite and Ti-oxide phases replaced the original brannerite. All post-brannerite processes only altered the original brannerite and redistributed uranium to form coffinite but they did not furnish new uranium.

10.5.1.1 Yuzhnaya Zone

The Yuzhnaya (southern) zone is by underground workings and up to 2 000 deep drill holes the best explored uranium zone in the Elkon Horst. Five large, more or less continuous gold-brannerite deposits are established, spread over a distance of about 20 km along the central section of the zone. They are arbitrarily defined as separate deposits, namely – from NW to SE – the *Elkon, Elkon Plateau, Kurung, Neprokhodimoye*, and *Druzhnoye* deposits. Each deposit consists of several northwesterly plunging ore bodies (Fig. 10.33).

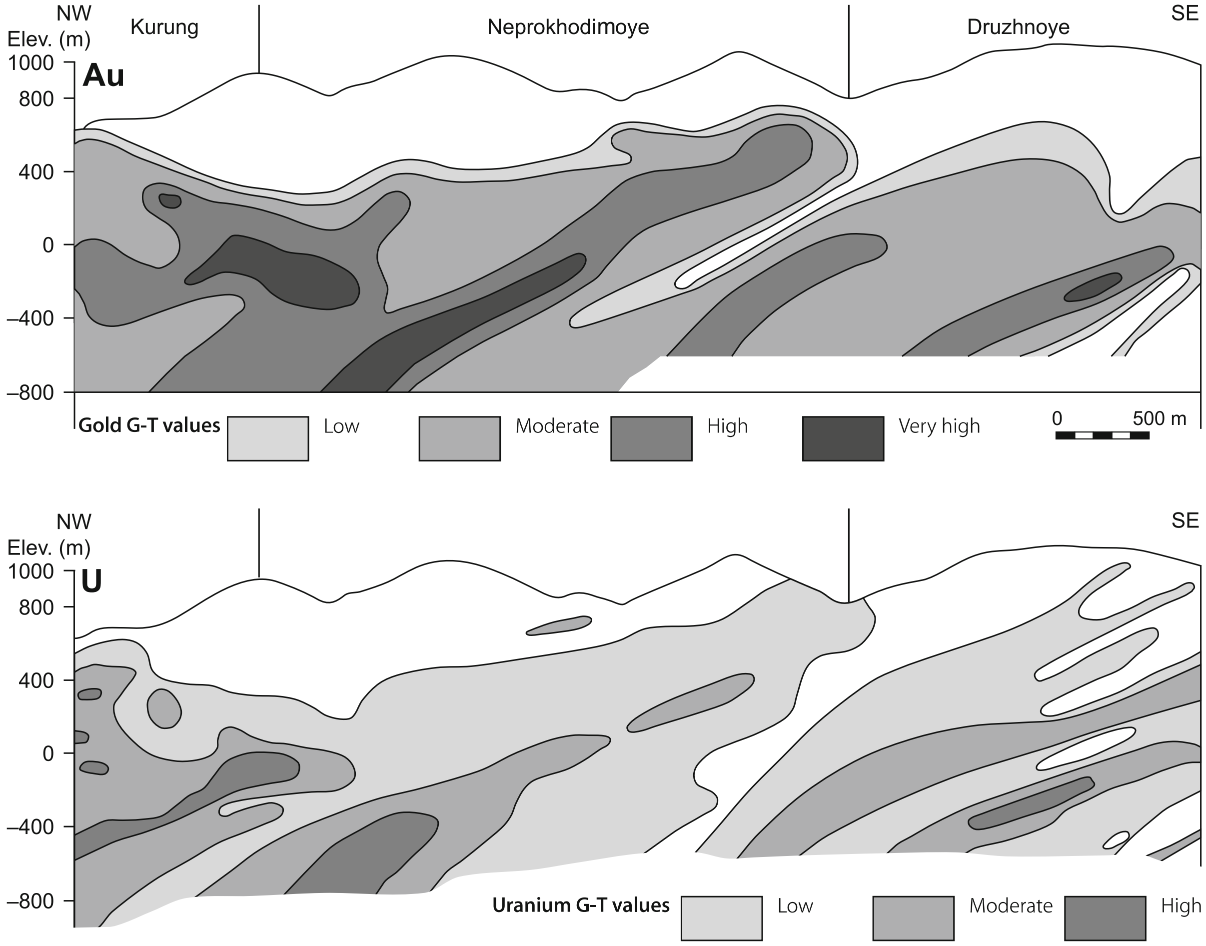
Ore control is by the NW-SE-trending and steeply SW dipping, approximately 30 km long and several hundreds of meters wide, ancient Yuzhnaya fault, which was reactivated during the Mesozoic, and by pyrite-carbonate-potassium feldspar altered rocks. Country rocks are Archean-Early Proterozoic ultrametamorphic lithologies. Mineralized sections are traced by blastomylonite imposed on Early Proterozoic metadiorite dikes.

