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Metallogeny of Siberia: tectonic, geologic and metallogenic settings of selected significant deposits*

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Siberia has a prominent position in Russia, in terms of mineral resources and mineral production including copper, nickel, PGM's, uranium, molybdenum, tungsten, tin, manganese, gold, silver, lead, tantalum–niobium, rare earths, diamonds and many other mineral commodities. These resources are represented by a vast array of mineral systems and deposit styles in their respective terranes spanning the Precambrian and Phanerozoic geological history. These mineral systems include VHMS and SEDEX lead–zinc, orogenic gold, sediment- and shear-zone hosted to intrusive-related silver to silver-tin, alkaline gold to gold–uranium and uranium, porphyry copper and copper–molybdenum, epithermal gold, gold–silver, silver, gold–antimony, mercury, uranium–fluorite, various granite-related deposits (W, Mo, Sn, Be, Ta, Co–Ni, etc.) including those associated with peralkaline granites (Nb–Ta–Zr–REE), skarn iron, lead–zinc, gold, tungsten, carbonatite tantalum–niobium, niobium–REE and REE, magmatic copper–nickel–PGM sulfide, PGM and mafic intrusion-hosted iron–titanium–vanadium deposits, and diamondiferous kimberlites. Some deposits are large and superlarge including the well-known Noril'sk nickel–copper–PGM and Udokan copper deposits, the Sukhoi Log, Olympiada, Nezhdaninskoe, Kubaka, Kupol gold deposits, the Dukat and Prognoz silver deposits, and the Yakutian diamondiferous kimberlites. Apart from the above-mentioned giant deposits, several others are poorly known and/or unknown to western geoscience. The study of these mineral systems can significantly contribute to our further understanding of the metallogeny of cratons and orogenic belts, orogenic collages, and anorogenic settings. This provides additions to, and further development of, existing classifications and genetic models of mineral systems, allowing researchers to elucidate unknown or poorly studied mineral systems and styles found in Siberia, and to search for some other important styles that appear to be missing, although they are present in other regions with similar geological and tectonic settings.

KEY WORDS: metallogeny, mineral deposits, Siberia, tectonic settings.

INTRODUCTION

In western literature, Siberia encompasses a vast territory, extending from the Ural mountain range in the west to the Pacific coast in the east. However, Russians geographically distinguish Western Siberia from the Ural mountains to the Yenisei River, Eastern Siberia from the Yenisei River to the Pacific coast, the Russian Far East as the southern part of the Pacific coast region, and the Russian Northeast as the northern part of the Pacific coast region. However, in this paper we consider Siberia as a whole in the sense adopted by western literature.

Siberia has a prominent position in Russia, in terms of mineral resources and mineral production (copper, nickel, PGM, uranium, molybdenum, tungsten, tin, manganese, gold, silver, lead, tantalum-niobium, rare earths, diamonds and many other mineral commodities). In particular, Siberia accounts for some 70% of the Russian copper resources (60 of 86 Mt), 98% of the PGM resources (13 of 13.3 kt), 95% of the uranium

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*Appendix 1 [indicated by an asterisk (*) in the text and listed at the end of the paper] is a Supplementary Paper; copies may be obtained from the Geological Society of Australia's website (URL <http://www.gsa.org.au>) or from the National Library of Australia's Pandora archive (URL: <http://nla.gov.au/nla.arc-25194>).

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resources (520 of 550 kt), 80% of the gold resources (8.7 of 10.9 kt), 85% of the molybdenum resources (1540 of 1840 kt), 90% of the tungsten resources ($\sim$200 of 225 kt WO_3), 100% of the tin resources (2250 kt), >90% of the lead resources (18.3 of 19.9 Mt), 70% of the zinc resources (43.5 of 62 Mt) and 80% of the silver resources (87 of 110 kt) [in the measured and indicated resource categories* (data as of 01.01.2008 from URL <http://www.mineral.ru>)]. An essential part of these resources is concentrated in the large and superlarge deposits including the well-known giant Noril'sk nickel–copper–PGM and Udokan copper deposits. The Sukhoi Log, Olympiada, Nezhdaninskoe, Kubaka and Kupol gold deposits host the majority of gold resources, while the Dukat and Prognoz silver deposits host world-class silver resources. The Yakutian kimberlites are host to world-class diamond deposit reserves.

Siberia is the region where many important mineral deposit styles and settings are present, which have been recognised and studied in detail. These studies have enabled Soviet, Russian and Western geoscientists to enhance developing models of ore genesis and wider-context metallogenic concepts applicable to various deposit styles pertaining to those present in Siberia. Most recently, new conceptual approaches, such as those of plate tectonics-related metallogenic zonation, mantle-plume tectonics and related metallogeny, have given rise to reconsideration of many regional to local tectonic settings of mineral deposits in Siberia. This is discussed in a series of important publications on leading metallogenic projects completed during the last decade including those on the metallogeny and mineral deposits of the Northern Pacific (Parfenov *et al.* 1995, 1999, 2003; Nokleberg *et al.* 1996; Nokleberg 2010), Siberian mantle-plume metallogeny (Borisenko *et al.* 2006; Pirajno *et al.* 2009), geology, metallogeny and mineral deposits of selected regions (Yakubchuk *et al.* 2005; Khanchuk 2006) and metallogeny of selected mineral deposit types in Siberia (Konstantinov *et al.* 2000; Kremenetsky *et al.* 2000; Frolov *et al.* 2003; Struzhkov & Konstantinov 2005; Levitan 2008; Struzhkov *et al.* 2008). A further series of publications has contributed to a better understanding of many of the important large and superlarge deposits of Siberia (Rundqvist 2004, 2006).

This paper endeavours to outline the most important mineral deposit types and selected individual deposits identified in Siberia, some of which are unknown and/or poorly represented in English language geoscience literature. A substantial body of knowledge comes from unpublished studies carried by the authors of this paper, many within the programs supported and/or sponsored by CERCAMS. In this contribution, besides providing an overview, we briefly describe the most significant and better studied representatives of the Siberian mineral systems and attempt to assign them to geotectonic and metallogenic settings. This makes it possible to emphasise their characteristic features, suggests new directions for mineral deposit and metallogenic studies in Siberia, and through this understanding provide useful vectors for new discoveries. We do not discuss in detail the Noril'sk Ni–Cu and diamondiferous kimberlites, as these mineral systems are well represented in the international literature. A list of the individual deposits treated in this paper is presented in Table 1. In addition, a more comprehensive list including 179 deposits, their main commodities, by-products, ore minerals and associated rocks, is provided in Appendix 1*. The position of the deposits discussed in this paper are shown in Figure 1.

TECTONIC AND GEOLOGICAL FRAMEWORK

Siberia incorporates several large tectonic terranes: (i) the Siberian craton (or platform); (ii) the Western Siberian Lowland; (iii) the Neoproterozoic–Paleozoic orogenic belts, adjoining the Siberian craton to the north and south; (iv) the Late Paleozoic–Mesozoic orogenic belts adjoining the Siberian craton to the east; and (v) the Cretaceous–Tertiary Okhotsk–Chukotka volcanic belt overprinting easterly orogenic belts (Parfenov *et al.* 2003). Smaller tectonic features such as Precambrian shields and microcontinents are distinguished within the craton and respective orogenic belts. Significant anorogenic and intraplate tectonic and magmatic events and associated metallogenic epochs were probably caused by several pulses of, and/or protracted mantle plume activity, which affected both the Siberian craton and surrounding orogenic belts (Figure 1). Below we describe key geological and tectonic features of the Siberian terranes that are important in relation to understanding their metallogeny.

Siberian craton

The Siberian craton occupies a large portion of Eastern Siberia, being bordered by the Yenisei and Lena Rivers to the west and east, respectively (Figure 1). The cratonic basement is composed of metamorphic and magmatic Archean rocks (gneisses, crystalline schists, charnockites, enderbites, anorthosites) and is exposed in the Precambrian Anabar and Aldan Shields and also in smaller uplifted blocks along the craton's periphery. It is believed that the Siberian craton might have formed part of the Columbia and Rodinia supercontinents (Rogers & Santosh 2004). Within these supercontinents, the Siberian craton had its northern edge along the present western margin of the North American cratonic blocks, whereas the southern margin of Siberia might have been facing a present northern margin of Australia. After the breakup of Rodinia, due to spreading ridges between the Australian and Siberian cratons, Siberia was translated 5000 km towards Eastern Europe for about 500 Ma (Yakubchuk 2008).

The Siberian cratonic platform cover has been forming since the Mesoproterozoic and between the Mesoproterozoic and the start of the Neoproterozoic (1600–800 Ma, commonly referred to as Riphean in Russian literature) and comprises several sedimentary and volcanic sequences of Mesoproterozoic, Vendian–

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*Russian 'reserves' of the $A+B+C_1+C_2$ categories are roughly equivalent to measured and indicated resources (Henley & Young 2009; Diatchkov 1994; Jakubiak & Smakowski 1994).

Table 1 Selected mineral deposits of Siberia mentioned in the text.

Selected examples	No. in Figure 1	Latitude	Longitude	Figure no.
1 Sediment-hosted stratiform				
Udokan (Cu)	39	56.53	118.36	2
2 Sedimentary exhalative sulfides and oxides (SEDEX)				
Gorevskoe (Pb–Zn)	31	58.12	93.55	3
Kholodninskoe (Zn–Pb)	35	56.22	109.82	4
Kholzunskoe (Fe)	34	50.33	84.38	–
3 Volcanic-hosted massive sulfide (VHMS)				
Ozernoe (Zn–Pb–Ag)	32	52.97	111.58	5
Kyzyl–Tashtyg (Pb–Zn–Cu)	–	52.02	95.98	–
Korbalikha (Zn–Cu–Pb)	33	51.18	82.22	–
Rubtzovskoe (Zn–Pb–Cu)	33	51.48	81.48	–
4 Carlin-like type				
Kuranakh (Au)	17	59.02	125.62	–
5 Orogenic lode/stockwork shear zone-hosted to intrusive-related				
Sukhoi Log (Au)	16	58.6	115.23	6
Natalka (Au)	22	61.65	147.73	7
Olympiada (Au)	15	59.88	92.91	8
Nezhdaninskoe (Au)	18	62.52	139.15	–
Sarylakh (Sb–Au)	27	64.28	142.78	–
Sentachan (Sb)	–	66.48	137.05	–
Maiskoe (Au)	21	68.98	173.79	9
Prognoz (Ag)	24	65.73	133.2	–
Mangazeya (Ag)	24	65.77	130.57	–
6 Epithermal volcanic-associated vein/stockwork				
Kupol (Au–Ag)	20	66.79	169.55	11
Dukat (Ag)	23	62.72	155.28	12
Kubaka (Au–Ag)	26	63.7	159.97	–
Baley (Au–Ag)	29	51.58	116.65	–
Taseevskoe (Au–Ag)	–	51.55	116.65	–
Pokrovskoe (Au)	–	53.23	126.35	–
Palyanskoe West (Hg)	–	69.01	172.32	–
Plamennoe (Sb–Hg)	–	68.23	176.92	–
Kyuchus (Au–Hg–Sb)	19	69.8	134.75	–
Strel'tsovskoe (U–Mo–Fl)	37	50.07	118.23	13
7 Granite-related hypothermal/mesothermal vein/stockwork/greisen				
Lebedinskoe (Au)	17	58.5	125.48	–
Klyuchevskoe (Au)	–	53.53	119.43	–
Zun-Kholba (Au)	–	52.13	101.0	–
Darasun (Au)	28	52.34	115.49	10
Mnogovershinnoe (Au)	30	53.95	139.97	–
Deputatskoe (Sn)	55	69.26	139.97	–
Spokoininskoe (W)	–	51.05	114.87	–
Iul'tin (Sn–W)	54	67.87	178.77	–
Pyrkakai (Sn)	56	69.41	171.95	–
Pravo-Urmiiskoe (Sn)	–	50.5	134.88	–
Bom-Gorkhon (W–Bi)	58	51.32	109.35	–
Solnechnoe (Sn)	53	50.77	136.4	–
Arsenyevskoe (Sn)	–	44.42	134.79	–
Pogranichnoe (Fl–Be)	52	44.33	132.30	–
Voznesenskoe (Fl–Be)	52	44.28	132.32	–
Ermakovskoe (Be, Fl)	–	51.6	109.48	–
Dzhida (W–Mo)	47	50.28	103.45	14
Kalguty (Mo–W)	42	49.41	88.12	15
Khapcheranga (Sn)	57	49.73	112.35	16
Khovu-Aksy (Co–Ni–U)	38	51.16	93.73	–
8 Peraluminous Li–F granite-associated and granitic pegmatites				
Orlovka (Ta–Nb–Sn)	50	51.03	114.75	17
Etyka (Ta–Nb–Sn–Li)	51	51.0	116.87	–
Goltsovoe (Ta–Nb–Li)	49	52.94	101.18	–
Vishnyakovskoe (Li–Ta)	48	55.22	97.75	–
Belorechinskoe (Li)	–	52.83	101.12	–
Kyiskoe (REE)	–	59.25	91.53	–
9 Porphyry				
Peschanka (Cu–Au–Mo)	40	66.6	164.5	18
Sorskoe (Mo–Cu)	41	54.0	90.2	–

(*continued*)

Table 1 (*Continued*).

Selected examples	No. in Figure 1	Latitude	Longitude	Figure no.
Shakhtama (Mo–Cu)	–	51.28	117.9	–
Zhireken (Mo–Cu)	–	52.83	117.35	–
Ryabinovoe (Cu–Au)	–	58.63	125.92	–
Aksug (Cu–Mo)	–	53.45	96.60	–
Bystrinskoe (Au–Cu)	45	51.48	118.57	–
Bugdaya (Mo–W–Au)	44	51.15	117.72	–
10 Skarn				
Nikolaevskoe (Pb–Zn)	–	44.60	135.55	19
Dalnegorskoe (B)	46	44.55	135.58	–
Savinskoe (Pb–Zn)	–	50.45	117.98	–
Vostok–2 (W–Cu)	43	46.50	135.90	20
Lermontovskoe (W)	–	46.87	134.43	–
Abakan (Fe)	10	52.52	90.08	–
Sinyukha (Au)	25	51.83	85.75	–
11 Iron oxide–copper–gold (IOCG)				
Angara-Ilim ore district:				
Rudnogorskoe (Fe)	11	57.25	103.70	–
Korshunovskoe (Fe)	12	56.53	104.13	–
Aldan shield:				
Sivagli (Cu–Co–Fe)	14	57.48	125.53	–
Seligdar (REE–Fe–apatite)	13	58.60	125.18	–
12 Peralkaline rock-associated				
Katuginskoe (Ta–Nb–REE)	6	56.28	119.18	21
Zashikhinskoe (Ta–Nb–Zr–REE–Sn)	8	53.60	98.75	–
13 Carbonatite-associated				
Tomtor (REE–Ta–Nb)	5	70.82	117.46	22
Beloziminskoe (Nb–Ta)	7	53.57	100.55	23
Karasug (REE–Fe)	9	51.32	92.10	–
14 Kimberlite/lamproite-hosted diamond				
Mir	–	62.52	113.98	–
Udachnaya	–	66.43	112.32	–
Internatsionalnaya	–	62.46	113.71	–
15 Mafic intrusion-hosted				
Chiney (Fe–Ti–V, Cu)	4	56.53	118.56	–
16 Magmatic sulfide				
Noril'sk (Cu–Ni–PGE)	1	69.30	88.40	–
Talnakh (Cu–Ni–PGE)	–	69.45	88.35	–
Oktyabrskoe (Cu–Ni–PGE)	–	69.52	88.43	–
Kingash (Cu–Ni–PGE)	3	54.90	95.45	–
17 Magmatic pge				
Kondyor (PGE)	2	57.66	134.583	24
18 Other types				
Elkon (U–Au–Mo)	36	58.78	126.22	–

Location data: WGS84 datum. A list of 179 Siberian mineral deposits with coordinates and further details is given in Appendix 1*.

Cambrian, Ordovician–Silurian, Devonian–Lower Carboniferous, Upper Carboniferous–Middle Triassic, Upper Triassic–Cretaceous and Cenozoic age. These rocks are intruded by various igneous suites, including basalts (Siberian traps), ultramafic–alkaline rocks, carbonatites and kimberlites.

Anabar and Aldan Shields

The Anabar and Aldan Shields are the largest uplifts of ancient basement within the Siberian craton (Figure 1). The Anabar Shield is composed of Archean and Proterozoic sequences including granulite facies metamorphosed plagiogneisses and mafic rocks dated at 3.1–3.0 Ga, and plagiogneisses, charnockites and enderbites dated at 2.4 Ga (Zlobin *et al.* 2002). These rocks have been overthrusted by granite–greenstone terranes dated at 2.4–2.3 Ga, with cross-cutting 2.1–1.8 Ga granites. The total thickness of metamorphic sequences exceeds 20–25 km.