The bulk of the ore is composed of brannerite and gold and related alteration products contained in breccias and, more rarely, in fractures cutting the altered host rocks. Ore bodies consist of closely spaced brannerite stringers and impregnations that group to en echelon arranged, linear, 500–700 m long along strike and dip, and 0.5–10 m wide ore bodies.

Upper limit of ore is at a depth between 200 m and 500 m. Depth persistence exceeds 2 000 m. Low ore grades of up to about 0.1% U prevail in upper levels, down to about 500–600 m. Grades increase downwards to 0.2% U and more at about 1 000 m and further below. Uranium and gold are spatially closely associated both along strike and dip, and show no signs of mineral changes and pinch out at explored depth suggesting that mineralization probably continues into greater than the drill intercepted depth. The spatial association is also documented by the fact that massive pyrite-carbonate-orthoclase alteration facies hold 72% of the whole gold of the Yuzhnaya zone and 62% of which is contained in uranium ore.

Late baryte-quartz and carbonate-quartz veins and veinlets accompanied by molybdenite mineralization occur in the upper, near-surface, low gold and uranium intervals at the southeastern flank of the Yuzhnaya zone. The here situated Druzhnoye deposit contains elevated amounts of molybdenite associated with a uranium mineral that was tentatively defined as a uranium oxide.

Fig. 10.33.
Elkon District, Yuzhnaya zone, NW-SE longitudinal section along the southeastern part of the structural zone with projection of grade-thickness values (or productivity) of gold (Au, upper section) and uranium (U, lower section) (after Boitsov VE and Pilipenko 1998 based on Prilensk PGO)



The ore minerals occur in few centimeters to 2.5 m wide, flattened stockworks composed of veinlets, and black, earthy masses, crusts and coatings within breccias (Boitsov VE and Pilipenko 1998).

10.5.1.2 Sokhsolookhsk Zone

The Sokhsolookhsk zone is several tens of kilometers long and contains gold-brannerite deposits including *Konkulaakh*. It parallels the Yuzhnaya zone at a distance of 5–6 km to the southwest. Similar to the Yuzhnaya, the Sokhsolookhsk zone is a reactivated old fault, but of en echelon nature and, in consequence, the gold-uranium mineralization is less continuous, although the mineral composition is the same. Ore bodies are roughly of the same size as those of the Yuzhnaya zone (Boitsov VE and Pilipenko 1998).

10.5.1.3 Severnoye, Pologaya, Vesennyaya, and Agdinsk (or Agda) zones

The Severnoye, Pologaya, Vesennyaya and Agdinsk (or Agda) zones contain gold-brannerite occurrences similar to those of the Yuzhnaya and Sokhsolookhsk zones. Ore bodies at Pologaya, Vesennyaya, and Agdinsk have a lenticular shape, are several tens of centimeters to 2 m thick and from several tens to several hundreds of meters long. Pologaya ore bodies are elongated down dip. Vesennyaya and Agdinsk have complexly shaped ore bodies at fault intersections (Boitsov VE and Pilipenko 1998).

10.5.1.4 Nadezhda and Interesnaya Zones

The Nadezhda and Interesnaya zones are in the northwestern sector of the Elkon District where Mesozoic intrusive stocks and dikes are abundant (Fig. 10.34). Both zones trend parallel, about 2 km apart, in NW-SE direction and are located close to the NW of a 700 m wide and 2 500 m long, alkaline intrusion. Gneiss around the intrusion is intensely fenitized. The Interesnaya zone is 1–5 m wide and largely controlled by displaced contacts of a vogesite dike. The Nadezhda zone is situated on the northwestern extension of the Sokhsolookhsk zone. At some distance from the intrusion, both zones are characterized by gold-bearing pyrite-carbonate-orthoclase altered facies with superimposed brannerite mineralization. This facies grades within the fenitization aureole, at a distance of about 500 meters from the intrusion, into narrow, up to 2 m wide, en echelon arranged bodies of fine-grained orthoclase-biotite-aegirine-augite-amphibole-magnetite rock cut by pyrite-bearing carbonate stringers. The pyrite contains grains of native gold and is locally accompanied by galena, chalcopyrite, pyrrhotite, and valleriite. Uraninite occurs associated with biotite, orthoclase, sphene, and pyrite in superimposed younger fractures.

Post-uraninite processes are testified by less than 1 m wide grorudite or sölvsbergite dikes, which cut the gold-uraninite ores. In turn, the dikes are traversed by veinlets composed of oligoclase, aegirine with Fe- and Cu-sulfides, pectolite, adularia, quartz, baryte, calcite, fluorite with sphalerite and galena. Gold was not found in the veinlets.

Ore bodies are small and of irregular configuration. They extend for several tens of meters along strike and dip but have better uranium grades than the brannerite-gold deposits. Early pyrite tends to be the essential host of native gold. Concentrates of the early pyrite yield values from 9.1 to 24.5 ppm Au (Boitsov VE and Pilipenko 1998).

10.5.1.5 Fedorovsk Zone

The Fedorovsk zone in the southwestern Elkon District carries brannerite-silver-gold mineralization. It occurs in an area with multiphase Mesozoic dikes. The structural zone is of Mesozoic

Fig. 10.34.