The Aldan Shield is also composed of Archean and Proterozoic metamorphic sequences. Large granite cupolas or domes are the oldest igneous elements and their cores are composed of amphibolitised and migmatitic Archean metabasites (mostly pyroxenites) and ∼3.6 Ga enderbites, metamorphosed under granulite-facies conditions. The cupolas are surrounded by younger rocks (3.3–3.1 Ga), such as amphibolites, amphibole–pyroxene and amphibole–biotite crystalline schists, dolomites, metamorphosed under amphibolite-facies conditions. The Archean is represented by (3.1–2.9 Ga) greenstone belts that are mostly composed of amphibolites, granite–gneisses and metabasites (Jahn *et al.* 1998; Orlov & Malich, 2002; Smelov & Timofeev 2005). The Archean sequence is intruded by large plutons of plagiogranites,

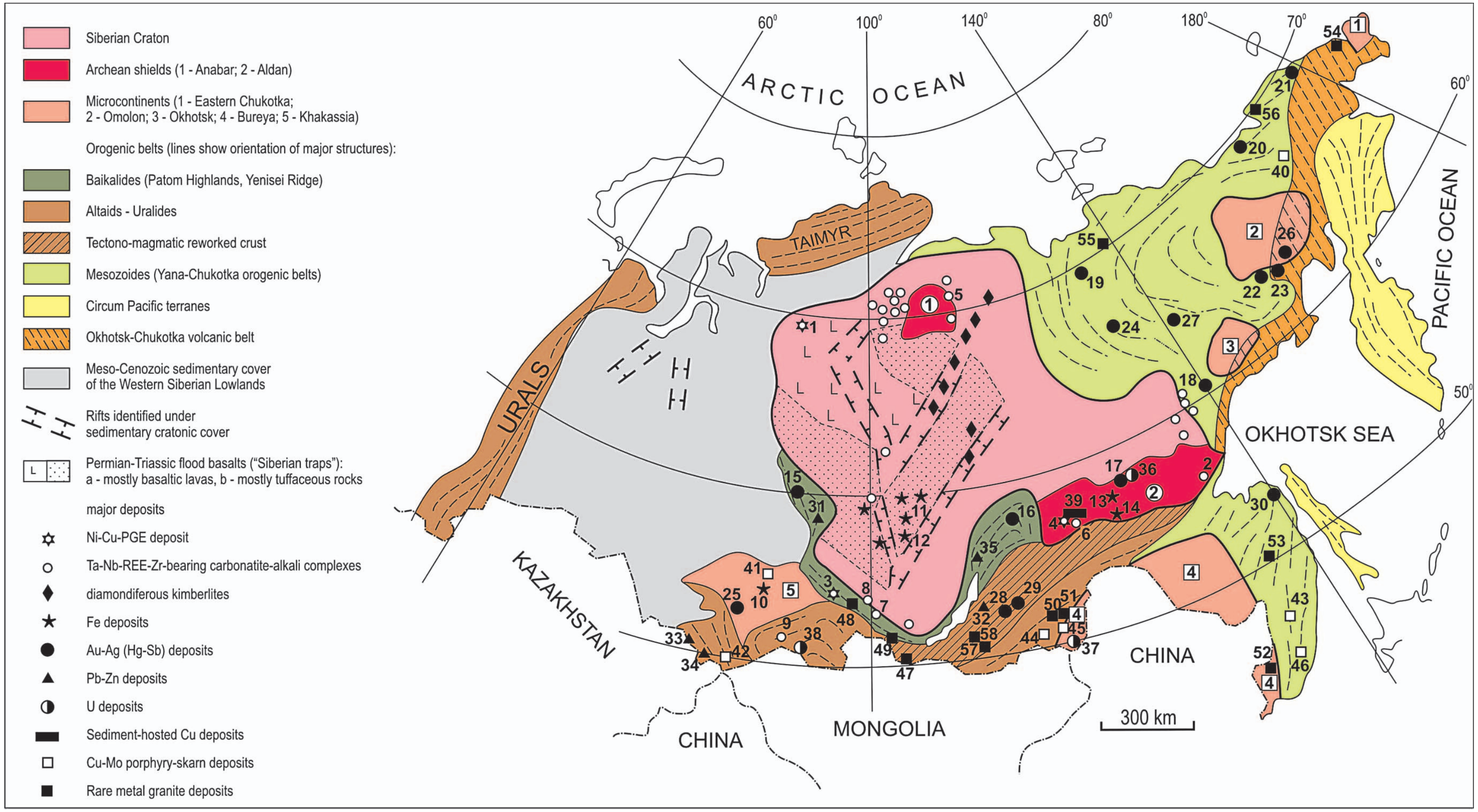

Figure 1 Major terranes, tectonic structures and mineral deposits of Siberia. Key to numbered deposits (see also Table 1): 1–4, Ni–Cu–PGE deposits (1, Noril'sk, 2, Kondyor; 3, Kingash; 4, Chiney); 5–9, Ta–Nb–REE–Zr-bearing and other carbonatite and peralkaline granite complexes (5, Tomtor; 6, Katuginskoe; 7, Beloziminskoe; 8, Zashikinskoe; 9, Karasug); 10–14, Fe, Fe apatite and Fe–Cu deposits (10, Abakan; 11, Rudnogorskoe; 12, Korshunovskoe; 13, Seligdar; 14, Sivagli); 15–30, Au–Ag (Hg–Sb) deposits (15, Olympiada; 16, Sukhoi Log; 17, Kuranakh and Lebedinskoe; 18, Nezhdaninskoe; 19, Kyuchus; 20, Kupol; 21, Maiskoe; 22, Natalka; 23, Dukat; 24, Prognoz and Mangazeya; 25, Sinyukha; 26, Kubaka; 27, Sarylakh; 28, Darasun; 29, Baley; 30, Mnogovershinnoe); 31–35, Pb–Zn and Fe sediment- and volcanic-hosted deposits (31, Gorevskoe; 32, Ozernoe; 33, Korbalikha and Rubtzovskoe; 34, Kholzunskoe; 35, Kholodninskoe); 36–38, U and Ni–Co deposits (36, El'kon; 37, Strel'tzovskoe; 38, Khovu-Aksy); 39, Sediment-hosted Cu deposits (Udokan); 40–46, Cu–Mo porphyry skarn, W skarn and Pb–Zn skarn deposits (40, Peschanka; 41, Sorskoe; 42, Kalguty; 43, Vostok-2; 44, Bugdaya; 45, Bystrinskoe; 46, Dalnegorskoe); 47–58, Sn–W and other rare-metal granite-related and pegmatite deposits (47, Dzhida; 48, Vishnyakovskoe; 49, Goltsovoe; 50, Orlovka; 51, Etyka; 52, Pogranichnoe and Voznesenskoe; 53, Solnechnoe; 54, Iul'tin; 55, Deputatskoe; 56, Pyrkakai; 57, Khapcheranga; 58, Bom-Gorkhon).

tonalites (trondhjemites) and potassic granites, as well as anorthosites and gabbro-anorthosites assigned to the Paleoproterozoic. Peralkaline biotite, amphibole, and riebeckite granite intrusives are also present. There are also several younger (Neoproterozoic?) ultramafic–alkaline–carbonatite complexes (e.g. Kondyor and Inagli). The Archean and Proterozoic rocks are discordantly overlain by subhorizontal Mesoproterozoic–Vendian (750–550 Ma) and Cambrian carbonate sequences that represent cratonic cover.

Proterozoic terranes of the Yenisei Ridge and Patom Highlands

These two orogenic belts, adjoin the western (southwestern) and southern (southeastern) edges of Siberian craton, respectively (Baikalides in Figure 1). They include Archean terranes (crystalline schists, granulites, gneisses) and predominating thick Mesoproterozoic–Neoproterozoic sequences. The latter are composed of metamorphosed shales, sandstones, siltstone, and minor marbles, dolomites and amphibolites that formed on passive continental margins (Obolenskyi *et al.* 1999). Precambrian granitic and mafic alkaline rocks are locally present. In places, the Precambrian sequences are unconformably overlain by Lower Cambrian carbonate rocks.

Western Siberian Lowland

The Western Siberian Lowland (Figure 1) is comparable in size to the Siberian craton and underlies most of Western Siberia. It is situated west of the Siberian craton and is bordered by the Yenisei River to the east and Ural Mountain Range to the west. To the south, the Western Siberian Lowland extends geographically to the Russia–Kazakhstan border, further to the southwest it is adjoined by the Altai–Sayan orogenic belts and, to the north, by the Arctic Ocean. A large orogenic system referred to as the Yenisei Ridge separates southern parts of the Western Siberian Lowland and Siberian craton. The basement of the Western Siberian Lowland comprises Precambrian and Paleozoic folded structures of the Uralian–Mongol orogenic superbelt, specifically the Altai–Sayan orogenic belt in southwest Siberia, and immediately east of the Urals. However, for the most part in Western Siberia, the basement is overlain by thick (4–6 km) Mesozoic–Cenozoic (Triassic and younger) cover comprising terrigenous sedimentary rocks. These cover rocks host giant oil and gas deposits.

Neoproterozoic–Paleozoic orogenic belts of Northern and Southern Siberia

The Taimyr–Novaya Zemlya orogenic belt adjoins the Siberian craton in northwestern Siberia. This terrane is separated from the Siberian craton by the Yenisei–Khatanga trough composed of Triassic–Oligocene marine–terrigenous sedimentary rocks, and has Baikalian (Neoproterozoic–Mesoproterozoic) metamorphic basement, with inclusion of Archean blocks (microcontinents). This basement is rimmed to the north by Mesoproterozoic–Devonian terrigenous–carbonate rocks, and to the south by Ordovician–Triassic terrigenous-carbonate rocks with minor basalts.

Orogenic belts of Southern Siberia are part of the Central Asian Orogenic Belt or the Altaid orogenic collage. In particular, as noted by Obolenskyi *et al.* (1999), the Central Asian Orogenic Belt experienced several stages of geodynamic processes in the course of its transition from (i) a Mesoproterozoic continental margin of the Siberian craton, which evolved from the breakup of Pangea to accretion–collisional orogens in the late Neoproterozoic, through (ii) the Vendian–Early Paleozoic and then (iii) formation of Middle Paleozoic island arcs and active continental margins, and (iv) corresponding belts of collisional and post-collisional granitoids; finally (v) intraplate Mesozoic igneous complexes and rifting occurred.

The Altai–Sayan orogenic system adjoins the eastern part of the Western Siberian Lowland and western part of the Siberian craton to the south (Figure 1) and is part of the Altaid orogenic collage (Sengor *et al.* 1993). This orogenic system incorporates several smaller separate terranes including the Altai (Russian side), Kusnezk Alatau, Western Sayan and Eastern Sayan, Tuva–Sangilen and Tuva–Mongol terranes. The complex Central Asian Orogenic Belt accretion–collision orogenic system is characterised by a transition from Neoproterozoic orogens close to the Siberian craton toward younger Early and then Middle Paleozoic orogens, at increasing distances from the craton. This orogenic collage represents parts of the Neoproterozoic, Mesoproterozoic–Vendian and Paleozoic island arcs, active and passive continental margins, oceanic sequences (ophiolites, oceanic plateaux, oceanic islands), turbidite basins, continental slopes and shelves accreted to the Siberian craton (Obolenskyi *et al.* 1999; Gordienko 2001, 2006). Archean and Proterozoic blocks (microcontinents) are also present.

Similarly, the large Mongol–Transbaikalian, or Mongol–Okhotsk orogenic belt adjoins the southeastern margin of Siberian craton and extends for over 3000 km from Central Mongolia to the Okhotsk Sea and Pacific Ocean (Parfenov *et al.* 1995, 2003; Zorin 1999; Kravchinsky *et al.* 2003). Formation of this belt began in the Mesoproterozoic–Vendian as a continental margin of the Siberian craton, and was followed by opening and partial closing of Mongol–Okhotsk paleo-ocean (forming a large gulf within the Paleopacific ocean) in the Paleozoic, with the emplacement of collisional and post-collisional granitoid batholiths in the Late Paleozoic.

Final closure of this ocean occurred in the Early to Middle Jurassic and was followed by widespread intraplate magmatism up to the Cretaceous.

Yana–Chukotka orogenic superbelt

This Mesozoic orogenic superbelt adjoins the Siberian craton to the east and extends to the Pacific Ocean (Mesozoides in Figure 1). It incorporates several terranes, or smaller orogenic belts, including: (i) the Verkhoyansk foreland and related anticlinorium immediately adjoining Siberian craton; (ii) the Yana–Kolyma thrust and fold belt; (iii) the Kolyma and

Omolon microcontinents; and (iv) the Oloy and Chukotka terranes. Formation of this superbelt began in the Mesoproterozoic on the eastern passive continental margin of Siberian craton, and culminated in the Late Paleozoic–Mesozoic (Permian–Early Jurassic) with the deposition of thick (10–12 km) terrigenous sandstone–shale sequences, locally with minor volcanic rocks. In the Late Jurassic–Cretaceous, this succession was folded, faulted and intruded by granitic batholiths. These rocks now form the Verkhoyansk and Yana–Kolyma terranes.

The Kolyma microcontinent divides the Yana–Kolyma terrigenous belt from the Oloy and Chukotka terranes and comprises Archean and Proterozoic rocks surrounded by Ordovician–Carboniferous largely carbonate sequences. Besides the Kolyma microcontinent, the superbelt incorporates several smaller continental blocks such as Omolon, Okhotsk, Taiganoss and Chukotka microcontinents. These microcontinents are also composed of Paleoproterozoic crystalline schists overlain by Mesoproterozoic, Paleozoic and Mesozoic rock successions.

Okhotsk–Chukotka volcanic belt

This Mesozoic–Cenozoic volcanic belt is superimposed over the eastern part of the Yana–Chukotka orogenic superbelt and thus divides this orogenic system from the Cenozoic Koryak–Kamchatka orogen situated further east (Figure 1). As a result, the Okhotsk–Chukotka volcanic belt has a Mesozoic basement composed of Upper Triassic, Jurassic and Lower Cretaceous sedimentary and volcanic sequences and is unconformably overlain by thick (locally >5 km) Lower and Upper Cretaceous and younger (up to Paleocene) volcanic sequences. The rocks are represented mostly by rhyolite (ignimbrite), andesite and basaltic volcanics.

Further south along the Pacific coast the Okhotsk–Chukotka volcanic belt evolves into the Sikhote–Alin orogen (Figure 1). The latter is characterised by abundant volcanics including Late Cretaceous rhyolites (ignimbrites), Late Cretaceous–Paleogene rhyolite–dacite, Late Paleogene rhyolite–basalt–andesite suites, and Neogene andesite and basalt.

Intraplate (or intracontinental) tectonic and magmatic activity

The Siberian terranes have experienced several intense intraplate anorogenic tectono-thermal events. These events are characterised by the presence of various igneous suites within the Siberian traps, alkaline igneous suites, ultramafic-alkaline intrusions, carbonatites, kimberlites and lamproites. These magmatic events have been ascribed to mantle plume activity (Yarmolyuk *et al.* 2000; Dobretsov 2005; Borisenko *et al.* 2006).

In particular, the Siberian traps constitute one of the most voluminous lithological packages of Paleozoic–Mesozoic cover on the Siberian craton, and are estimated to have an extent of around 7×10^6 km^2, including continental low-Ti tholeiitic flood-basalts, their possible feeders and comagmatic sill-like intrusions (Ivanov *et al.* 2008). Siberian flood volcanism that caused formation of the traps was likely a phenomenon of worldwide importance triggering a mass-extinction event and possibly defining the Permian–Triassic (~250 Ma) boundary (Kamo *et al.* 2003). It is generally recognised that the traps formed mostly flood-basalt lavas in the northern and northwestern parts of Siberian craton, and volcaniclastic sequences in the southern parts of the craton. The giant Noril'sk nickel–copper–PGM deposit is hosted in mafic sills associated with the traps.

Intraplate tectonic and magmatic processes also resulted in emplacement of diamondiferous and barren Siberian (Yakutian) kimberlites at numerous locations in the Siberian craton, between the Devonian and the Mesozoic.

Mesozoic tectonic and magmatic processes also affected other ancient terranes of the Siberian craton. In particular, in the Aldan Shield, these processes included tectonic restructuring, with the formation of rift-associated depressions and horsts. This was accompanied by emplacement of numerous alkaline plutons and associated volcanic rocks. These depressions host Mesozoic (Jurassic) coal-bearing continental terrigenous sequences that include sandstone, siltstone, minor conglomerate, argillite, commonly with coal seams. Middle and Upper Jurassic volcanogenic–sedimentary units contain trachyte, and pseudoleucite porphyry tuffs, tuff breccias, ignimbrites, Mesozoic lamproite dykes, sills and stocks (pipes) are along the southern margin of the Aldan Shield.

In the Altai–Sayan and Mongol–Okhotsk orogenic belts, the anorogenic processes included formation of various alkaline igneous suites. In particular, in the Transbaikalian segment of the Mongol–Okhotsk belt, Jurassic–Cretaceous rifting processes resulted in the formation of high-K and shoshonitic suites that are also host to widespread gold mineralisation.

METALLOGENIC EVOLUTION IN SPACE AND TIME

The vast territory of Siberia has indeed experienced long-lasting metallogenic evolution since the Early Precambrian, caused by various regional and global factors. Work conducted by a number of researchers has provided an understanding of the major features of tectonic–metallogenic features of many important mineral systems, respective metallogenic belts and provinces. The metallogenic evolution of Siberia has been summarised by Obolenskyi *et al.* (1999), Gordienko (2001), Distanov *et al.* (2006) and other authors. These authors generally agree that the metallogenic evolution of the Siberian craton and surrounding orogenic terranes is typified by the multiple occurrence of passive and active continental margins followed by terrane accretion toward the Siberian craton, with the formation of the Central Asian Orogenic Belt, Mongol–

Okhotsk and other orogenic collages and corresponding development of the consolidated orogenic systems outward. This has resulted in a series of subparallel metallogenic belts, incorporating similar deposit associations, which become progressively younger further away from the craton.

However, this repetition of tectonic processes has caused metallogenic overprinting represented by the development of similar deposits, but of different ages, within the same terranes. Pokalov (1984) was probably the first to have distinguished two metallogenic associations of Paleozoic and Mesozoic age: (i) porphyry molybdenum deposits in southern and southeast Siberia; and (ii) gold plus copper–gold mineral systems. Similarly, Komarov & Tomson (1995) distinguished three major tectonic–magmatic cycles of magnetite skarns, rare metal greisens, gold-sulfide, lead-zinc, uranium, fluorite, gold-silver, and antimony–mercury mineralisation in southeast Siberia. Correspondingly, continuing tectonic–magmatic activity in the Altai–Sayan and Mongol–Okhotsk orogenic belts and possibly cycles of mantle-plume activity, caused multiple generations of anorogenic igneous suites and related mineralisation within Siberian craton itself. The most productive metallogenic epochs are briefly described below.

Archean epoch

The Archean metallogeny of Siberia is still poorly understood. Nevertheless, there are strong indications for the presence of Archean gold and especially uranium mineralisation in some terranes, although none appear to be economic at present. Of greater significance are the Archean iron oxide deposits and occurrences (banded iron-formations) represented by metamorphosed volcanic–sedimentary ironstone deposits such as the large Nizhne–Angarskoe iron deposit. The latter contains some 3 Gt of ore averaging ~40 wt% Fe. Iron, gold, uranium and possibly other (such as komatiite-hosted Cu–Ni) mineralisation may be related to Archean granite–greenstone belts.

Paleoproterozoic epoch

The Paleoproterozoic metallogenic epoch is characterised by the formation of greenstone belts and numerous rift structures. These were accompanied by emplacement of potassic granitoid suites (e.g. Kodar suite in southeastern Siberia), mafic–ultramafic plutons hosting nickel–copper mineralisation (e.g. Chiney pluton), peralkaline granitic suites surrounded by haloes of intense metasomatism, with large faults and associated niobium–tantalum–REE–zirconium (e.g. Katugin deposit) and uranium mineralisation. Large iron oxide (±copper) deposits (such as Taezhnoe, Des and Sivagli) that show similarities with deposits of the IOCG (iron oxide copper–gold) family (Soloviev in press b), as well as metasomatic apatite deposits (such as Seligdar, Ukduska) situated on the Aldan Shield, are of Paleoproterozoic age (2.2–1.8 Ga). The super-large sediment-hosted Udokan copper deposit is also situated in a Paleoproterozoic trough.