Elkon District, Interesnaya zone, geological sketch illustrating the relationship between U mineralization along the tectonic contact of a pre-ore vogesite dike; both are cut by syenite porphyry and grorudite dikes (after Miguta 1997)

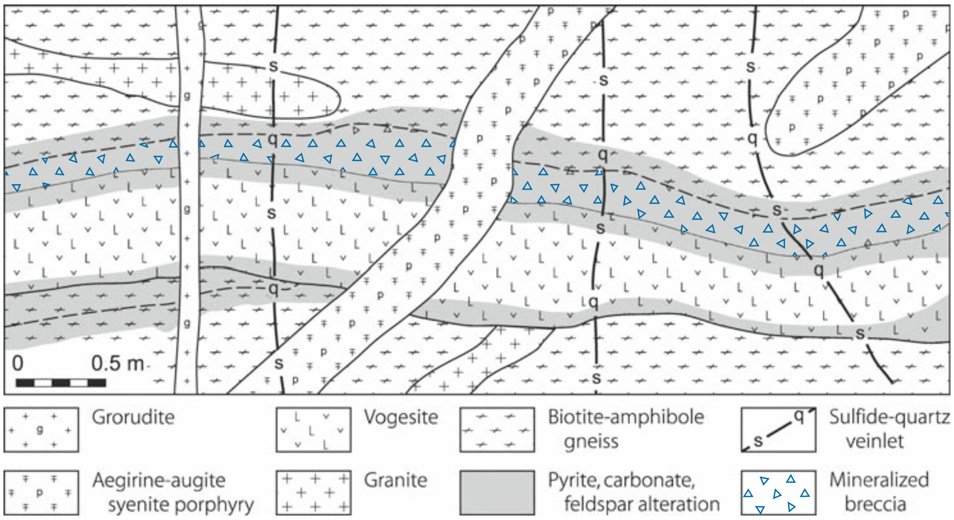
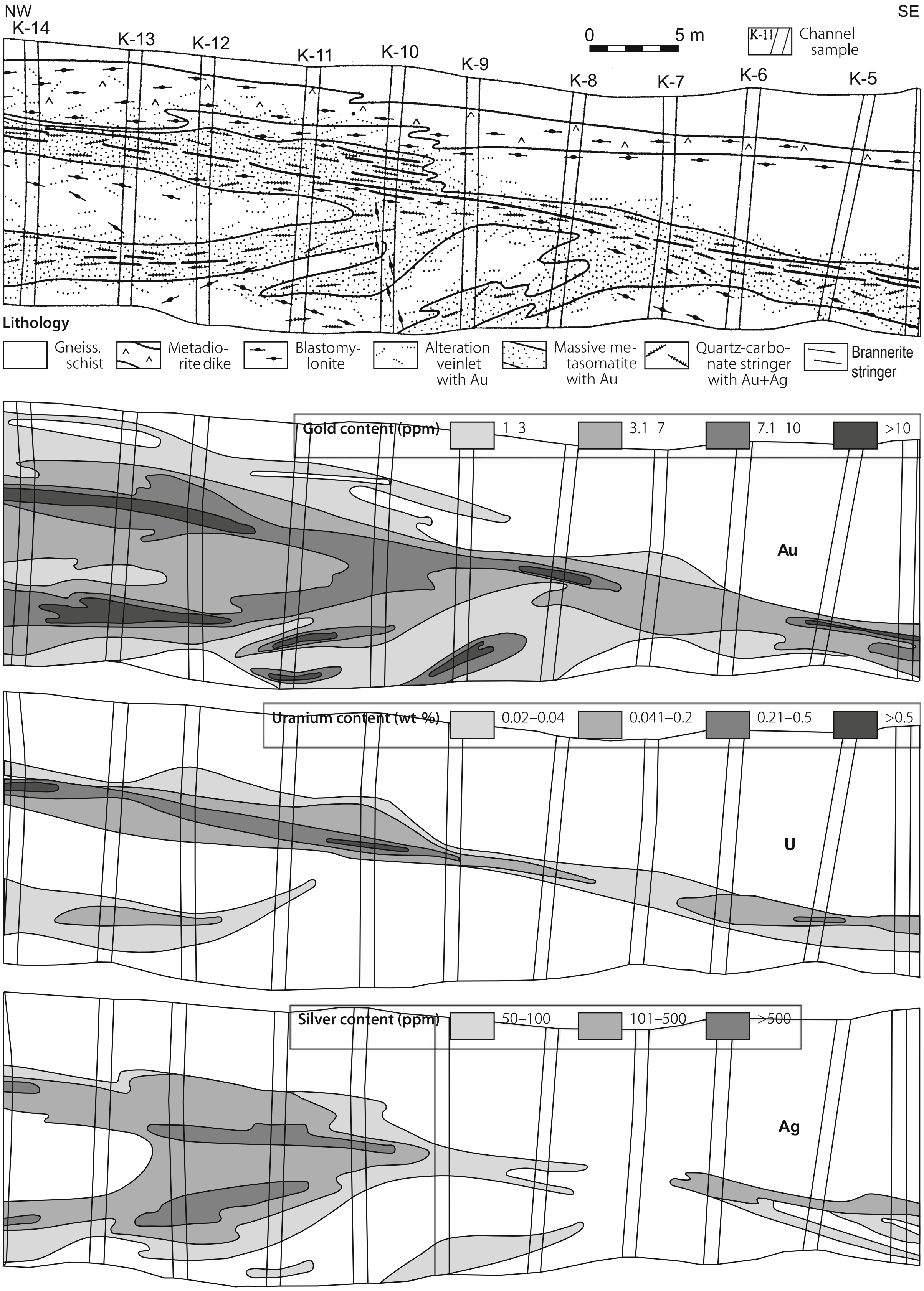