Neoproterozoic–Mesoproterozoic–Vendian epoch

According to Distanov *et al.* (2006) and other authors, this metallogenic epoch included formation of passive continental margins along the periphery of the Siberian craton, also with mantle-plume activity and further break-up of the Rodinia supercontinent. The pericratonic troughs focused intense magmatic activity, submarine volcanism and related hydrothermal mineralisation. This has resulted in the formation of large SEDEX lead–zinc, stratiform iron and manganese deposits, and the enrichment of black shales in gold. Later accretion formed a regional-scale ophiolite belt extending from southwestern to southeastern Siberia, which hosts important gold, gold–antimony and other deposits. Vernikovsky *et al.* (2003) recognised at least two events of emplacement of collisional granitoids corresponding to the initial Late Mesoproterozoic collision of island arcs and microcontinents and to the major Vendian collisional–orogenic event. This was accompanied by formation of lineament zones, bordering the Siberian craton and leading to the establishment of Southern Siberian pericratonic metallogenic belt incorporating tantalum–niobium–REE deposits associated with peralkaline granites and carbonatites (e.g. Belaya Zima carbonatite).

Early–Middle Paleozoic epoch

The Early Paleozoic (Vendian–Silurian ~600–400 Ma) epoch was characterised by the formation of volcanic island arcs, peripheral continental volcano-plutonic belts, and collisional granitoids, in an active continental margin overprinting older orogenic terranes and microcontinental fragments of the Siberian craton. Island arc volcanism was accompanied by formation of VHMS deposits (Kyzyl–Tashtyg), volcanogenic–exhalative and skarn iron deposits. Pre- and syn-collisional gabbro–monzonite–granite and granitic suites were also emplaced. These are accompanied by iron oxide (e.g. Telbess), copper, copper–molybdenum porphyry and related skarn, vein, stockwork, and skarn gold and gold–sulfide deposits (e.g. Natalya, Berikul and Saraly). In turn, these igneous suites were accompanied by post-collisional calc-alkaline and peralkaline granitoids.

The Middle Paleozoic (Devonian–Early Carboniferous ~400–300 Ma) epoch was also characterised by active continental margins formed over heterogeneous basement incorporating terranes of the preceding passive and active continental margins and microcontinents. This was accompanied by the formation of rift systems and respective volcanic–plutonic belts. According to Distanov *et al.* (2006), this epoch was particularly well developed in southwest Siberia (e.g. the Altai region), where Devonian–Early Carboniferous volcanic–plutonic belts were formed. These are Cordilleran-type magmatic arcs superposed on Ordovician–Silurian basement and include suites of basalt–rhyolite associated with numerous and commonly large VHMS deposits of the Eastern Kazakhstan and Russian Altai (e.g. the Korbalikha and Rubtsovka deposits). Within these rift systems, significant copper, iron, iron–copper deposits were also formed. Pre- and syn-collisional granitoid suites were accompanied by copper and copper–molybdenum porphyry systems (e.g. Sorskoe), tungsten–molybdenum–beryllium greisens and molybdenum stockwork deposits, and intrusive-related gold and epithermal gold–silver, lead–zinc–silver, and fluorite deposits.

Late Paleozoic–Mesozoic epoch

The Late Paleozoic–Mesozoic (Permian–Cretaceous ~260–100 Ma) epoch was dominated by intraplate anorogenic tectonic and magmatic activity in Western and Eastern Siberia, and by orogenic processes in the Yana–Kolyma orogenic superbelt.

These intraplate anorogenic processes included formation of rift troughs and grabens, fault-controlled depressions, and have resulted in emplacement of numerous igneous suites in Siberia. These include the previously mentioned and well-known Siberian traps, and alkaline plutonic and volcanic suites in the Aldan Shield. Peralkaline, alkaline (shoshonitic) and calc-alkaline plutonic and volcanic suites in many orogenic systems of the Altaids, and various carbonatite, kimberlite, lamproite and other suites are related to this epoch. These suites are associated with world-class mineralisation including the Noril'sk nickel–copper–PGM deposits, Angara–Ilim and other iron oxide deposits, tantalum–niobium–REE-bearing carbonatites and peralkaline granites, rare-metal-bearing lithium–fluorine granites, various lead–zinc, copper–gold, gold–sulfide, gold deposits, tin–tungsten greisens, and molybdenum stockwork deposits.

Many authors correlate these intraplate anorogenic processes with the development of a widespread Permian–Triassic mantle plume or superplume activity. In particular, Borisenko *et al.* (2006) suggested that regional metallogenic zonations associated with the Mesozoic Siberian superplume indicate that older nickel–copper–PGM deposits occur towards the plume centre, zoning outwards to younger nickel–cobalt–arsenic, mercury, gold–mercury, and copper–molybdenum deposits towards the plume margin.

Obolenskyi *et al.* (1999) distinguished two distinct metallogenic belts in Southern Siberia in response to these and other anorogenic processes: (i) the Late Paleozoic–Early Mesozoic Altai–Transbaikalian metallogenic belt; and (ii) the Late Mesozoic Altai–Okhotsk metallogenic belt. The first contains molybdenum–tungsten, tin–tungsten, and tantalum–niobium–lithium mineralisation largely in the west, and copper–molybdenum mineralisation in the east. The second belt has a broader range of mineralisation styles represented by tin–tungsten, tantalum–niobium–lithium, tin–base metal, copper–molybdenum and copper porphyry deposits, and gold, lead–zinc, silver–antimony, uranium, mercury and fluorite deposits. Rybalov (2000) attempted to separate these evolutional trends in the Altai–Okhotsk belt and divided them into (i) gold–molybdenum, (ii) tantalum–niobium–lithium–uranium–base metal and (iii) fluorite–gold–silver trends.

In the Yana–Kolyma orogenic superbelt, the Mesozoic metallogenic epoch is characterised by the formation of gold, gold–tin, gold–antimony and other deposits related to syn- and post-collisional granitoids. A special feature of this orogenic system includes the presence of silver–base-metal and related tin–silver and tin–base-metal deposits (e.g. the Prognoz, Mangazeya, Deputatskoe, Kupolnoe and Alaskitovoe deposits). These deposits are characterised by long extensive periods of mineralisation, resulting in the common superposition of different styles of mineralisation (Gamyanin *et al.* 1998).

In the Sikhote–Alin orogen, the Mesozoic metallogenic epoch included formation of tungsten–base-metal skarn and associated tin–tungsten greisen deposits (Gonevchuk *et al.* 2010).

Mesozoic–Tertiary epoch

Mineralisation associated with this metallogenic epoch is best represented in the Okhotsk–Chukotka volcanic belt and includes numerous epithermal gold–silver, silver, mercury, mercury–antimony and other deposits. According to Izikson (1979), the epithermal gold–silver and silver deposits are closely associated with bimodal rhyolite–andesite–basalt volcanism related to rifting. The volcanic rocks have elevated potassium and are characterised by the widespread formation of ignimbrites that pre-date mineralisation. Epithermal gold–silver deposits of this epoch are accompanied by mercury and mercury–antimony deposits. Tin mineralisation of Late Cretaceous–Paleogene age is also present, although the relationship of tin and tin–base-metal deposits with mercury deposits is unclear; the latter are located at the periphery of tin-mineralised districts. In total, this region is characterised by the presence of several complex mineralised districts that form clusters, hosting gold–tin–silver, tin–silver–base metal, gold–antimony, and gold–tungsten–antimony mineralisation.

In the Sikhote–Alin orogen, the Tertiary metallogenic epoch also hosts numerous lead–zinc and boron skarns, plus associated tin–base-metal deposits.

SIGNIFICANT DEPOSIT TYPES AND KEY EXAMPLES

It is clear from the above that thousands of significant mineral deposits are located in Siberia, and it is quite a challenging task to select which should be described in this contribution. In order to do so, we have used size, such as the amount of contained metal, and importance for deposit classification schemes, as presented in Goodfellow (2007) and in other Western classifications of mineral deposits (Misra 2000; Laznicka 2006; Pirajno 2009). However, some large and significant Siberian deposits cannot be readily accommodated within known classification schemes, thus providing an opportunity for improvement.

Sediment-hosted copper deposits

A group of large to superlarge sediment-hosted Cu deposits* are located in Paleoproterozoic rift basins in the western part of Aldan Shield (SE Siberia). They include the *Udokan Cu deposit* (Figure 2) , which is the largest Cu deposit in Russia (Soloviev 2009 and references therein). It contains about 1.2 Gt of Cu ores, averaging 2 wt% Cu and 24 Mt of contained Cu, making Udokan one of the ten largest Cu deposits in the world (Laznicka 2006). Copper contents vary from 0.2% to 4% and more, up to 6–7% in some intervals. The ores also have elevated contents of Ag (from traces to 95.6 g/t Ag, average 13 g/t Ag) and gold (from traces to 20 g/t Au, average 0.3–0.5 g/t Au for some types of the ores).

The deposit is represented by series of Cu-bearing horizons found within the Paleoproterozoic metasedimentary sequence, which includes metamorphosed rhythmically bedded rocks of deltaic and shallow-water facies, polymictic sandstones and siltstone with minor argillites, conglomerate–breccias and sandy limestones. These rocks form a shallow-dipping (from 10–12° to 25–30°) oval-shaped brachysyncline, about 10×15 km across (Figure 2). Most Cu mineralisation occurs in the brachysyncline limbs complicated by flexures. The bottom part of the brachysyncline, with subhorizontal bedding in the fold closure, is at a depth of about 1.5 km from the surface (Krendelev *et al*. 1983; Chechetkin *et al*. 2000).

Stratabound Cu-bearing zones have variable (2–113 m) thickness and concordant tabular, lens- and ribbon-like shape forming multilevel and *en échelon* successions totaling some 20–330 m in thickness; Cu-rich sectors are traceable for 2–3 km along strike. Three major types of ore associations are distinguished—pyrite–chalcopyrite, chalcopyrite–bornite and bornite–chalcocite ores—forming fine (0.01–1 mm) sulfide dissemination in sandstones or siltstone. Pyrite, magnetite, hematite and minor sphalerite, valleriite, molybdenite, wittichenite, pyrrhotite, marcasite, tennantite, polydymite, stromeyerite and native Ag are also present. Cu-mineralised breccias occur locally in stratigraphic unconformity surfaces and horizontal to subvertical fractured zones. Magnetite is constantly present in the most abundant bornite–chalcocite ores; according to Smirnov (1977) magnetite content together with bornite and chalcocite locally attains 50 vol%. Hematite is also widespread within, and especially below, the Cu-bearing horizons. Volodin *et al*. (1994) reported magnetite and hematite in elevated concentrations (>5 vol%) in Cu ores; where these minerals are represented by ‘clastic’ and ‘regenerated’ varieties, with the latter forming disseminations in sandstones. Hematite is also present in veinlets and matrix of tectonic breccias.

Gold mineralisation is also common, averaging 0.3–0.5 g/t Au in some deposit sectors, but locally attains much higher grades of 10–20 g/t Au. Enrichment of Cu-bearing zones and associated magnetite mineralisation in gold, with relatively higher Au contents in bornite–chalcocite–magnetite and chalcopyrite ores occurs in the lower Cu-bearing horizons (Abramov 2008). Typically, native Au occurs as fine (0.01–0.1 mm) inclusions in chalcocite, bornite and chalcopyrite. Highest Au grades are recorded in quartz–sulfide veins and sulfide stockwork zones, the latter with pyrite, chalcopyrite, arsenopyrite, and trace sphalerite, marcasite and galena. In contrast, quartz–feldspar sandstones with no essential Cu mineralisation but enriched in martite and magnetite bear just trace Au (typically 0.01–0.04 g/t Au, locally up to 2.5 g/t Au).

The deposit is characterised by the broad occurrence of various hydrothermal–metasomatic alteration features, of which sodic and propylitic alteration are most notable. Pervasive alteration (quartz, chlorite, muscovite, epidote) is present in Cu-mineralised sandstone horizons, coincident with networks of fine sulfide and quartz–sulfide stringers, whereas barren argillites and siltstone are only little altered (Smirnov 1977). Krendelev *et al*. (1983) observed intense potassic alteration in the exocontacts of the Kodar granitic suite, in proximity of Cu-mineralised zones, with networks of fine stringers and larger veinlets of microcline locally associated with apatite and epidote. Sodic alteration is also present and is represented by albite and quartz–albite veinlets, accompanied by pyrite dissemination.

The origin of the Udokan deposit remains controversial. Most authors (Krendelev *et al*. 1983; Volodin *et al*. 1994) believed the Cu mineralisation was originally deposited contemporaneously with sedimentation in a large delta of a hypothetical northbound Paleoproterozoic river, eroding Archean Cu and Cu–Fe deposits. Although no such source deposits were identified, this model is favoured by the deltaic nature of the host sedimentary rocks, and by the apparent distribution of Cu sulfides concordantly to shallow-dipping primary bedding. However, many authors also recognise the role of post-sedimentary diagenetic and alteration (metamorphic to metasomatic) processes that further contributed to the formation of economic Cu mineralisation (Krendelev *et al*. 1983; Chechetkin *et al*. 2000). In contrast, other authors suggested an intrusive-related hydrothermal origin of Cu mineralisation or at least the critical importance of intrusive-related processes in the concentration of Cu mineralisation. Some authors assumed an unidentified deep-seated pluton to be genetically related to the mineralisation. Soloviev (in press b) suggested similarities of the Udokan deposit with deposits of the IOCG family.

Sedimentary exhalative (SEDEX) sulfide and oxide deposits

Deposits of this style are present mostly in Precambrian and Early–Middle Paleozoic orogenic terranes, adjoining the Siberian craton. These terranes are considered to represent passive continental margins, characterised by the accumulation of terrigenous and terrigenous–carbonate sedimentary sequences, with minor coeval volcanic rocks. However, these terranes may also represent parts of rift basins, with alkaline basaltic dykes which may have been implicated in ore-forming processes. Many deposits were subjected to regional

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*Large copper deposits are in excess of 4 Mt contained Cu whereas the lower limit of superlarge copper deposits is set at 10 Mt contained Cu (Rundqvist 2006; Rundqvist *et al*. 2006) (Tables 1, 2).

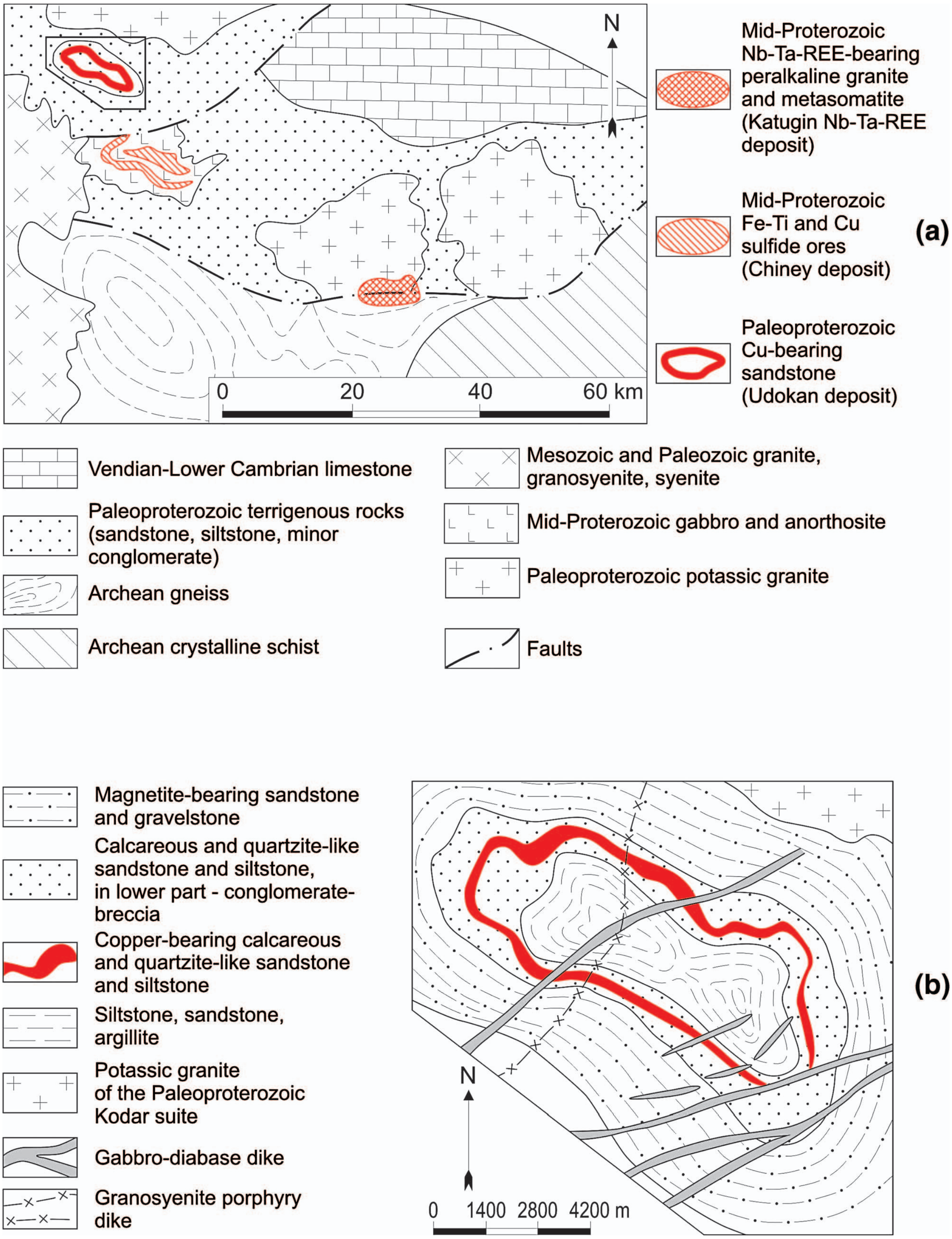

Figure 2 (a) Simplified geology of the Kodar–Udokan mineralised district (modified after Arkhangel'skaya *et al.* 1993). (b) Geological map of the Udokan deposit (modified after Krendelev *et al.* 1983; Chechetkin *et al.* 2000).