Fig. 10.35.
Elkon District, Fedorovsk zone, geological plan of a trench floor along a blastomylonite zone with distribution of gold (*Au*), uranium (*U*) and silver (*Ag*) grades (after Boitsov VE and Pilipenko 1998)



age, trends NW-SE for 10 km long and dips steeply to the SW. It largely follows metadiorite dikes and blastomylonites. Wall rocks are overprinted by post-fault gold-bearing pyrite-carbonate-orthoclase alteration. Massive metasomatic rocks are well developed. Structure controlled oxidation persists to a depth in excess of 300 m.

As far as established, mineralized sections can be as much as 30 m wide and persist at least to a drill indicated depth of about 1 000 m. Ore bodies are 1–2 m thick, several tens of meters long, and elongated down dip. They consist of gold-bearing metasomatic rocks intersected by thin brannerite stringers and a younger generation of small quartz and carbonate veinlets with pyrite, native gold, native silver, and acanthite. Although there is widely a close spatial coincidence of uranium, gold, and silver in the Fedorov zone, there are also some intervals where the late gold-silver-paragenesis prevails.

The altered melanocratic host rocks carry up to 15 vol-% of gold-bearing pyrite and up to 35 vol-% of carbonate. Due to the increased amount of gold-bearing pyrite coupled with the presence of the late gold-silver assemblage, the Fedorov zone carries markedly elevated tenors of gold and silver. Gold values commonly range from 3 to 10 ppm and silver from 15 to 200 ppm but local maxima can be in excess of 10 ppm Au and up to 1 400 ppm Ag. Most of the ore has U grades between 0.02 and 0.2% U but local enrichments exceed 0.5% U (Boitsov VE and Pilipenko 1998) (➲ Fig. 10.35).

10.5.1.6 Marsovaya, Mramornaya, and Zvezdnaya Zones

Some additional zones with brannerite-gold-silver mineralization were discovered to the southwest of the Fedorov zone. They include the Marsovaya and Mramornaya zones in neotectonic Mesozoic faults and the Zvezdnaya zone controlled by a reactivated ancient blastomylonite structure. Mineralization of these zones consists of native gold- and silver-bearing carbonate veinlets and an erratic distribution of both, early gold-bearing pyrite-carbonate-orthoclase alteration and brannerite mineralization. Ore bodies at Marsovaya have a lenticular shape, are several tens of centimeters to 2 m thick and from several tens to several hundreds of meters long and elongated down dip (Boitsov VE and Pilipenko 1998).

10.6 Amur and Ussuri Rivers Region/Far East Region

Several small uranium deposits and occurrences are reported from this region. They are grouped in two U districts as described below.

10.6.1 Khankaisky District

The Khankaisky District is situated to the northeast of the town of Vladivostok. Estimated total resources of the district are reportedly 25 000 t U. Four small deposits have been explored. Resources of individual deposits range from several hundreds to several thousands tonnes of uranium. Grades are less than 0.1% U.

Sinegorskoye and *Fenix* are volcanic vein-type deposits. They contain U-Mo mineralization in quartz-sericite-hydromica/beresite altered Devonian rhyolite close to a leucogranite body. *Lipovskoye* is a metasomatite vein-stockwork deposit hosted by an up to 50 m wide albitized cataclastic zone within skarn-altered Cambrian continental carbonate rocks adjacent to Devonian granite. *Rakovskoye* is of basal-channel sandstone type. It consists of elongated, up to 1 km long, 100 m wide, and 5–10 m thick ore lenses in Cenozoic lignite-bearing sandstone that fills a paleochannel incised into granite. Coffinite and sooty pitchblende are the principal ore minerals.

10.6.2 Bureinsky District

This district is located to the northwest of the town of Khabarovsk. Nine small uranium deposits are reported. Five of which, *Lastochka, Kamenushinskoye, Skalnoye, Svetloye*, and *Tigrovaya Pad*, are of volcanic vein-stockwork type associated with Cretaceous felsic volcanics (rhyolite and felsite) similar to deposits in the Streltsovsk District. Four deposits, *Molodezhnoye, Osenneye, Sentyabrskoye*, and *Sularinskoye*, are of metasomatite vein-stockwork type hosted in Upper Paleozoic rocks altered to beresite and albitite.