Table 2 Comparison of lower limits of reserves/resources for large deposits applied by Geological Surveys of selected countries (Rundqvist *et al.* 2006).

Commodity	Basis for calculation	Unit	Russia (1997)	China (1997)	France (1999)
Fe	Ore[a]; Fe[b]	Mt	300[a]	100[a]	100[b]
Mn	Ore[a]; Mn[b]	Mt	30[a]	20[a]	10[b]
Cr	Ore[a]; Cr_2O_3[b]	Mt	10[a]	5[a]	5[b]
Ti	Rutile, placers	Kt	1	0.05	0.2
	ilmenite, placers	Kt	5	0.5	2
	Ti_2O, hard ore	Mt	10	5	2
Cu	Cu	Mt	1	1	1
Pb	Pb	Mt	1	0.5	0.1
Zn	Zn	Mt	1	0.5	0.2
Al	Bauxite	Mt	50	100	100
Ni	Ni	Kt	200	100	200
W	WO_3, hard ore	Kt	100	50	5
	WO_3, placers	Kt	15	–	–
Sn	Sn, hard ore	Kt	50	40	10
	Sn, placers	Kt	10	–	–
Mo	Mo	Kt	50	100	50
Hg	Hg	Kt	15	2	5
Sb	Sb	Kt	100	100	10
Au	Au, hard ore	t	50	10	50
	Au, placers	t	3	4	
Ag	Ag	Kt	3	1	3
Nb	Nb_2O_5	Kt	300	100	50
Ta	Ta_2O_5	Kt	5	1	0.5
Li	Li_2O, hard ore	Kt	200	100	500
	LiCl, salt lake brines	Kt	–	250	–
Be	Be[a]; BeO[b]	Kt	10[a]	10[a]	5[b]
TR	TR_2O_3	Kt	–	500	30
Zr	ZrO_2	Kt	1500	–	100

Reserves for some commodities, in different countries, are calculated in different ways. For example, iron or manganese may be estimated as reserves of ore (Russia, China) and as reserves of metal (France); chromium as ore or oxide; beryllium as oxide or metal: [a] and [b] are used for correct identification where appropriate.

and/or contact metamorphism that significantly changed their structure and mineral composition.

The *Gorevskoe Pb–Zn deposit* (Figure 3) situated in the Neoproterozoic–Mesoproterozoic Yenisei Ridge terrane is the largest Pb–Zn deposit in Russia (M. Sherman unpubl. data). It has reserves (Russian B+C_1 reserve categories) of 5.8 Mt Pb and 1.2 Mt Zn contained metal averaging 7.07 wt% Pb and 1.37 wt% Zn. The ores contain up to 40 g/t Ag.

The deposit is hosted in Mesoproterozoic terrigenous and carbonate rocks intensely deformed and metamorphosed under greenschist facies. The deposit occurs in a limestone–shale sequence and consists of concordant lens-like sulfide bodies in syncline folds within a larger anticline. Three sets of large steeply–dipping *en échelon* orebodies are present; their thickness varies from 20 to 150 m, strike length attains 1200 m, and the downdip extent is 1000 m. The ore minerals include galena, pyrrhotite and sphalerite, minor pyrite, marcasite, boulangerite–bournonite, jamesonite and arsenopyrite, and trace chalcopyrite, tennantite, argentite, proustite–pyrargyrite, sternbergite, dyscrasite, native Ag and loellingite. The ores have been subjected to intense metamorphism, which resulted in their redistribution into large shear zones. Hydrothermal gangue minerals include quartz, siderite, ankerite and muscovite. The orebodies are characterised by distinct zonation, with the predominance of pyrrhotite–sphalerite–galena in the footwall zones, galena–pyrrhotite–sphalerite in the central zone, and galena–pyrrhotite in the hangingwall zone (Smirnov 1977; Distanov & Kovalev 1995).

The *Kholodninskoe Zn–Pb deposit* (Figure 4) is situated in the Northern Baikal–Patom orogenic belt bordering the Siberian craton to the south (Figure 1), within a graben-like trough filled by carbonaceous terrigenous and carbonate–terrigenous sequences, common presence of high-Mg tholeiitic basalt and minor rhyolite (Distanov & Kovalev 1995). The deposit has reserves (Russian B+C_1 reserve categories) of 2 Mt Pb and 13.3 Mt Zn contained metal, averaging 4.33 wt% Zn, 0.68 wt% Pb, 9.4 g/t Ag and 0.1 g/t Au.

The deposit is hosted in Mesoproterozoic quartz–garnet–micaceous and quartz–micaceous schists alternating with quartzite and marble intensely sheared and folded into narrow isoclinal folds, and metamorphosed under amphibolite facies. The ore-bearing carbonaceous unit is stratigraphically higher and comprises alternating micaceous–carbonate and quartz–micaceous schist, graphitic sandstone and graphitic sandy limestone. The presence of volcanic (tuffaceous) rocks is suggested but they are strongly masked by alteration. The deposit consists of three large steeply dipping lens-like sulfide bodies, varying in thickness from 5 to 230 m (averaging 85 m), extending for 4.7 km along strike and for 800 m downdip. Total strike extent of the mineralisation exceeds 7 km. The ores are represented by thin-layered,

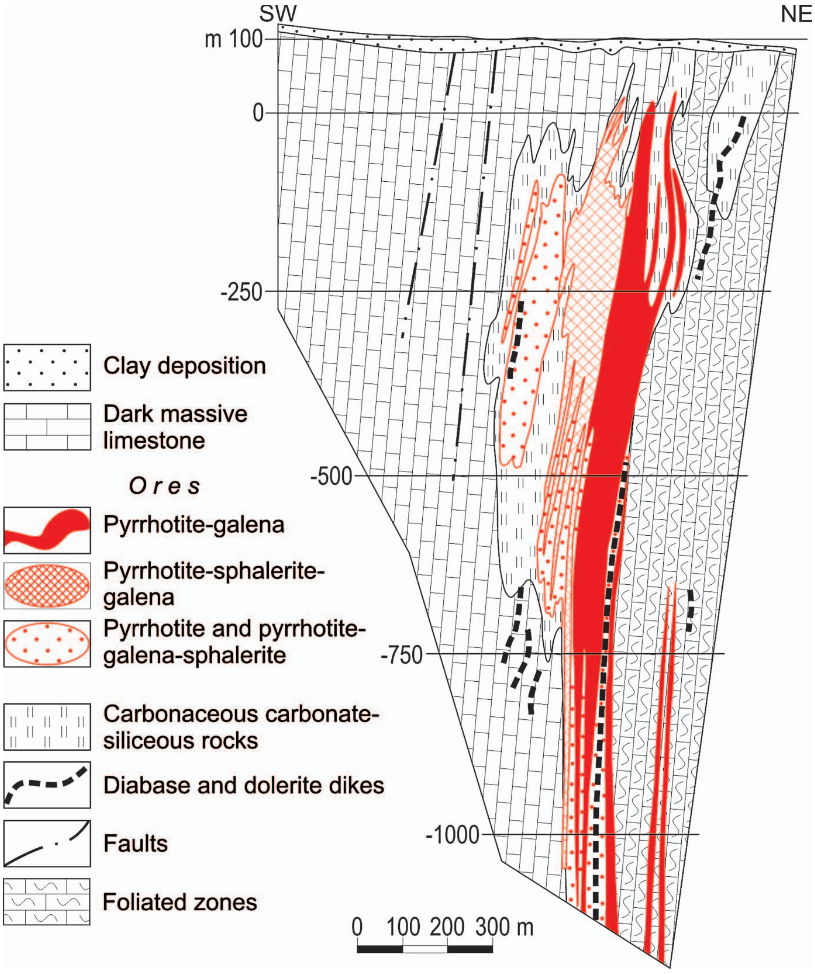

Figure 3 Cross-section through the 4th line Gorevskoe deposit (after M. Sherman unpubl. data).

massive and disseminated sulfides with major pyrite, pyrrhotite, sphalerite, galena and chalcopyrite, and minor fahlores, arsenopyrite magnetite. The Zn:Pb:Cu ratio is 4:1:0.3. The ores have been subjected to deformation and metamorphism resulting in intense folding, boudinage, mylonitisation as well as remobilisation and redeposition of sulfides into fold closures and shear zones (Ruchkin 1984; Distanov & Kovalev 1995).

The *Kholzunskoe Fe oxide deposit* is considered to be of SEDEX type, although its origin is highly controversial, as other models (IOCG, skarn) have been suggested (Gusev *et al.* 2006). The deposit is situated in the Russian Altai part of the Altai–Sayan orogenic belt, within a local rift basin also hosting minor Mn and Pb–Zn mineralisation. The deposit contains 800 Mt averaging some 30 wt% Fe.

The deposit is hosted by Middle Devonian limestone, intercalated with dacite, trachydacite and trachyandesite. The Fe oxide mineralisation forms several steeply dipping to subvertical lens-like bodies of significant (30–100 m) thickness. The mineralised horizon is traceable for 9 km along strike and for 1.3 km downdip. There are three Mn-bearing horizons, with two of them below the Fe-rich horizon, and one superimposed on it. Most of the Mn mineralisation occurs in the distal flank parts of the Fe horizon, where the Fe ores has elevated Mn contents, which vary from 0.11 to 0.32 wt% Mn averaging 0.19 wt%. The Fe mineralisation is represented by magnetite, less commonly hematite. Some authors reported a close association of the Fe mineralisation with trachyandesite lavas, the latter containing 10–33 wt% Fe. Apatite is locally abundant as well as sulfides and gangue minerals such as amphibole, biotite, carbonate, and strong enrichment in apatite, garnet and pyroxene is present near the contacts with a Permian granitoid pluton. The host rocks and Fe–P association are also suggestive of an affinity with Kiruna-type mineral systems (Nyström & Henríquez 1994).

Volcanic-hosted massive sulfide (VHMS) deposits

The *Ozernoe deposit* (Figure 5) (180 Mt: 6.2% Zn, 1.2% Pb, 23.5% Fe, 21.1% S) lies 350 km east of Lake Baikal in Eastern Siberia. The deposit is situated in a remnant (12 × 24 km) of Early Cambrian volcanogenic–terrigenous sequence, enclosed in the Angaro–Vitimsk Middle Paleozoic batholith. The tectonic setting of this region is

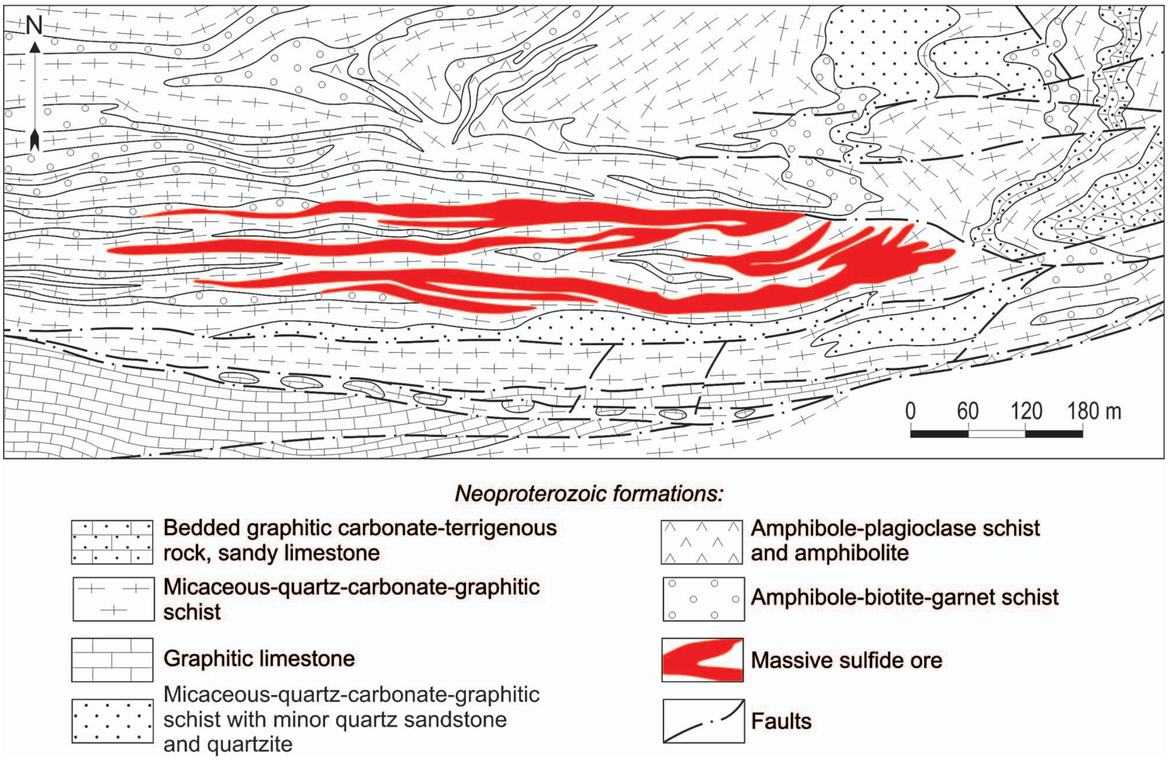

Figure 4 Geological map of the Pb–Zn Kholodninskoe deposit (modified after Distanov & Kovalev 1995).

that of an oceanic island arc system, formed near the boundary with the Barguzin continental massif. Here a northeast-trending inter-arc volcanic depression contains more than 20 sulfide and Fe-oxide deposits and occurrences, grouped together as the Ozerninsk orefield. The sulfide ores generally found in the axial parts of the depression, whereas Fe-oxide facies occupy the flanks. The ore-bearing Ozerninsk–Vasilevsk graben-shaped syncline structure (2.5 × 5 km) occurs in its central area and is filled with extensive volcanogenic–sedimentary turbidite rocks >1600 m thick. This structure is framed by reefal limestones and northeast- and northwest-trending faults. The sequence consists of tuff, tuffaceous rocks, pelite, greywacke, siltstone, chert and limestone. The massive sulfides and hydrothermal sediments occur at three stratigraphic levels (0–350 m, 817–893 m 1349–1367 m), each representing a cycle of andesite–basaltic volcanism (Distanov *et al.* 1972; Kovalev *et al.* 2003). In all cases, the ores are located at the top of turbidite units in fine-grained sedimentary rocks and chemical sediments. The uppermost horizon of the Ozernoe ore deposit contains high-grade sulfide ore. The ores are located in a third-order brachysyncline structure, which is ~2.4 km long, 1.5 km wide and 350 m deep. The deposit is composed of 12 manto-like sulfide and siderite–sulfide orebodies separated by horizons of tuffaceous units, organic and chemical limestone, chert, coarse sedimentary breccia, in places carbonaceous (C_{org} ~0.5%), siltstone, pelite, dolomite and siderite. The orebodies are from 5 to 40 m in thickness and extend for 2.2 km along strike. Each of the orebodies has a layer-cake geometry. Siderite-rich, low-sulfide ores and massive pyrite ores are occasionally interstratified with unmineralised reef limestones.

The ore minerals consist of globular or very fine-grained pyrite, sphalerite and galena. Locally, diagenetic arsenopyrite porphyroblasts are present, whereas tetrahedrite–tennantite and Ag-sulfosalts may be part of redistributed ore minerals. The gangue consists of silica, Mn-siderite, ankerite, dolomite, and rare rhodochrosite. Barite is absent in the banded ores. Galena–sphalerite layers grade up to 45.6% Zn, 5.2% Pb; pyrite layers contain 41.9% Fe, 30.1% S; siderite layers contain 27.2% Fe and 4.2% Mn. Sulfide layers can contain up to 38.1% SiO_2 or carbonate (up to 11.2% CaO). The ores contain trace amounts of Cd (0.017%), Tl (0.001–0.03%), and Ag (37.5 g/t). The dark siderites are characterised by elevated Ge concentration (up to 0.01 g/t). The ores are poor in Au (0.01–0.1 g/t).

The Altai region is situated adjacent to the well-known VHMS metallogenic province of Rudny Altai of the eastern Kazakhstan. Together, these provinces are related to a Devonian island arc established over a passive Ordovician–Silurian continental margin forming the terrigenous–carbonate basement of the Devonian volcanic–plutonic belt. Here, Devonian bimodal basalt–rhyolite suite is accompanied by volcanic–exhalative polymetallic (Cu–Pb–Zn) and barite–polymetallic deposits formed in submarine conditions, also with hydrothermal–metasomatic alteration, which affected

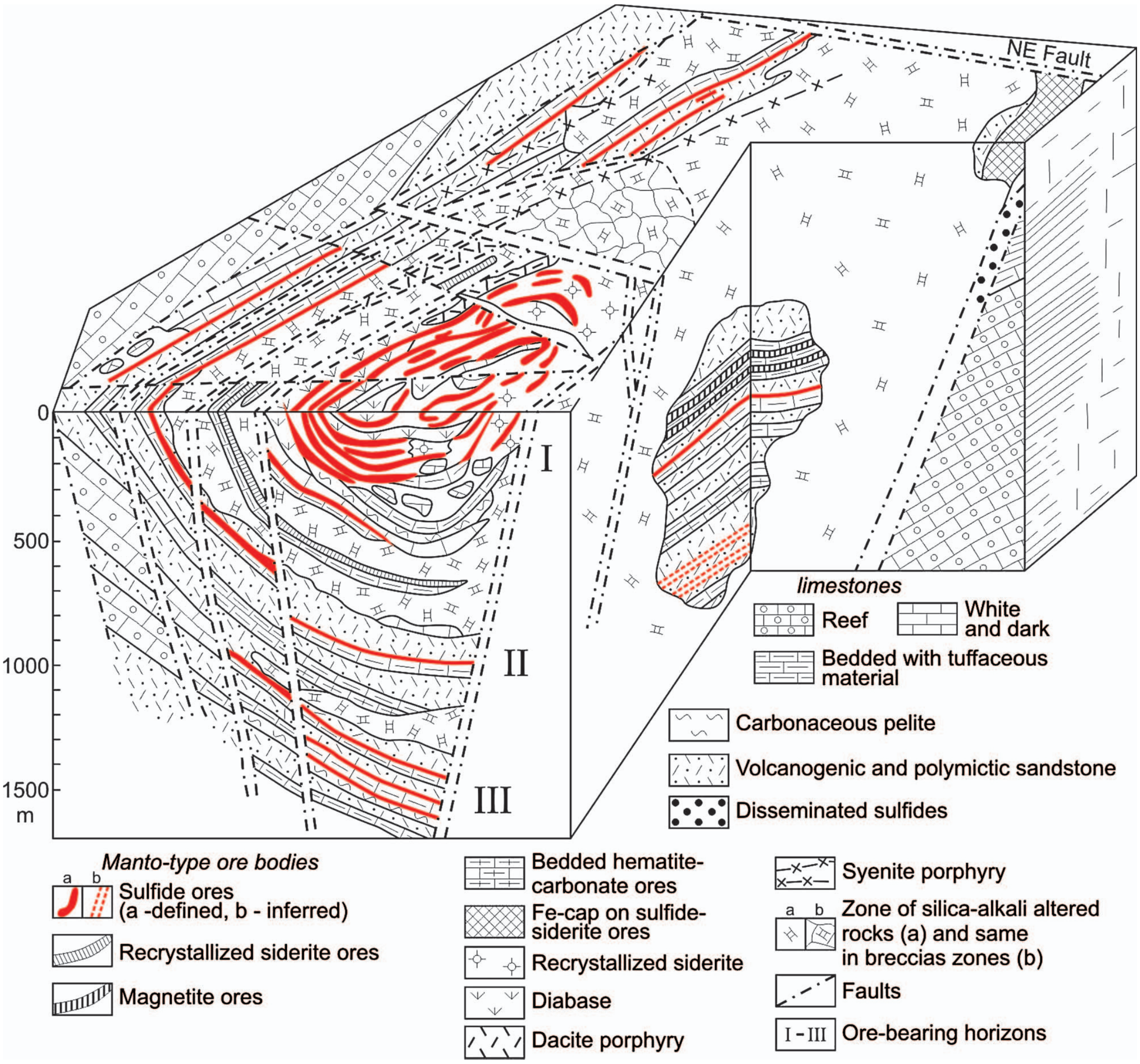

Figure 5 Schematic block diagram of the Ozernoe ore-bearing graben depression (after Distanov *et al.* 1972).

weakly lithified sediments, along conduits of ascending fluids. Relatively early mineralisation associated with mostly rhyolitic suites is represented by barite–Pb–Zn VHMS deposits, with elevated Au and Ag contents, whereas younger rhyolite–dacite and basalt–andesite suites host Cu–Zn–Pb VMS deposits (Eremin & Dergachov 1998; Distanov *et al.* 2006).

VHMS deposits are quite common in the Altai–Sayan orogenic belt (southwest Siberia), with the most prominent example provided by the Cambrian Kyzyl–Tashtyg deposit in the Tuva region and numerous Devonian deposits in the Russian Altai region (Gaskov *et al.* 1999). The *Kyzyl–Tashtyg deposit* contains 12.9 Mt of Zn–Pb ore, 2.1 Mt of Cu ore and 6.3 Mt of pyritic ore. The Zn–Pb ores average 10.2 wt% Zn. (Simonov *et al.* 2010) The deposit is hosted in a Lower Cambrian sequence composed of volcanic and volcanic–sedimentary rocks, including numerous sill-like mafic and felsic subvolcanic bodies and small porphyry intrusives. The volcanic rocks belong to differentiated basalt–andesite–dacite suite. Sedimentary rocks are minor and include carbonaceous siltstone, sandstone and limestone. Three stratigraphic units are distinguished in the deposit area: (i) a lower essentially basaltic unit; (ii) an intermediate unit of alternating cherty siltstone, sandstones, andesite–basalt and dacite tuffs; and (iii) an upper unit composed of andesite–basalts and intermediate tuffs. The mineralisation is hosted in the intermediate unit, within a local paleovolcanic depression rimmed by volcanic extrusive domes; the depression extends for about 2 km along strike and is 600–800 m wide. In total, 51 orebodies are known; 33 of which are composed of Zn–Pb ores, 9 of Cu ores, and 9 of pyritic ores. The host rocks and subconcordant orebodies dip steeply at 70–80°, with some flattening to 40–50°. The orebodies have lenticular and stock-like shapes, and extend for tens to hundreds of metres along strike (up to 600 m) and vary in thickness from 3 to 60 m.

The *Korbalikha Zn–Cu–Pb deposit* has reserves of 28 Mt containing 328.1 kt Cu, 466.4 kt Pb and 2.2 Mt Zn; the Pb:Cu:Zn ratio is 1:0.6:3.6. The deposit is located in Middle–Upper Devonian terrigenous and volcanogenic–sedimentary sequences. The latter are subdivided into five units including rhyolite and rhyolite–dacite tuffs, tuffaceous sandstones, andesite–basalt lavas and tuffs, argillites and rhyolite–dacite tuffs. There are Devonian subvolcanic intrusive rocks represented by dolerite porphyries, gabbro–dolerites and rhyolite porphyries, and Late Paleozoic gabbroic dykes. The deposit structure is characterised by the combination of small folds and variously oriented fault zones including thrust faults. Sulfide mineralisation occurs over the entire volume of the volcanic–sedimentary sequences but major economic orebodies are related to the Upper Devonian tuffaceous sandstone horizon. The ores are accompanied by chloritic and quartz–sericite alteration and are represented by a sphalerite–chalcopyrite–pyrite assemblage, with minor sphalerite–pyrite, sphalerite–galena and barite–galena assemblages. Distinct mineral zonation is expressed by the predominance of barite–Pb–Zn mineralisation in the upper part, massive pyrite and Pb–Zn sulfides in the central part, and Cu–pyrite mineralisation in the lower part of the deposit. The orebodies extend for up to 1000 m along strike and are traced to a depth of 750 m.

The *Rubtzovskoe Zn–Pb–Cu deposit* has smaller reserves but higher grades: it contains 2.425 Mt averaging 4.5% Cu, 6.5% Pb, 12% Zn, and 1.8 t Au and 351 t Ag. The deposit is located in volcanogenic–sedimentary sequence that includes Middle Devonian siltstone, overlain by Upper Devonian volcanogenic rocks, locally with subvolcanic rhyolitic intrusive the deposit area. The rhyolite is overlain by Upper Devonian rocks represented by cherty argillite, arkose sandstone, siltstone, tuffite with rare interbeds of tuffs and limestone. The section is overthrust by Lower Carboniferous sedimentary rocks (conglomerate, gravelstone, limestone). The mineralisation is hosted by Upper Devonian terrigenous rocks and is represented by a single lens-like orebody outcropping at the surface and extending to a depth of 100–215 m.

The orebody is composed of massive, veinlet-disseminated and mylonitised (brecciated) Pb–Zn sulfides, to lesser extent Cu–pyrite and Cu–Zn–Pb ores. The overall Cu:Pb:Zn ratio is 1:1.5:2.5. The massive ores form major part of the orebody, evolving into veinlet-disseminated ores toward its flanks and in the footwall zone, where they form a steeply dipping sulfide stockwork. Brecciated ores occur in fault zones cross-cutting the orebody. Major ore minerals include sphalerite, galena, pyrite and chalcopyrite, with minor tennantite and barite. The pyrite–sphalerite assemblage is the most abundant; a chalcopyrite–pyrite–galena assemblage forms veinlets in the pyrite–sphalerite ores.

Sediment-hosted/stockwork/shear zone-related lode Au and associated deposits

In Siberia, this group of Au deposits usually referred to as orogenic-gold deposits (Goldfarb *et al.* 2001) is represented by numerous and commonly large (to superlarge) deposits* in virtually all Proterozoic–Paleozoic and Mesozoic orogenic belts surrounding the Siberian craton, including the Altai–Sayan, Mongol–Okhotsk and Yana–Kolyma orogens (Figure 1) (e.g. Sukhoi Log, Olympiada, Natalka, Nezhdaninskoe, Zun-Kholba). In many regions, these Au deposits are closely associated with Sb–Au, Sb (Sarylakh, Sentachan) deposits formed in similar metallogenic environment. Their common features include lack of clear relationships with magmatic (plutonic or volcanic) bodies although in many cases these relationships are inferred. The predominance of sulfide hosted Au (together with pyrite and arsenopyrite), high fineness of gold, and geochemical associations of Au with As, Sb and W, are among the distinctive features of these deposits. The mineralisation is generally controlled by deposit- to district-scale folds and large fault (including thrust-fault) zones; in many cases, a long-lived ore-forming system is evident, with early (typically subeconomic) Au mineralisation forming fine disseminations in metasedimentary (terrigenous to terrigenous–carbonate) sequences, and later higher-grade Au concentrations being more probably related to plutonic activity. The intrusion of granitoid plutons may have generated hydrothermal fluids circulation, which in turn could have caused the redistribution of ore components.

The *Sukhoi Log Au deposit* (Figure 6) is the largest Au deposit in Russia and one of the world's largest; it has reserves of 1953 t Au (Russian C_1+C_2 reserve categories), with the average grade of 2.1 g/t Au, and also substantial inferred resources. The deposit is situated in the Lena goldfield in the Patom Highlands orogenic system, bordering the Siberian craton east of Lake Baikal (Figure 1). The Lena goldfield has been known since the 1840s with the discovery of alluvial gold. Interesting accounts of the history of the Lena goldfield and Sukhoi Log can be found in Distler *et al.* (2004) and Wood & Popov (2006). Wood & Popov (2006) proudly stated that the discovery of Sukhoi Log was made by geologists who used new conceptual models.

The Patom Highlands terrane is composed of a Neoproterozoic terrigenous sequence metamorphosed to greenschist facies and intruded by Paleozoic granitoid plutons and series of felsic to lamprophyre dykes. This terrane hosts the large Bodaibo mineralised district including, apart from Sukhoi Log, Vysochaishyi, Verninskoe, Zapadnoe, Chertovo Koryto, Nevskoe and many other large- and medium-sized Au deposits as well as giant Au placers. The placers have already produced >700 t Au. An important feature of the Bodaibo district is the presence of two different styles of Au mineralisation. The first style is represented by quartz veins bearing extremely irregularly distributed coarse native Au. In contrast, the second style is represented by fine Au dispersed in sulfides in quartz–sulfide stockworks.

The Sukhoi Log deposit is described in numerous papers, most recently by Distler *et al.* (2004), Wood &

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*Large gold deposits are in excess of 200 t contained Au whereas the lower limit of superlarge gold deposits is set at 1100 t contained Au (Rundqvist 2006; Rundqvist *et al.* 2006) (Tables 1–3).

Popov (2006) and Large *et al.* (2007). It is hosted in a Neoproterozoic black shale and siltstone (with minor quartz sandstone and limestone) sequence forming a tight overturned linear anticline, with the core portion composed of carbonaceous phyllites underlain by carbonate rocks. Total thickness of the carbonaceous rocks

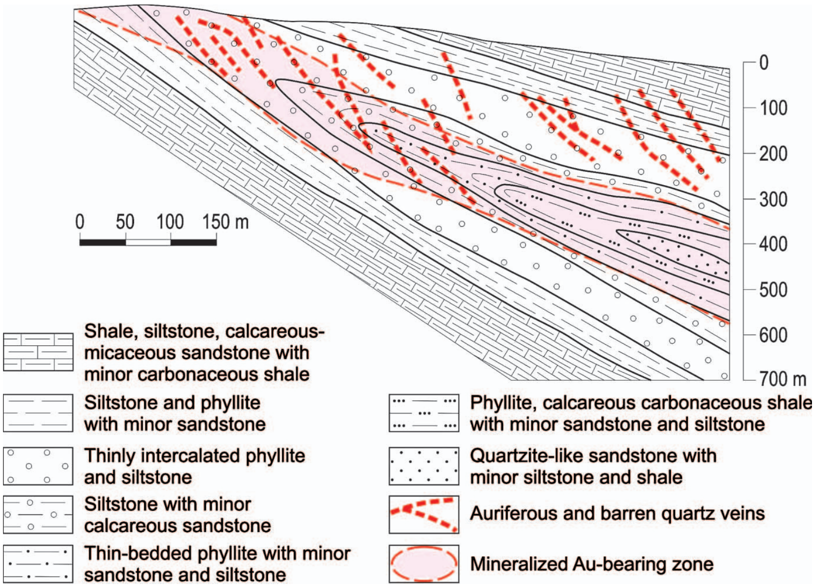

Figure 6 Geological section through the Sukhoi Log Au deposit (modified after Konstantinov *et al.* 2000).

Table 3 Criteria for large and superlarge deposits accepted in the database for large and superlarge deposits (Rundqvist 2006, Rundqvist *et al.* 2006).

	Commodities	Basis for calculation	Unit	Large (lower limit)	Superlarge (lower limit)
1	Silver	Ag	t	5000	28 000
2	Aluminium	Al_2O_3	Mt	40	250
3	Gold	Au	t	200	1100
4	Boron	B_2O_3	Mt	2	20
5	Beryllium	BeO	Kt	5	25
6	Cobalt	Co	Kt	50	400
7	Chromium	Cr_2O_3	Mt	4	40
8	Copper	Cu	Mt	4	20
9	Diamonds	Diamond	Kt	20	200
10	Fluorine	Fluorite, cryolite	Mt	2	20
11	Iron	Fe	Mt	100	1000
12	Mercury	Hg	Kt	10	100
13	Potash	K_2O	Mt	100	1000
14	Lithium	Li_2O	Kt	100	1000
15	Manganese	Mn	Mt	10	100
16	Molybdenum	Mo	Kt	100	500
17	Niobium	Nb_2O_5	Kt	100	1000
18	Nickel	Ni	Kt	500	4500
19	Phosphorus	P_2O_5	Mt	40	400
20	Lead	Pb	Mt	1	5
21	Platinoids	ΣPGE	t	100	1000
22	Antimony	Sb	Kt	25	250
23	Sheet muscovite	Sheet mica crude	Kt	20	100
24	Sheet phlogopite	Sheet mica crude	Kt	50	500
25	Tin	Sn	Kt	50	350
26	Tantalum	Ta_2O_5	Kt	2	25
27	Titanium	TiO_2	Mt	2	25
28	Rare earths	ΣTR_2O_3	Kt	100	1500
29	Uranium	U	Kt	20	80
30	Vanadium	V_2O_5	Kt	250	1500
31	Tungsten	WO_3	Kt	50	400
32	Zinc	Zn	Mt	2	9
33	Zirconium	ZrO_2	Kt	150	1000

attains 300 m near the land surface and increases to 450–500 m at depth. A significant fraction of these carbonaceous rocks was converted to chlorite–carbonate–quartz metasomatites, overprinted by an Au-bearing quartz–sulfide stockwork and larger (0.5–1.0 m thick and up to 150–200 m long) veins. As a result, the entire core part of the anticline is contoured (using 1.5 g/t Au cutoff) as a single tabular gently (15–20°) dipping Au orebody. To the east, this single orebody splits into two branches corresponding to the hangingwall and footwall limbs of the anticline. Total strike extent of the orebody exceeds 3 km; it was traced for 0.8–1.8 km downdip and varies from 15–35 m to 70–90 m in thickness.

The major fraction (~75%) of the Au reserves is contained in fine sulfide (pyrite) and quartz–sulfide stringers and dissemination that are typically bedding-parallel and appear to follow folding. The hinge zone of the anticline contains more bedding-parallel veinlets and has higher Au grades. Individual pyrite stringers are 0.2–5 cm thick; locally, the stringers merge forming pyrite aggregations up to 10 cm thick. Almost all gold in this structural type of mineralisation occurs in pyrite stringers. An interesting and detailed study of auriferous pyrite from the Sukhoi Log deposit was conducted by Large *et al.* (2007), who identified six generations of pyrite (Py1 to Py6) each with different features and trace-element endowment, thereby unravelling a complex series of events that eventually led to the formation of the Sukhoi Log Au mineral system.

The total sulfide content at Sukhoi Log varies from 2 to 5 vol%; pyrite forms up 95 vol% of sulfides, whereas pyrrhotite and arsenopyrite are minor. Galena, sphalerite, chalcopyrite and other sulfides occur in trace amounts. Native Au (fineness 900–920) is very fine and typically occurs in microfractures in pyrite and rarely in pyrrhotite and arsenopyrite; a minor late variety of native Au has lower fineness (~860). The remaining portion (25%) of the Au reserves is found in larger quartz and quartz–carbonate (siderite, ankerite, dolomite and calcite) veins, with trace muscovite, chlorite. The veins contain minor (<3 vol%) sulfides (mainly pyrite, trace galena, sphalerite, chalcopyrite, arsenopyrite); native Au is represented by a relatively low-fineness (820–880) variety.

Large *et al.* (2007), on the basis of the above-mentioned study of pyrites, proposed a multi-stage scenario for the origin of the Sukhoi Log mineralisation. In the first stage, sedimentation of organic-rich shales and exhalation of reduced basinal H_2S-rich and Au–As-bearing fluids along east–west rift faults occurred, producing syngenetic Py1 and Py2. In a second stage, late diagenesis, folding and deposition of carbonates followed, while basinal fluids carrying Au–As–Te–Pb flowed laterally through the organic-rich shales, near the feeder faults and below an impermeable cap provided by the carbonate rocks. This stage deposited bedding-parallel Py3. Deformation and metamorphism followed during a final multiphase stage, with tight folding and thrusting. Metamorphic fluids were then produced, which dissolved the early pyrites and redistributed lattice-bound Au, resulting in overprinting of Py1, Py2, Py3 and Py4, with Py5 and Py6 being post-peak metamorphism. The released Au formed inclusions of free Au, Au tellurides and dissolved Ag–Bi–Te in the latest pyrite generations.