Total resources of the Bureinsky District are estimated at 29 000 t U in the high cost category. Ore grades range from 0.03 to 0.2% U. 3 900 t U (RAR + EAR-I) of the Bureinsky resources are contained in the underground explored *Lastochka* deposit. Lastochka was discovered in 1965 in the southern part of the Bureinsky Massif, to the north of the Amur River. Nearest town is Khabarovsk in 100 km distance to the SE of the deposit. Vein-stockwork lodes occur in felsite of a small Upper Cretaceous caldera. Paleozoic granites form the basement. U minerals include pitchblende, sooty pitchblende, β-uranotile, and uranophane. In situ ore grade is 0.1–0.2% U.

10.7 Okhotsk Region

The Okhotsk U region is located to the west and northwest of the town of Okhotsk on the Sea of Okhotsk. Exploration in this region began in the early 1950s (by Dalstroi organization) and led to the discovery of U occurrences, e.g. *Tas-Kastabyt* and *Butuguchag*, in granite massifs in the Magadan District. Subsequent exploration in neighboring terrane resulted in the discovery of volcanic-type U occurrences associated with the Uliya and Kuidusun volcanogenic depressions in Khabarovsk territory and the adjacent Sakha-Yakutia Republic and Magadan territory.

Source of information: The subsequent description is a synopsis of the paper by Kirillov and Goroshko (1997), who elaborate on the geological environment and mineralogy of U occurrences in the Okhotsk region but do not give any data on resources and grades. They note, however, that most occurrences are small, of limited vertical and lateral extent, and of low grade except for some deposits with economic potential.

Regional Geological Setting of Mineralization

The U-hosting *Uliya* and *Kuidusun* volcanogenic depressions are situated in the western Okhotsk segment of the Okhotsk-Chukotka marginal continental volcanic belt. Tuffaceous sediments, lavas, subvolcanic intrusions, and intrusive rocks constitute the principal lithologies. These rocks are grouped into four volcano-plutonic complexes, which were emplaced during four main episodes of igneous activity.

The Khakarin Complex is made up of Paleogene basalt and basaltic andesite.

The Urak Complex consists of Late Cretaceous tuffs, ignimbrites, and felsic lavas. These rocks differ from the Amka rocks (see below) by the presence of glass, larger amounts of subvolcanic and extrusive formations, and a considerable abundance of comagmatic intrusive rocks. In addition, the volcanics of this complex are more silicic and contain more alkalis, especially potassium, as compared to the Amka volcanic rocks.

The Amka Complex comprises the Late Cretaceous Khetanin Formation (andesite, basaltic andesite, and basalt) and the Amka Formation (tuff, ignimbrite, and minor dacitic andesite, dacite, rhyodacite, and rhyolite lavas intercalated with tuffaceous sediments as well as scarce subvolcanic and extrusive bodies).

The Okhotsk Complex includes the Early Cretaceous Alan Formation (mainly continental tuffaceous sediments) and the Ulberikan Formation (andesite, basaltic andesite, and related tuffs).

The Cretaceous volcanics rest upon Archean metamorphic rocks, Proterozoic quartzose or quartz-feldspar sandstones, and Devonian volcanogenic lithologies of the Okhotsk Massif. Major faults trend NNW to NNE, and NW-SE.

Principal Host Rock Alteration

Alteration phenomena relate to the wide variety of lithologies and presumably also to variations in hydrothermal solutions. Prominent alteration features include early stages of greisenization, followed by propylitization, beresitization, argillization, and silicification. Albitization and carbonatization developed locally. Beresitization (particularly of sericite-hydromica facies) and argillization reflect the most typical alteration of wall rocks associated with U mineralization. (For more details see description of individual types.)

Principal Characteristics and Types of U Mineralization

Most U occurrences are hosted in uraniferous felsic intrusive and extrusive volcanic rocks of the Cretaceous *Urak Complex*. One U occurrence was found in Devonian volcanics. U mineralization is structurally controlled and occurs preferentially in large, submeridional fault zones that border volcanogenic depressions in the Okhotsk Massif.

U minerals include pitchblende, nasturan (sooty pitchblende?), uraninite, brannerite, uranothorianite, and a great variety of uranyl hydroxides, silicates, phosphates, arsenides, and molybdates. U-bearing minerals are thorite, fergusonite, betafite, samiresite (U-bearing pyrochlore). U is also concentrated in goethite (0.2–0.3% U), pyrite (up to 0.3%), fluorite (up to 0.3%), orthite (0.7%), sphene (0.05%), wolframite (0.1%), and plant remains (up to 0.4%). Arsenic (<2%) is the most abundant accessory element. Other frequently-associated elements (present in fractions of a percent) are Cu, Pb, and Zn. Other metals that may or may not be locally present include Ag, As, Au, Bi, Mo, Nb, Sb, Th, V, Y, and Zr.

Uraniferous mineral assemblages can be grouped into two principal ore types:

1. U mineralization in mostly beresitized and/or argillized rocks. Based on predominant minerals, this assemblage can be subdivided into three subtypes: *(a)* pitchblende (nasturan)-sulfide, *(b)* pitchblende-quartz, and *(c)* pitchblende-hydromica; and
2. REE-Th-U mineralization in apatite-orthite metasomatite and pegmatites.