The *Natalka Au deposit* (Figure 7) is the second largest Au deposit in Russia; its resources were recently (Polyus Gold 2010) announced as being 1449 t Au (Russian $B+C_1+C_2$ reserve categories), with the average grade of 1.7 g/t Au (0.6 g/t Au cutoff). The deposit is situated in the Magadan region of northeast Russia, in the southeast part of Yana–Kolyma orogenic belt

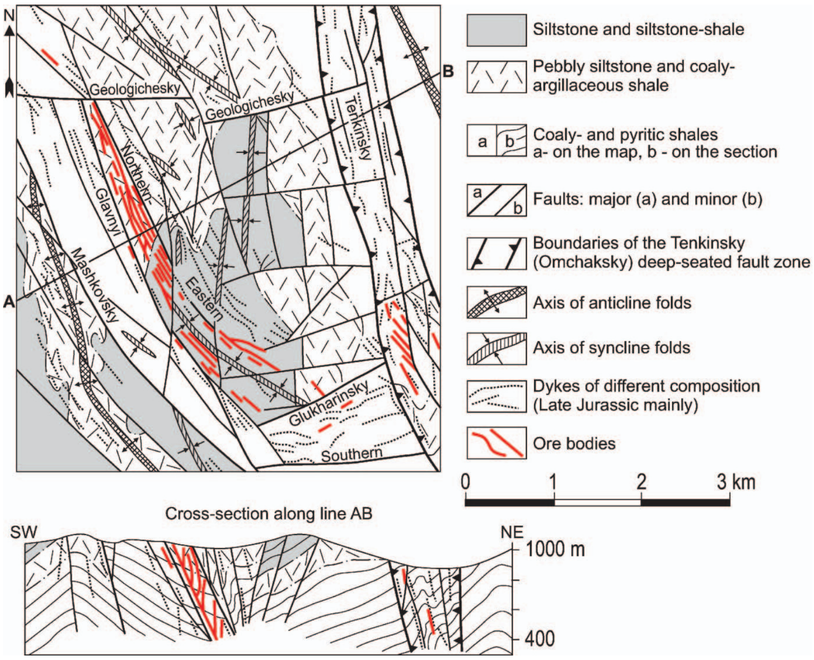

Figure 7 Schematic geological map and section through the Natalka Au deposit (modified after Eremin *et al.* 1994; Konstantinov *et al.* 2000). Distance along line AB is about 6 km, vertical axis of cross-section is about 600 m.

(Figure 1). The deposit area is within a limb of a district-scale syncline composed of Permian terrigenous (sandstone, siltstone, argillite, conglomerate) and minor tuffaceous rocks and complicated by series of high- to low-angle faults. Igneous rocks form small stocks and numerous mafic, intermediate and felsic dykes. Lamprophyre dykes dated at 159–130 Ma pre-date the productive Au mineralisation, whereas lamprophyre and rhyolite dykes dated at 100 Ma post-date it (Goryachev *et al.* 2008).

The deposit is situated in a wedge-like tectonic block delimited by faults and is represented by a series of steeply dipping mineralised zones characterised by thin branching or paralleling quartz veinlets/stringers (typically <3 cm thick; 50% of the veinlets are <5 mm thick) accounting for 5–50 veinlets/1 m (Eremin *et al.* 1994). Locally the deposit setting resembles a 'horsetail' structure or has features of a large thrust-fault. The stockworks include both vertical (dominant) and accompanying diagonal veinlets. Some intervals of the stockworks show also thicker (up to 5 m thick) 'pivot' quartz veins extending for hundreds of metres, whereas others, such as brecciation, show pervasive alteration and sulfidisation. More intense stockworks as well as higher Au values locally exhibit lithological controls by selected metasedimentary units, such as carbonaceous shales and tuffaceous rocks. Some higher-grade ore zones are coincident with lamprophyre and diorite porphyry dykes. However, in general the stockwork margins are determined by cutoff grades rather than by distinct geological boundaries. On the basis of the 0.6 g/t Au cutoff, the deposit is contoured as a single tabular orebody about 200 m thick and 4.5 km long.

The mineralised stockworks are accompanied by intense silica, carbonate (calcite, dolomite, ankerite, siderite) and phyllic (quartz–sericite) alteration. A zonation pattern is characterised by a central carbonate zone surrounded by zones of sericitic and chloritic alteration. Local alteration assemblages include apatite and magnetite, closely associated with sulfide minerals. The ores have low sulfide content (<3 vol%). The sulfides are dominated by arsenopyrite and pyrite, with very minor pyrrhotite, Co–Ni–As–S minerals, sphalerite, chalcopyrite and galena. Trace scheelite, tetrahedrite, bournonite, boulangerite and stibnite are locally present. At depth, the relative amount of pyrite increases, whereas that of arsenopyrite decreases. The Au mineralisation is represented by both Au-bearing sulfides (arsenopyrite, pyrite) and predominant native Au (fineness 670–750). Three mineralising events are distinguished: (i) an early metamorphic event, with formation of barren quartz veins; (ii) a main productive event with quartz–scheelite–pyrite–arsenopyrite, sulfosalt–sulfide and quartz–stibnite stages; and (iii) a late barren quartz–carbonate event (Goryachev *et al.* 2008).

The *Olympiada Au deposit* (Figure 8) had pre-production reserves of some 550–600 t Au; currently remaining reserves are about 415 t Au (Russian C_1+C_2 reserve categories), with the average grade of 3–4 g/t Au in primary ores and ~ 10 g/t Au in supergene ores. The deposit is situated in Central Siberia near the western edge of the Siberian Craton in the Yenisei Ridge terrane composed of Paleoproterozoic to Upper Neoproterozoic (Mesoproterozoic)–Lower Paleozoic metasedimentary and igneous rocks, metamorphosed to amphibole and amphibole–epidote greenschist facies. Here, an important belt of Au and Au–Sb deposits (Olympiada, Veduga, Eldorado, Sovetskoe, Udereiskoe, Gerfed) extends along the margin of the Siberian craton (Yakubchuk *et al.* 2005 and references therein; Nokleberg 2010).

The Olympiada deposit area is characterised by metasedimentary terrigenous–carbonate; locally carbonaceous rocks form a large roof pendant in surrounding (and probably underlying) Neoproterozoic granitoid batholiths (Konstantinov *et al.* 2000). The Au mineralisation occurs in the contact zone between quartz–mica and carbonate–quartz–mica schists, and is controlled by a district-scale anticline, incorporating bedding-subparallel fractures, and its intersections by transverse fault zones. Several orebodies are present, with the largest one, about 130–170 m thick, up to 400 m long in the fold closure, accounting for about 90% of the reserves: this large orebody can be subdivided into two branches extending for 520 m and 320 m along strike, respectively, and steeply (60–80°) plunges down, where it was traced for at least 800 m. The orebodies are composed of carbonate–quartz–mica metasomatites containing 3–5 vol% sulfides (mostly arsenopyrite, pyrite, pyrrhotite, stibnite) and scheelite. Very minor chalcopyrite, sphalerite, galena, tennantite–tetrahedrite and Bi-minerals are locally present. Gold occurs in dispersed form in sulfides (arsenopyrite, pyrite) and as free native Au, with the fineness of 910–990 in early (pyrite–arsenopyrite) assemblages and 650–750 in late (stibnite) assemblages. Arsenopyrite contains up to 2100 g/t Au (Genkin *et al.* 2002). The oxidised (supergene) ores are at a depth of 120–300 m; and are composed of a soft micaceous sandy–clay mixture corresponding to Cretaceous–Paleogene paleoregolith and containing up to 10 vol% sulfides. This material is dominated by native Au, with local bonanza grades of up to 450 g/t Au.

The *Nezhdaninskoe Au deposit* has resources >950 t Au, with an average grade of ~ 4 g/t. It is situated in the southern part of the Yana–Kolyma orogenic belt and is hosted in a weakly metamorphosed Permian to Triassic sandstone–shale sequence, intruded by small Cretaceous granitic intrusions and dykes. In the deposit area, the intrusions comprise at least two larger granite stocks about 5–7 km^2 (121–92 Ma) and various dykes, lamprophyre and gabbro–diorite (153–137 Ma), quartz diorite, granodiorite and plagiogranite porphyry (140–110 Ma) and rhyolite (81–79 Ma) (Bortnikov *et al.* 1998). The deposit occurs in the closure of a regional (10×60 km) anticline and is related to series of generally steeply dipping to subvertical and flat-lying cataclastic and shear zones. This structural setting determines continuity of individual mineralised zones for at least 15 km along strike and 2 km downdip. The deposit area has more than 100 individual mineralised structures with only about 10% explored in detail.

The Au orebodies are of several types including: (i) quartz–sulfide veins typically with grades >5 g/t Au; (ii) mineralised tectonic zones containing 2–4 g/t Au; and (iii) mineralised stockworks, up to 40 m thick, averaging 2–5 g/t Au. The mineralised intervals are accompanied by hydrothermal alteration, including silicification and

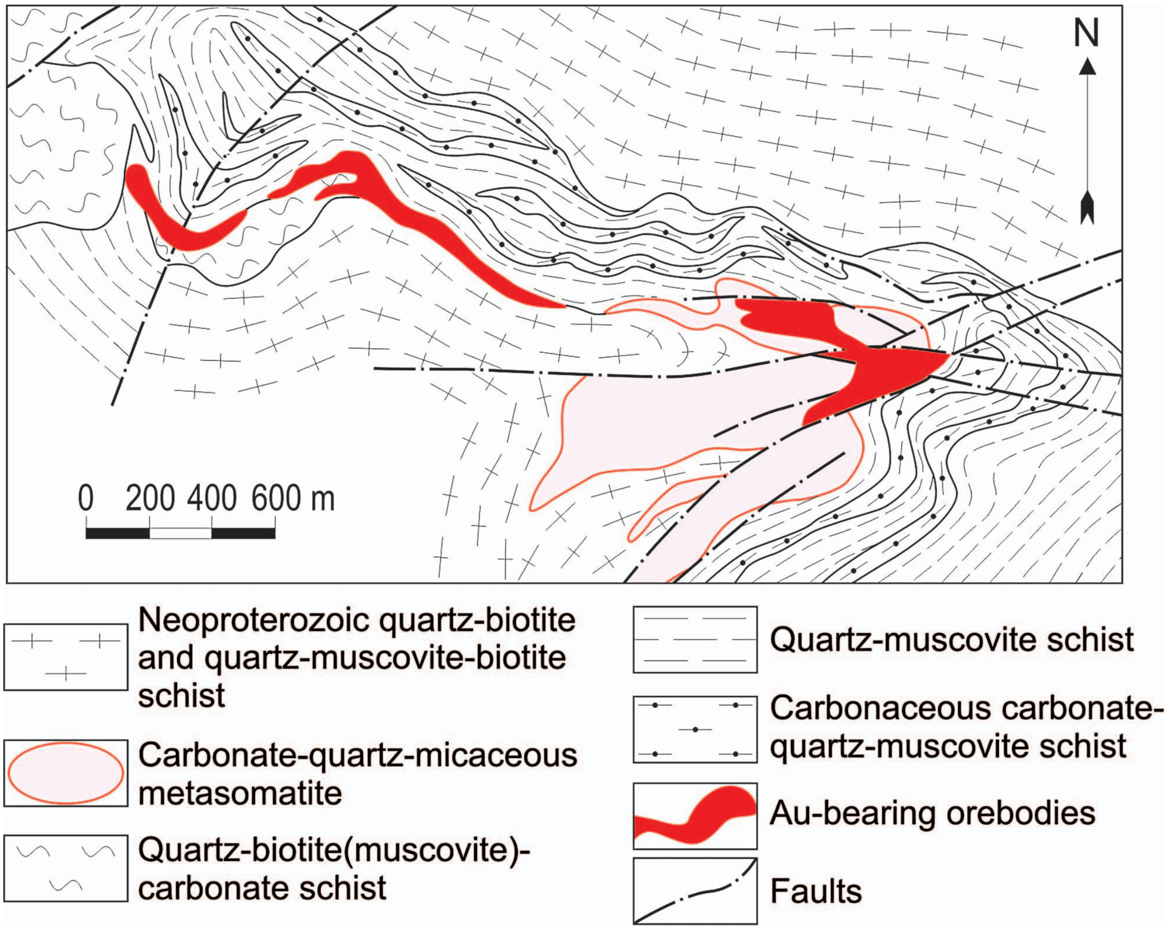

Figure 8 Geological map of the Olympiada Au deposit (modified after Konstantinov *et al.* 2000).

quartz–Fe-carbonate–sericite ± albite alteration. The mineralisation is characterised by low sulfide content typically not exceeding 5 vol%. The predominant sulfides are arsenopyrite and pyrite; both are enriched in Au (30–500 g/t Au in arsenopyrite and 10–150 g/t Au in pyrite). Other sulfides include sphalerite, chalcopyrite, galena, tennantite–tetrahedrite, bournonite, boulangerite and stibnite. Three major mineralising events are recognised: (i) a metamorphic event, with formation of low-Au (< 2 g/t) quartz veins; (ii) a main event with Au-bearing pyrite–arsenopyrite, scheelite–arsenopyrite–pyrite, sphalerite–chalcopyrite–galena and stibnite–fahlore stages, and related quartz–Fe-carbonate–sericite alteration; and (iii) a late hydrothermal event, with redistribution of earlier minerals and formation of freibergite–pyrargyrite–electrum assemblage. Gold varies in fineness from 560 to 900 (Bortnikov *et al.* 1998). In places, Au-bearing intervals are enriched in graphite.

The *Sarylakh Sb–Au deposit* contains some 130 kt Sb, with an average grade of 6 wt% Sb and 6 g/t Au. The deposit is situated in the Yana–Kolyma orogenic belt and, similarly to other deposits (e.g. Nezhdaninskoe) in this region, is hosted in a Triassic sandstone–shale sequence (Gamyanin & Goryachev 1988). In the deposit area, these rocks form a syncline some 12 km across; the deposit is located in a district- to regional-fault zone intersecting the syncline. A quartz–diorite porphyry stock dated at 120 Ma, and plagiogranite porphyry sill dated at 133 Ma are present about 2 km from the deposit. The plagiogranite is intersected by quartz veinlets with pyrite, arsenopyrite and stibnite.

The deposit is represented by series of subvertical quartz–sulfide veins and vein zones, with the largest vein some 10–20 m thick traced for several hundred metres and accompanied by quartz–sulfide stockworks. There are several generations of stibnite, with the early giant crystalline (up to 15 cm-long crystals), deformed by mylonitisation. Stibnite and quartz predominate, whereas other minerals (pyrite, arsenopyrite, bertierite, ankerite, sericite) together account for 1–10 vol% of the vein. Trace minerals include native Au, Ag, Sb, galena, chalcopyrite, tetrahedrite, zinkenite and jamsonite. Mineralising stages are: (i) quartz–carbonate–pyrite; (ii) weakly auriferous quartz–pyrite–arsenopyrite; and (iii) quartz–stibnite–bertierite–polysulfide stages. The latter stage also bears high-fineness native Au (Berger 1978).

Carlin-like type Au deposits

Carlin-type (or Carlin-style) Au deposits constitute another group of sediment-hosted Au deposits found in Siberian terranes. To some extent, carbonate-hosted Au deposits of the Aldan Shield can be assigned to this category (Yakubchuk *et al.* 2005) although their close relationships to alkaline (with shoshonitic affinity) igneous suites suggest a genetic relationship with these igneous rocks (Vetluzhskikh *et al.* 2002).

The *Kuranakh Au deposit* is hosted in Vendian–Lower Cambrian carbonate and Lower Jurassic terrigenous rocks overlying Archean metamorphic rocks. Igneous activity occurred in the deposit area but is represented only by small stocks, dykes and sills of pyroxene–biotite and amphibole syenites, felsic rocks, and lamprophyres of Mesozoic age. Gold mineralisation forms subhorizontal tabular zones, located along contacts of Cambrian carbonate and Jurassic terrigenous units as well as within these units. These tabular zones are aligned with two submeridional fault zones extending for 10 km and 25 km, respectively. Thickness of individual orebodies varies from 1 to 40 m. Total measured and indicated resources of the deposit exceed 300 t Au.

According to Smirnov (1977), mineralisation and alteration were formed in two stages. The early stage was intense potassic alteration of brecciated carbonate and terrigenous rocks, with their almost entire replacement by K-feldspar–quartz–pyrite and K-feldspar–quartz–carbonate–pyrite, locally with minor arsenopyrite. In a second stage, these assemblages were replaced by Au-bearing quartz–pyrite, quartz–adularia–pyrite, and quartz–pyrite–hematite, with minor carbonate and fluorite. These late assemblages are most abundant along meridional fault zones, outlined by lamprophyre (minette) dykes. Before, during, and after mineralisation, the rocks were also subjected to multiple brecciation. The primary mineralisation includes pyrite, marcasite, native Au and sporadic chalcopyrite, pyrrhotite, magnetite, galena, sphalerite, arsenopyrite, Te minerals, bismutite, native Bi, tetrahedrite–tennantite, bornite and stibnite. Native Au is represented by fine ($<$50–250 μm) particles, with the fineness varying from 700 to 970. Pyrite content in quartz–pyrite metasomatites varies from a fraction of percent to 5–10 vol%. The primary hydrothermal mineralisation was subjected to supergene alteration, characterised by karsting, oxidation and decomposition of sulfides and Fe-oxides, kaolinisation of feldspars, gravitational crushing and mixing, with deposition of supergene gold. As a result, the mineralised material is represented by a sand-and-gravel mixture averaging about 1 g/t Au forming subhorizontal pinching-and-swell lenticular orebodies extending for kilometres along strike.

Intrusive-related gold and associated deposits

This group incorporates gold and related Ag, Sb, U deposits, whose relationships to intrusions are well established. In most cases, these deposits occupy a proximal position to the supposed causative plutons, or are closely associated with more distal dykes, small stocks and accompanying breccia pipes. These deposits can be subdivided at least into two types: (i) Au deposits likely associated with Sn and W deposits, according to the model suggested by Thompson *et al.* (1999); and (ii) Au and associated deposits related to alkaline igneous suites, typically with shoshonitic affinity, according to the model suggested by Müller & Groves (1997), Chamberlain *et al.* (2007) and Cooke *et al.* (2007).

Au AND Ag DEPOSITS ASSOCIATED WITH Sn AND W MINERALISATION

The Au deposits of this group are especially numerous in the Okhotsk–Chukotka volcanic belt; typically, they occur as parts of large mineralised districts characterised by Sn–W, Sn–Au, and Au–Sb (to Au–Sb–Hg) deposits and occurrences (Gonevchuk *et al.* 2010). The Ag deposits are located in separate Sn–sulfide, Ag–sulfide, and Pb–Zn districts. Some of the deposits described in this section may have relationships to the granite-related deposits described in the following sections.

The *Maiskoe Au deposit* (Figure 9) is situated in north-central Chukotka, where several large intrusive cupolas, associated with radial and circular fault systems, control a series of proximal Sn–sulfide and distal Au and Au–sulfide deposits and occurrences (Struzhkov *et al.* 2008). The deposit contains about 280 t of Au, with an average grade of 12 g/t Au and is characterised by abundant Au-bearing sulfides (pyrite, arsenopyrite, stibnite).

The Maiskoe deposit is hosted in Triassic sandstone and conglomerate, forming a dome-like horst-anticline structure possibly underlain by a large felsic intrusive, suggested by geophysical data, to a depth of 2 km. The area above this intrusive is crowded with dykes and small stocks as well as outcropping explosive breccias. The dykes include older and larger granodiorite and granite porphyry, aplite and lamprophyre dykes, and younger (Late Cretaceous?) subvolcanic rhyolite porphyry dykes. The Au–As–sulfide mineralisation overprints all these dykes and the explosive breccias.

In total, about 20 orebodies are recognised: they are 2–4 m thick, 200–1100 m long, and vary in dip from moderately ($<70^{\circ}$) to steeply dipping ($>70^{\circ}$). The productive mineralisation was traced for $>$800 m in vertical section and is expected to continue for at least 400 m, totalling some 1200 m. The orebodies are represented by mineralised breccia zones that have been subjected to silicification, less intense phyllic (sericitic) and argillic alteration. Sulfide content averages about 6–8 vol%, with dominant pyrite. Stibnite is a minor ($<$0.5 vol%) ore mineral and is associated with quartz veinlets and veins. The Au mineralisation is represented mostly (90%) by finely dispersed gold (fineness 950) contained in sulfides (acicular arsenopyrite, pyrite); a minor (10%) fraction of gold is represented by larger aggregations of native Au with a fineness of 850–890. Three mineralising stages are recognised: (i) an early ‘rare-metal’ stage; (ii) an intermediate ‘productive’ stage; and (iii) a late Au-bearing quartz–stibnite stage. The intermediate stage was responsible for the formation of the ores, whereas their overprinting by native a Au-bearing

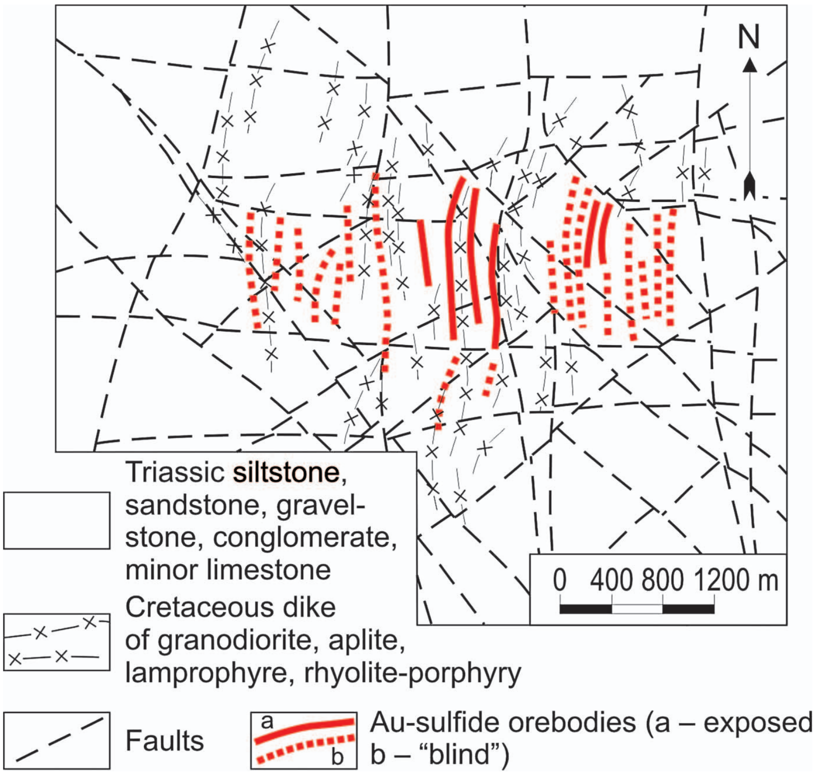

Figure 9 Geological map of the Maiskoe Au deposit (modified after Struzhkov *et al.* 2008).

quartz–stibnite assemblage provided the occurrence of localised higher-grade zones.

The *Prognoz* and nearby *Mangazeya Ag deposits* are situated in the Yana–Kolyma orogenic belt. Although they remain essentially underexplored, their reserve potential is significant. Current resources at Prognoz are about 7000 t Ag, with a potential that may possibly be double that figure. The average grade is 700 g/t Ag, These deposits were formed in distal intrusive-related settings and are associated with felsic dykes, assumed to be part of much larger intrusive-related district- to region-scale Sn–Ag mineralised systems (Gamyanin *et al.* 1998).

In particular, the Prognoz deposit is hosted in a Triassic sandstone–siltstone sequence, with a large granodiorite pluton, suggested by geophysical data, at a depth of 3 km. Diorite porphyry (113 Ma) and younger rhyolite porphyry and granite porphyry (82 Ma) dykes are present in the area, with the younger dykes intersected by Ag-bearing siderite–galena–sphalerite veinlets (Gamyanin *et al.* 1998). The deposit is sited in the closure of a large anticline, intersected by steeply dipping faults some of which host lamprophyre dykes. The mineralisation is controlled by these faults and the narrow orebodies commonly extend for 3–4 km along strike and are composed of brecciated sandstones with quartz–carbonate–sulfide cement. Quartz and quartz–carbonate veins with abundant sulfides are also present. Besides the common brecciated texture, the orebodies are also characterised by crustiform, cockade, colloform, banded and other textures suggestive of open-space filling. The mineralisation was formed during two major events: (i) an early event of quartz–sericite–carbonate–pyrite–arsenopyrite metasomatites affecting wide areas; and (ii) a late event of sulfide-dominated assemblages forming narrow veins. Galena, sphalerite and pyrite comprise ~10 vol% of the ores, although locally galena and sphalerite may constitute up to 40–50 vol%. Minor minerals are chalcopyrite, pyrrhotite, bournonite and various Ag–Pb–Sb sulfosalts. Tetrahedrite (freibergite) is the most important Ag mineral; it contains microinclusions of stannite, pyrargyrite and stephanite.

ALKALINE ROCKS AND RELATED Au DEPOSITS

These deposits are closely related to alkaline (alkalic) igneous suites, exhibiting shoshonitic petrological affinity (Cooke *et al.* 2007). In addition to Au–sulfide deposits commonly referred to as the shoshonite-related deposits (e.g. Lebedinskoe, Darasun, Mnogovershinnoe and other deposits), there are also U and U–Au deposits related to alkaline rocks.

The *Lebedinskoe Au deposit* is situated south of the Carlin-style Kuranakh deposit described above. In this area, Lower Jurassic terrigenous (<100 m thick) and Vendian–Lower Cambrian carbonate (dolomite and limestone 600–700 m thick) sequences overlie Archean gneisses, crystalline schists, granite gneisses and minor marbles. All these rocks are intruded by Mesozoic plutons of leucite-bearing to syenites and monzonites–syenites.

Gold mineralisation is localised in the Lower Cambrian carbonate rocks, and is represented by Au-bearing steeply dipping stockwork zones and subhorizontal replacement bodies, which tend to form multilevel systems. These replacement bodies include garnet–pyroxene, idocrase–pyroxene, chondrodite–pyroxene skarns near contacts of syenite intrusives. The subhorizontal orebodies are 3–10 m thick and extend for up to 1000 m, whereas the vertical veins attain 2000 m in strike length. The orebodies cut syenite dykes and intrusions.

According to Vetluzhskikh *et al.* (2002), the mineralisation consists of quartz, ankerite, pyrite, chalcopyrite, hematite and calcite with minor galena, pyrrhotite, tetrahedrite, sphalerite, bornite, scheelite and native gold. Major ore minerals are pyrite, chalcopyrite, sphalerite and locally hematite. Sulfides are abundant and commonly up to 75 vol% (mostly pyrite, locally chalcopyrite, galena, bornite); locally pyrite is replaced by hematite. Several mineralising stages are distinguished: (i) pyrite–ankerite (with scheelite); (ii) chalcedony quartz with adularia; (iii) hematite–quartz with chlorite; (iv) polysulfide stage (pyrite, chalcopyrite); (v) major Au-bearing stage with boulangerite and freibergite; and (vi) carbonate stage (calcite, siderite). Besides the Au-bearing orebodies, Pb, Zn and Cu sulfide mineralisation, as well as minor magnetite, also form separated tabular and vein-like concentrations. Native gold forms irregularly distributed fine inclusions in sulfides and gangue minerals; its fineness varies from 720 to 950. Gold grade is typically 1–2 g/t Au, locally up to 71 g/t Au. Some quartz–galena veins contain up to 295 g/t Au. In addition, fluorite and quartz–fluorite concentrations are common; fluorite occurs in subhorizontal concordant fracture systems and shallow-dipping breccia zones in association with quartz, chalcedony, calcite and galena.

The *Darasun Au deposit* (Figure 10) is situated in Eastern Transbaikalia (southeast Siberia, part of the Mongol–Okhotsk orogenic belt), where numerous Au deposits are part of large Mesozoic (typically Early Cretaceous) alkaline (shoshonite-related) mineralised systems that apart from Au, also include significant Cu–Au, Pb–Zn, Mo–Au, U and fluorite deposits. Many Au deposits, including Darasun, are considered to represent 'a porphyry component' of the respective porphyry–epithermal systems (Prokofiev *et al.* 2006). An example of epithermal Au deposit closely associated with the Darasun volcano-plutonic complex is described in the next section. An adjacent intrusion of Talatuy gabbrodiorite porphyry (opencast gold mine) has been dated by SHRIMP U–Pb zircon method (crystallisation age of 213.6 ± 2.8 Ma, Concordia age corrected for common lead, MSWD 0.19: R. Seltmann unpubl. data).

The Darasun deposit (Yurgenson & Yurgenson 1995) is related to a district-scale volcanic dome, with its central part occupied by subvolcanic plagiogranite porphyry intrusive accompanied by northwest-trending dyke-like apophyses. Explosive breccias are present in the central intrusive. The deposit incorporates >250

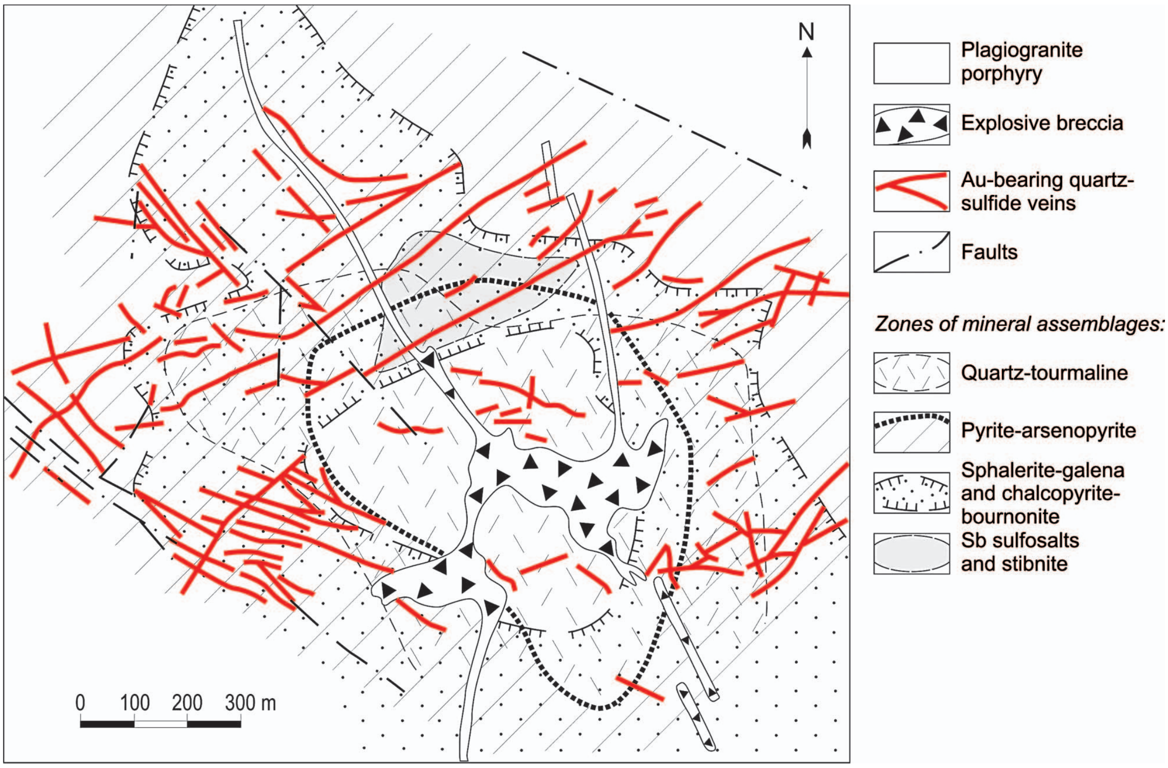

Figure 10 Geological and geochemical zonation scheme of the Darasun Au deposit (modified after Timofeevskyi 1972).

quartz–sulfide veins, with most of them striking northeast and northwest, thus, emphasising larger fault zones intersecting in the deposit area. Some veins are localised in concentric and radial fractures occurring in the volcanic dome.

The mineralised quartz–sulfide veins are accompanied by intense tourmaline, chlorite, quartz–sericite alteration that are also associated with the explosive breccias. Major sulfide minerals are represented by pyrite, arsenopyrite, chalcopyrite, sphalerite, tetrahedrite–tennantite, pyrrhotite and galena; minor sulfide minerals include stibnite, tetradymite and bournonite. Gold occurs in native form (fineness 890–900) and as Au tellurides closely associated with chalcopyrite, tetrahedrite–tennantite, and arsenopyrite. Four major mineralising stages are recognised: (i) barren quartz–tourmaline stage; (ii) quartz–pyrite–arsenopyrite stage; (iii) major productive quartz–polysulfide stage; and (iv) barren quartz–carbonate stage. Economic mineralisation averages about 15 g/t Au, accompanied by elevated silver (28 g/t Ag), copper (0.44% Cu), bismuth (0.015 wt% Bi) and arsenic (1.35 wt% As) concentrations.

The *Mnogovershinnoe Au deposit* is another large ($>$100 t Au) deposit related to shoshonitic magmatism. This deposit is located in the Circum-Pacific orogenic belt, more specifically, in the Sikhote–Alyn belt bordering the Asian continent south of the Okhotsk Sea (Figure 1) (Ivanov *et al.* 1989). The deposit area is composed of Upper Jurassic to Lower Cretaceous terrigenous sequences, unconformably overlain by Early Cretaceous and younger andesite–dacite volcanic suites; the volcanics also form necks and extrusions in local volcanic centres. These rocks are intruded by Paleogene monzonite, granite plutons and younger diorite to granite porphyry dykes as well as Neogene trachybasalt, trachyandesite, and syenite porphyry dykes. The deposit is localised in the contact zone of the monzonite–granite pluton intruding one of the volcanic centres.

All volcanic rocks found in the deposit area exhibit propylitic-type alteration (epidote–chlorite, epidote–biotite–amphibole), overprinted by phyllic alteration and host mineralised quartz veins and stockwork zones. Several tens of veins and stockworks are present, some of which can be traced for $>$3 km along strike and 500 m downdip. The ore zones are composed of quartz (90–95 vol%), adularia and sericite, with minor tourmaline, epidote and chlorite, and contain up to 5 vol% sulfides (pyrite, arsenopyrite, pyrrhotite, sphalerite, galena, chalcopyrite, tetrahedrite–tennantite and minor Ag, Te and Bi minerals), and locally magnetite and hematite. Minor molybdenite, cassiterite and wolframite are associated with a quartz–tourmaline stage overprinting Au mineralisation. The Au mineralisation is most intense in the altered volcanics, but is also present in the quartz monzonites. The mineralisation consists of several styles, including Au tellurides and native Au varying with fineness from 575 to 960. The Au:Ag ratio of the ores varies from 10:1 to 1:20. The early gold–chalcopyrite–fahlore and late gold–sphalerite–telluride assemblages represent the most productive ore.

The *El'kon mineralised district* in the Aldan Shield (southeast Siberia) includes large U (U–Au) deposits related to a Mesozoic alkaline plutonic suite and is in the vicinity of large sediment-hosted Au deposits (Kuranakh, Lebedinskoe) described above. Twenty-two significant U (U–Au) deposits distributed over an area of 500–600 km^2 have been explored, and measured and indicated resources are about 350 kt of U (Russian B+C$_1$+C$_2$ reserve categories), with inferred resources exceeding 300 kt of U (Russian P$_1$ resource category), making them some of the world's largest uranium concentrations. The deposits also contain about 1000 t Au, some Ag and Mo (Boytsov & Pilipenko 1998; Kazansky & Maximov 2000; Kazansky 2004).

The abundance of U mineralisation is so significant that the entire mineralised district can be considered as a giant stockwork of U-mineralised northwest-trending and submeridional fault zones. Structural and temporal coincidence of Mesozoic magmatism and U (U–Au) mineralisation is expressed in the spatial association of Jurassic alkaline dykes and brannerite–sulfide veinlets, cross-cutting dykes and zones of brecciation and hydrothermal alteration. The most impressive U-bearing mineralised fault zone (known as the Southern zone) is traced for almost 30 km; its central part about 20 km long, represents a single giant U deposit comprising a series of linear stockworks. The lateral extent of individual mineralised zones is typically 500–700 m and 0.5–10 m thick. Thicker U-bearing intervals usually incorporate several *en échelon* subvertical and subparallel linear stockworks. Uranium mineralisation is represented by brannerite and can be traced to a depth $>$1–2 km, with an average grade of 0.145 wt% U$_3$O$_8$. The average Au content in the U orebodies is $\sim$1 g/t Au, and Ag content is 8–15 g/t Ag (Kazansky & Maximov 2000).

Other mineralised zones are characterised by different geochemical features. For example, mineralisation in the Fedorovskaya zone (Lunnoe and other deposits) contains 3–10 g/t Au (average 4.7 g/t Au), 20–60 g/t (up to 1400 g/t) Ag and 0.1 wt% U$_3$O$_8$ (averaging 0.06 wt% U$_3$O$_8$ within the Au ore zones), thus constituting a distinct Au–Ag–U subtype. In contrast, in the Interesnaya zone attains an average grade of 0.3 wt% U$_3$O$_8$, whereas Au grade is lower (average 0.5 g/t Au). Finally, in the Mineevskoe deposit, the mineralisation also contains Mo, with an average grade of 0.15 wt%. Miguta (1997, 2001) distinguished a number of mineralising stages that, from early to late, include: albite–sericite–chlorite–hematite, adularia–carbonate–pyrite, carbonate–pyrite, quartz–barite–sulfide, brannerite (the main ore-bearing stage), fine-grained quartz, molybdenite–brookite, carbonate–coffinite, uraninite–anatase and carbonate–quartz–fluorite stages. Sulfides associated with barite, also include chalcopyrite, tennantite–tetrahedrite, enargite, galena and sphalerite. Pyrite contains significant mixtures ($\sim$75–80 g/t Au) of dispersed gold; native Au (fineness 700–980) in the carbonate–coffinite stage locally reaching grades of up to 100 g/t Au. Abundant fluorite is present in some deposits.