Geotectonic Setting of U mineralization

Kirillov and Goroshko (1997) recognized four geotectonic settings of U mineralization: (1) superimposed terrigenous basins, (2) volcano-tectonic depressions, (3) extrusive volcanic domes, and (4) intrusive domes, in which the authors identified the following fourteen types of U mineralization based on lithological setting, wall rock alteration, and mineralogy. Types 1–5 are enveloped by clay-altered wall rocks and types 6–11 by beresitized wall rocks.

Type 1: Argillized sections in superimposed terrigenous depressions

The *Atandzhakan* occurrence is the only known example for this environment. It is a U-V occurrence located on the western side of the Uliya Basin in argillized, carbonaceous tuffogenic sediments of the Early Cretaceous Alan Formation. The tuffaceous unit is intercalated with siltstone, sandstone, and greywacke and rests upon Precambrian granite. Host rock alteration is reflected by argillization that was superimposed on propylitization. Altered facies are characterized by chlorite, chalcedony, hydrosericite, kaolinite, montmorillonite, quartz, and limonite. Sulfides are scarce.

Mineralization occurs in several stratiform bodies, up to 20 m in thickness, in the lower Alan Formation. Mineralized horizons typically contain up to 10% organic matter. Better grade mineralization is concentrated at ore intersecting faults. U minerals include pitchblende (nasturan) and more abundant U^{6+} minerals. Some U is in apatite, pyrite, limonite, and plant remains. U minerals form nests, veinlets, and elongated masses. Ag, Cu, Mo, Pb, V, and Zn occur in elevated concentrations. U mineralization was dated at 89–119 Ma.

Atandzhakan mineralization may be to some extent comparable with U-V mineralization of the Salt Wash Formation on the Colorado Plateau.

Type 2: Argillized sections in volcano-tectonic depressions

Rocks of volcano-tectonic depressions that are altered by argillization (kaolinite and hydrosericite) contain locally small occurrences of pitchblende (nasturan) associated with galena.

Type 3: Argillized sections in volcanic domes and extrusive viscous-lava bodies

Felsic lava sheets and extrusive bodies of the Urat Complex contain structurally controlled small U occurrences in poorly eroded areas of the *Uliya Basin*. Mineralization is related to argillized sections (kaolinite, hydrosericite, and colloform quartz) that often occur in zones of fumarolic and solfataric alteration.

An exception with economic potential is the *Mulachen* deposit. This deposit is controlled by NE-SW-trending faults cutting brecciated felsite, trachydacite, dacite, and rhyolite tuff. In mineralized zones, host rocks exhibit an alteration succession from adularization to argillization (kaolinite, hydrosericite), and to extensive silicification (quartz, opal, chalcedony). Mineralization consists of U^{6+} minerals, dominated by uranophane, which often occur in opal masses in association with jarosite. Associated minerals are sulfides and, less commonly, cornwallite, scorodite, and fergusonite. Ore has elevated contents of Ag, As, Au, Mo, Pb, and Sb. U-Pb isochronal ages range between 127 and 72 Ma.

Type 4: Argillized sections in intrusive domes

Intrusive domes of the Tas-Kastabyt granite massif at the NE margin of the Okhotsk Massif host U occurrences in argillized intervals. Gabbro and granodiorite constitute the main petrographic phase of the massif while porphyry-like quartz diorite and subalkaline leucocratic granite with xenoliths of metamorphic rocks form a later phase. Uranium is mainly concentrated in porphyry-like granite. This granite was intruded into Triassic clastic sediments and contains up to 9 ppm U in subparallel NW-SE-trending extensive fault zones that enclose belts of glassy rhyolite and felsite dikes.

Type 5: Argillized contact zones of dikes cutting sandstone

Contact zones between sandstone and intrusive dikes host locally linear zones with strike-persistent U mineralization. U minerals occur as disseminated particles and veinlets. Brecciated ore textures are also noted. Axial parts of mineralized zones are dominated by argillic (mainly kaolinite), while margins are dominated by beresitic alteration (sericite-hydromica with minor chlorite and carbonate locally). Argillization is superimposed on tourmaline-muscovite greisens and beresites. Uranium mineralization is more abundant in beresitized than in argillized rocks.

Pitchblende is the principal primary U mineral. U^{6+} minerals include uranyl arsenates and phosphates, enriched in copper and lead. Age dating yields 60–50 Ma for U mineralization. Ore contains sulfides and elevated concentrations of As, Cu, F, Sn, and Zn but these minerals/elements are of pre-uranium origin and presumably are related to the greisenization phase.

Type 6 and 7: Beresitized sections in volcanic domes and extrusive lava

Beresite-altered sections in or at (sub)volcanic domes and extrusive, low-viscosity lava bodies of felsite or rhyolite composition with elevated background U concentrations are favorable sites for many U occurrences. Denominated U occurrences include *Vinto-Khalyya, Druzhnoye, Raduzhnoye*, and *Zergan* in the *Kuidusun Basin*, and *Amagaran, Iskra*, and *Kotla* in the *Uliya Basin*.

U mineralization is commonly bound to small domal edifices situated within larger volcanic structures, mainly within volcano-tectonic depressions. Ore bodies are fault controlled and occur within and adjacent to these subvolcanic and extrusive bodies.

In spite of similar structural settings and identical wall rock alteration, ore bodies have variable ore compositions: The *Zergan* occurrence is characterized by abundant fluorite; *Druzhnoye* by chloritization and diverse non-radioactive minerals; *Raduzhnoye*, *Kotla*, and *Vinto-Khayya* by the almost absence of non-radioactive minerals. These differences are believed to be the result of geochemical different hydrothermal solutions. Accordingly, some occurrences contain complex U mineralization, whereas others consist of practically monometallic uranium. In more detail:

Type 6: Mineralization associated with intrusive domes

Numerous U showings have been discovered in beresitized Devonian volcanic rocks around the Uliya Basin, and north of the Verkhnemaiskiy intrusion, where Devonian volcanics occur in the central part of an intrusive dome of Mesozoic diorites and leucogranites.

Most uranium is hosted by the Taabyrdaakh Formation (felsic lava, ignimbrite, and tuff) in which it occurs in breccias with a hematite-quartz matrix. NW-SE, NE-SW and W-E faults control mineralized sections. These faults are located in a major NE-SW-trending fault zone, which is characterized by dike swarms and a large area (12 × 2 km) of beresitic alteration.

Wall rocks are altered by beresitization that developed after greisens. The beresite assemblage includes quartz, sericite, hydromica (schilkinite), ankerite, calcite, goethite, hydrogoethite, chlorite, baryte, and rutile. Uranium was deposited as pitchblende when the beresitization stage changed from sericitization to hydromicazation. Pitchblende occurs as thin veinlets, nests, or disseminated particles in cryptocrystalline quartz aggregates. Secondary U minerals include silicates, and uranyl phosphates and arsenates. Ag, As, Cu, Pb, Sb, and Zn occur in substantial amounts (samples contain more than 3% As, Pb, and Sb, and more than 1% Cu). Mo ranges locally up to 0.05%. Sulfides, mainly galena and pyrite, are common ore constituents.

U-Pb dating indicates three episodes of U deposition: 390–370 Ma (Devonian), 215 Ma (Triassic), and 150–110 Ma (Cretaceous). K-Ar dating of micas in altered wall rocks yields ages of 332 and 110 Ma. Mesozoic tectonomagmatic reactivation fragmented the original ore and fragments were transported into Triassic sediments and Lower Cretaceous tuffogenic sediments of the Alan Formation. U ore pebbles in Triassic deposits evidence the Paleozoic age of initial U deposition.

Type 7: Mineralization in extrusive viscous lava bodies

The *Druzhnoye* occurrence provides an example for Mesozoic U mineralization for this environment. Druzhnoye is located in the Nyut volcanic-tectonic depression, which is filled with volcanic and volcanogenic-sedimentary rocks of the Arnka and Urak complexes. NW-SE and NE-SW faults control the position of ore bodies. Wall rocks consist of beresitized volcanics of the Amka Complex and rhyolite extrusions of the Urak Complex. Three beresite facies are identified: muscovite-sericite, sericite, and sericite-hydromica. Higher-temperature products are replaced by low-temperature phases. Uranium associated with chamosite and carbonate was deposited during the late alteration stage. U minerals are pitchblende and, less commonly, uraninite; they occur as disseminated particles and intermittent veinlets. U^{6+} minerals are mainly silicates and minor hydroxides and phosphates as well as uranyl molybdates. Uranium is closely correlated with Co and Ni, which are concentrated in chlorite, and with Ba and Sn as well. Associated minerals include sulfides of As, Pb, Mo, Sb, and Zn; commonly formed in pocket-like masses. Emplacement of Mo and U mineralization was not coeval as indicated by a lack of U and Mo correlation. Mo minerals crystallized during a feldspathization event, whereas U minerals formed during beresitization dated at 90–100 Ma.

Type 8: Beresite overprinted by hornfels contact metamorphism

U occurrences in hornfels adjacent to subvolcanic intrusions of the Urak Complex (e.g. *Tarakan* and *Ketanda*) derived by contact metamorphism that locally overprinted progenitor U mineralization in beresitized rocks similar to that noted under types 6 and 7. As a result, ore was locally redistributed; pitchblende recrystallized to uraninite, and hornfels-related minerals, mainly biotite, were formed.

At *Tarakan*, mineralization is controlled by N-S-trending faults that cut beresitized rhyolites and their tuffs in a volcanic dome with widespread subvolcanic rhyolite intrusions. Neoformed minerals are andalusite, actinolite, muscovite, and garnet of an early stage, and chlorite, biotite, hydrobiotite, spinel, and sulfides of a later stage. Pitchblende and uraninite are associated with hydrobiotite and spinel. Late stage (?) sulfides are abundant. As, Bi, Cu, F, Pb, Th, and Y occur in elevated concentrations.

Type 9: Beresitized volcanogenic sediments in volcanotectonic depressions

The central Kuidusun volcanotectonic depression hosts U mineralization in beresitized volcanogenic sediments. An example is the *Astra* occurrence; it is hosted in tuffaceous siltstone with carbonized plant remains that is cut by a N-S-trending fault zone. Beresites are of hydromica facies and contain fluorite, chlorite, carbonate, and hematite. Small pitchblende grains are enclosed in plant remains. Ore has elevated concentrations of As, Mo, Pb, and Zn. Age dating gives 110–90 Ma for the ore formation.

Types 10 and 11: Beresitized intrusive rocks

Beresitized intrusive rocks of the Arkhimed and Pestraya complexes in the eastern *Nyut-Ulbei batholith* contain numerous small U occurrences. The eastern part of the *Arkhimed Massif* consists of medium-grained biotite granite and small stocks or sheets of fine-grained subalkaline granite dated at 76–74 Ma (K-Ar). Beresitic alteration is concentrated along fissures that accompany major NW-SE- and N-S-trending faults. U minerals include pitchblende, U-silicates, and metatorbenite. Ag, Bi, Cu, Pb, Sn, and Zn occur in elevated concentrations. In the *Pestraya Massif*, U mineralization occurs at the contact of xenoliths of sediments in granodiorite or subalkaline quartz diorite, and in NE-SW- and N-S-trending fault zones. Wall rocks are altered by beresitization that overprinted earlier greisens. U mineralization comprises only U^{6+} minerals that form nests and veinlets, and was dated at 70–60 Ma.

Type 12: Albitized felsic volcanics

This type is scarce and is characterized by prominent albitization with some hematite, chlorite, and apatite alteration of felsic volcanics along steeply dipping faults. The *Bulakag* U occurrence is an example. It is controlled by a NE-SW fault that transects ignimbrites of the Urak Formation in the central Kuidusun Basin. Alteration phases include extensive early propylitization followed by a later event with significant removal of potassium (from 4–5% to roughly 0%) and addition of sodium (from 2 to 6%). Mineralization forms a lenticular, steeply dipping ore body. Masuyite is the principal U mineral. Hematite contains up to 0.3% U. Mo, Pb, and As occur in high concentrations. Age dating yields 132–104 Ma for the ore formation.

Type 13: Metasomatized syenite porphyry

Syenite porphyry intrusions of the *Nyut-Ulbei batholith* that were modified by orthite-apatite metasomatism host U mineralization in the form of closely spaced, subparallel veinlets within cataclastic zones. Uraniferous minerals include apatite, orthite, and minor monazite, zircon, and Y-rich uranothorianite.

Type 14 Alaskitic gneiss-granites and pegmatites

Alaskitic gneiss-granite and pegmatite of the crystalline basement contain numerous small occurrences of U and, more commonly, Th or U-Th mineralization. Uranothorianite is the prevailing U-bearing mineral. It occurs as disseminated grains that are locally concentrated to loosely packed accumulations. Zones of these accumulations usually show evidence of high-temperature quartz-microcline metasomatism.

Metallogenetic Aspects

In summary, Kirillov and Goroshko (1997) provide the following metallogenetic concept:

U occurrences in the Kuidusun and Uliya Basins are of volcanic type and are associated with intrusive and extrusive volcanic rocks of variable age. U-Pb dating documents repeated mineralizing events during Devonian, Cretaceous, and Paleogene episodes of tectonomagmatic activity; but the most productive episode of U mineralization was related to Late Mesozoic revival of tectonomagmatic activity in the Okhotsk Massif.

The mode of U mineralization and wall rock alteration suggest that most of these U occurrences were generated by metasomatism. Residual melts of shallow magma chambers are thought to have served as a U source. Uranium transport, deposition, and wall rock alteration resulted from low temperature residual hydrothermal solutions. These fluids were active during the waning emplacement phase of magmatic bodies, and commonly affected autometasomatised zones of previous greisenization and propylitization.

10.8 Southern Kalyma River Region

One deposit, *Butugichag* (Butygychagskoye), is reported from the southern Kalyma River, about 250 km NW of the town of Magadan on the north coast of the Okhotsk Sea. This vein-type U deposit was hosted in Mesozoic granite and formerly mined. It is depleted. Reserves were reportedly between 1 500 and 5 000 t U.

10.9 Chukotsky Region

The region is between the Arctic Ocean and the Bering Sea in the extreme northeast of Asian Russia. Five deposits are recorded, four of volcanic vein-stockwork type associated with Jurassic calderas (*Severnoye, Katumskoye, Chaika,* and *Keef*) and one of lignite type (*Chaplinskoye* at the Bering Sea) hosted in Jurassic continental sediments. All deposits have low grades of less than 0.1% U, and are small in size containing few hundreds to few thousands tonnes of high cost uranium. *Severnoye*, located 80 km to the east of the settlement of Pevek at the East Siberian Sea, was formerly mined and is depleted.

References and Further Reading for Chapter 10 · Russian Federation – Asian Territory

For details of publications see Bibliography.

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