Epithermal volcanic-associated vein/stockwork deposits

This style of hydrothermal mineralisation is represented by several Au, Au–Ag, Ag, Hg, and U deposits, mostly situated in the easternmost metallogenic belts of Siberia, such as Mongol–Okhotsk and especially Okhotsk–Chukotka belts. These deposits include Balei, and Taseevskoe in Eastern Transbaikalia, Pokrovskoe Au deposit in the Amur region, Kuchus Au–Hg deposit in the Yana–Kolyma belt, Kupol, Kubaka, Dukat and other Au–Ag and Ag deposits in the Okhotsk–Chukotka belt, Zapadno–Palyanskoe, Plamennoe Hg deposits in the Okhotsk–Chukotka belt, Streltzovskoe, U and U–fluorite deposits in the Mongol–Okhotsk belt (Figure 1). All these deposits are related to volcanic activity and in many cases are part of large porphyry–epithermal systems.

In particular, the *Baley Au deposit* is situated in Eastern Transbaikalia (southeast Siberia), on the south-southeast continuation of a blind fault zone traceable from the Darasun Au–sulfide deposit described above. As previously mentioned, it is generally considered (Prokofiev *et al.* 2006) that these deposits are part of a porphyry–epithermal system, with the Darasun deposit representing the porphyry sector, and the Baley deposit representing the epithermal environment.

The Balei deposit (high-sulfidation) is in a graben-like trough containing Upper Jurassic continental molasse ~800–1000 m thick. The Au mineralisation is concentrated in the southern and central parts of the graben and occurs as series of subparallel steeply dipping veins 0.2–2.0 m and more thick, and a complex stockwork of steeply dipping and flat veins in the northern part of the graben. The veins are for 90–99 vol% composed of fine-grained and chalcedony-like quartz, with minor carbonates, adularia and kaolinite. Sulfides form <1 vol% of the veins and are represented by pyrite, marcasite, arsenopyrite, tennantite–tetrahedrite, pyrargyrite, miargyrite and Te minerals. At the junctions of flat-lying and steeply dipping fractures there are high-grade ore shoots composed of native Au, tennantite–tetrahedrite and pyrargyrite. The late mineralising stage included formation of chalcedony quartz and carbonates associated with stibnite.

The *Kupol Au–Ag epithermal low-sulfidation-style deposit* (Figure 11) is situated in the Chukotka sector of the Okhotsk–Chukotka volcanic belt. It has reserves (Russian C_1+C_2 categories) of ~140 t Au, with the average grades of 23–25 g/t Au, and Ag reserves of ~1000 t, with the average grade of ~250 g/t Ag. The deposit is localised within a 10 km-wide caldera emplaced in Jurassic sedimentary sequences and composed of Cretaceous felsic tuffs and ignimbrites, andesite to andesite–basalt lavas, and felsic tuffs and lavas (Struzhkov *et al.* 2008). These volcanics are overlain by Paleogene basalts. The andesitic units are intruded by rhyolite and basalt dykes as well as by rhyolite and dacite extrusive domes.

The deposit is represented by a subvertical (typically 75–90°) vein zone up to 20 m thick consisting of quartz and quartz–adularia veins extending for almost 4 km along strike and traced for >400 m downdip. Several subvertical rhyolite and rhyolite–dacite dykes, up to 70 m thick, are present within or adjacent to the quartz veining zone; they contain xenoliths of mineralised quartz veins. Garagan & Cameron (2006) reported the linear character of the vein zone at Kupol, with local dilational jogs, sinusoidal sways, branches, anastomosing vein sets and sigmoidal loop structures. The jogs often correspond to first- and second-order dilational zones with resultant thickening of the veins and development of higher-grade shoots.

According to Garagan & Cameron (2006), the quartz–adularia veining is accompanied by proximal silicification, potassic and argillic alteration grading into distal propylitic (chlorite–calcite–sericite–pyrite–epidote) alteration. A broad chlorite zone is present at depth, with chlorite–pyrite+magnetite-rich bands and clots within the banded quartz veins. A jarosite–gypsum-rich clay–sulfate alteration is common, with local predominance of either smectite–kaolinite, or (at deeper levels) illite–montmorillonite–smectite assemblages. Alteration halos are as wide as 300–400 m. Two productive stages are distinguished: (i) weakly productive quartz–adularia–pyrite stage; and (ii) major quartz–adularia–pyrargyrite–stephanite–gold stage. Gold and silver mineralisation occurs in low sulfide (<2% sulfides) and high sulfide (2–7% sulfides) massive and brecciated colloform- to crustiform-banded quartz–adularia veins and polyphase breccias. The high-sulfide veins carry the highest grades. The Au:Ag ratio is 1:11. The predominant Au and Ag minerals are electrum, native Au (fineness 300–875), freibergite, acanthite and various sulfosalts dominated by stephanite and pyrargyrite. Coarse-bladed stibnite is present locally. Later quartz, including amethyst, commonly occurs as open-space filling. Quartz pseudomorphs of bladed calcite (lattice texture; due to boiling fluids) are present throughout most of the deposit but are more prevalent near-surface. Vuggy, drusy and frothy textures, representing a near-surface environment, are also present.

The *Kubaka Au–Ag deposit* (probably low-sulfidation) is situated further south in the Okhotsk–Chukotka volcanic belt (northeast Russia) with pre-production reserves of about 100 t Au, and an average grade of ~8 g/t Au. The deposit is within a large trough composed of Paleozoic and Mesozoic sedimentary and volcanic sequences overlying the Omolon microcontinent. Felsic, intermediate and alkaline magmatism occurred in the Early and Middle Paleozoic, Jurassic and Cretaceous. The Kubaka mineralised district incorporating also other smaller Au and Au–Ag deposits corresponds to a large Middle–Late Devonian stratovolcano. The central part of the stratovolcano is composed of trachyrhyolite ignimbrites and lava breccias, and its periphery is composed of tuffaceous sandstones, argillites, intermediate and felsic tuffs, less often ignimbrites and agglomerates. Subvolcanic bodies of trachyrhyolite and rhyolite–dacite are common.

The Kubaka deposit is located at the periphery of the stratovolcano, and is represented by fault-controlled subvertical veined zones composed of Au-bearing quartz–adularia, quartz, and carbonate–quartz altered rocks, forming a widening upward fan-like structure. Thickness of individual veins is 1–3 m, and that of vein zones varies from a few metres to 30–40 m. The vein zones can be traced for 500–700 m downdip but economic mineralisation is in the uppermost 220 m. The veins are characterised by multiple brecciation and superposition of several mineralising stages.

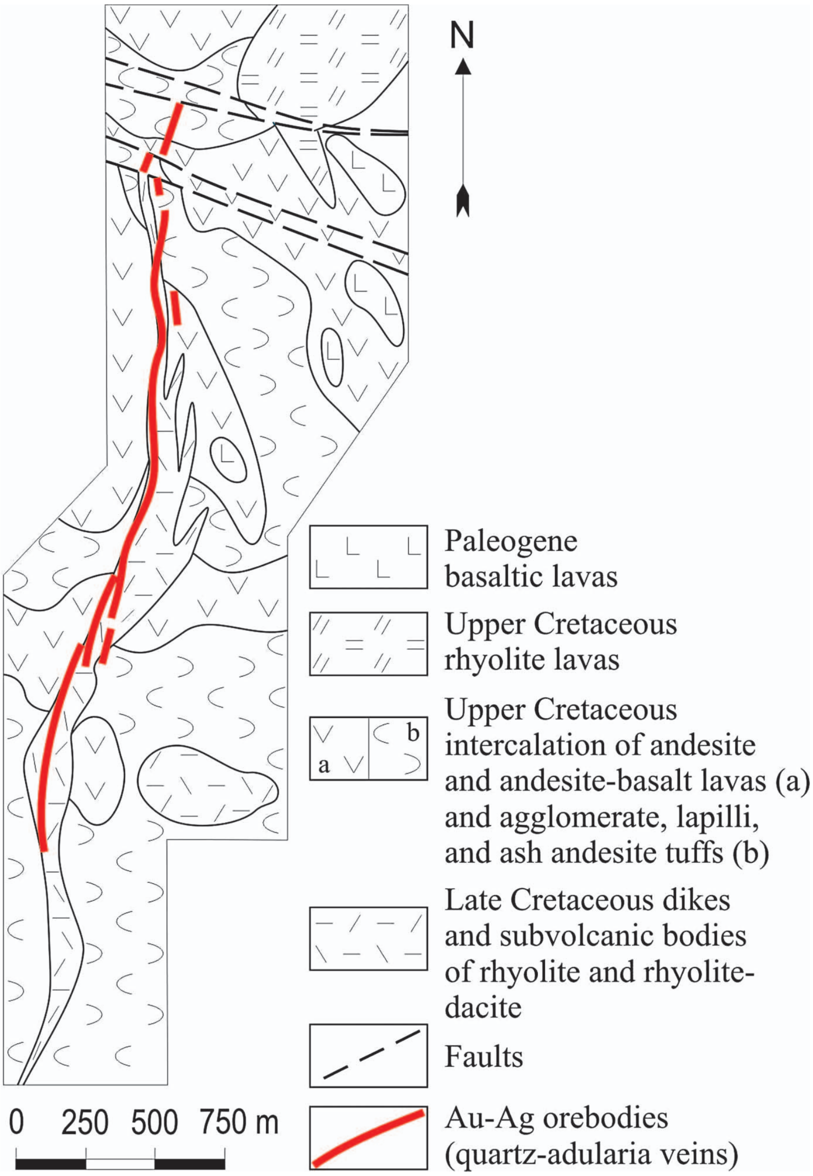

Figure 11 Geological map of the Kupol Au–Ag deposit (modified after Struzhkov *et al.* 2008).

Two major Au-mineralising stages are recognised, namely, an early quartz–anorthoclase–carbonate stage, and a late quartz–adularia–chlorite stage. They are separated by breccias that have quartz–chalcedony cement and are weakly mineralised. Content of ore minerals in the Au-bearing veins is low (~0.5 vol%); these minerals include native Au (fineness 600–750), pyrite, arsenopyrite, galena, freibergite, akantite, electrum, kustelite and native Ag. The Au:Ag ratio is high (1:2). Free native Au predominates. The ores are characterised by colloform, banded, crustified and other textures indicative of near-surface environments. The veins are accompanied by chlorite–hydromica alteration.

The *Dukat Ag deposit* (Figure 12) is also situated in the Okhotsk–Chukotka volcanic belt; it has pre-production Ag reserves of about 17 kt Ag, with the average silver grade of 500 g/t Ag. It also contains substantial Au reserves (40 t Au), with an average grade of 1 g/t Au. The Dukat and several smaller Ag deposits are within the Omsukchan rift, established in the Early Cretaceous over Triassic–Jurassic basement and composed of thick continental coal-bearing molasse, overlain by andesite and rhyolite lavas, with younger subvolcanic facies (Konstantinov *et al.* 2000). Cretaceous multiphase diorite–granodiorite–granite plutons and Late Cretaceous K-rhyolite, porphyritic rhyolite, rhyolite–dacite–porphyry and Paleogene basaltic dykes are widespread.

The deposit area is spatially associated with an intrusive–volcanic dome composed of ultrapotassic rhyolite lavas, ignimbrites and tuffs overlain by andesite lavas intercalated with black argillites. Numerous subvolcanic bodies and dykes of rhyolites, magmatic breccias of rhyolite, ring dykes of rhyolite and diorite

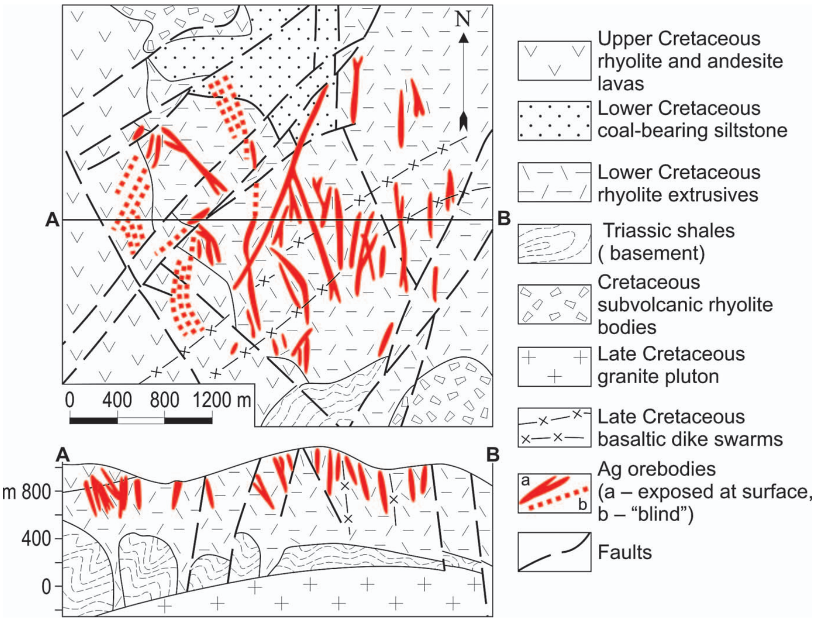

Figure 12 Geological map and cross-section through the Dukat Ag deposit (modified after Konstantinov *et al.* 2000).

stocks are present. They are within a semicircular zone (ring complex) surrounding the dome. In the central parts of the deposit, large biotite granite and granodiorite intrusive bodies were encountered by drilling at a depth of 1200–1500 m; these intrusions intersect volcanic rocks. The dome is also intersected by basaltic dyke swarms. The Early Cretaceous ultrapotassic rhyolite, rhyolite ignimbrite and argillite horizons are the major hosts for Ag mineralisation. Subvolcanic rhyolite is on the periphery of the dome and hosts pipe- and vein-like bodies with Ag and Ag–Pb–Zn mineralisation. The mineralisation was immediately preceded by injection breccias forming dykes, lenses, veins and veinlets composed of pebble-like rock fragments. These breccias are most closely associated with the hydrothermal system that formed the mineralisation.

The orebodies are controlled by both steeply dipping (60–90°) and flat-lying fracture zones, with the dominantly important steeply dipping zones hosting >60% of Ag reserves, and being characterised by strong variability in shape, vertical and lateral extent, and thickness, with common pinching-and-swelling, branching and splitting (Konstantinov *et al.* 2000). The mineralisation consists of: (i) quartz–chlorite–magnetite–pyrite–Pb, Zn, Cu sulfides–fahlores–akantite; (ii) quartz–adularia–Pb, Zn, Cu sulfides–native Au–kustelite–native Ag–pyrargyrite; (iii) quartz–rhodonite–rhodochrosite–garnet–axinite–tourmaline–helvine, Pb, Zn and Cu sulfides, native Ag–akantite; and (iv) supergene native Ag+Au. Apart from native Ag, this precious metal is contained in a number of minerals including akantite, polybasite, pyrargyrite and kustelite, and also galena and sphalerite. Gold is present in native Ag, kustelite, electrum and native Au; Au fineness in native Ag is 50–150, kustelite 150–600, native Au and electrum 320–570, occasionally 800–900. Supergene native Ag (55–60%) predominates over hypogene native Ag. The ores are characterised by highly variable textures including banded, brecciated, massive and crustified. In general, the amount of sulfides increases with depth, as do albite, calcite, garnet and magnetite.

The *Kuchus Au–Hg–As–Sb–Ag deposit* is situated in the northern part of the Yana–Kolyma orogenic belt (Figure 1). It contains 135 t Au (Russian C1+C2 reserve categories), with average grades of 8.5 g/t Au, 1.0 g/t Ag, 0.4–0.5 wt% Sb, 0.024 wt% Hg and 1.5 wt% As. The deposit is represented by steeply dipping (70–80°) mineralised breccia zones, 1–5 m thick, extending 0.3–3.5 km along strike and traced for 150 m downdip.

According to Berger (1978), the early Au–stibnite mineralisation is overprinted by a younger carbonate–cinnabar–dickite assemblage. Two generations of stibnite are recognised: (i) an early cataclastic stibnite associated with high-fineness (950–960) native Au; and (ii) a late acicular stibnite associated with low-fineness (260–365) native Au, cinnabar, realgar, chalcedony and Mn–siderite. Both the early and late native Au contain Hg mixtures of 11 wt% and 17–19 wt%, respectively.

The *Zapadno-Palyanskoe Hg deposit* is also situated in the Okhotsk–Chukotka volcanic belt, in its northern (Chukotka) part, and contains 11 kt Hg, with an average grade of 0.53 wt% Hg. The deposit is localised within a large Hg–Sb–Au metallogenic zone that includes, besides this deposit, the Plamennoe Hg–Sb deposit and several other Au–Ag deposits.

The *Plamennoe Sb–Hg deposit* is situated in the northern Okhotsk–Chukotka volcanic belt. It is localised in a district-scale fault zone and is represented by large flat-lying orebody and series of lenses and veins. They are in a Lower Cretaceous rhyolite sequence, below a horizon of argillic-altered tuffs, tuffaceous lavas and breccias overlain by a rhyolite sheet. The mineralisation is accompanied by intense silicification, opalisation of rhyolites, with the formation of abundant chalcedony. Several brecciation events are distinguished, with brecciation and recrystallisation of early metasomatites and further replacement of opal and chalcedony by quartz, and again by replacement of quartz by chalcedony. Cinnabar–stibnite mineralisation overprints silicified rocks and is accompanied by hydromicas and marcasite, and distally by dickite (Berger 1978).

Small veins are composed of fine-banded chalcedony and opaline silica, with alternating fine bands of chalcedony, stibnite and marcasite. Some veins also contain fine-grained cinnabar, metacinnabarite and pyrite. In contrast, the main orebody is composed of disseminated cinnabar–dickite–quartz mineralisation, with the presence of prismatic and acicular stibnite, realgar, marcasite, microdrusy quartz and dickite. At the intersections of the early and late veinlets, recrystallisation of early chalcedony and stibnite into drusy and prismatic aggregations is observed. The Sb content in the mineralisation increases with depth.

The *Streltsovskoe U (U–fluorite) deposit* (Figure 13) is situated in southeast Siberia (Eastern Transbaikalia: Figure 1) and is part of a cluster of U deposits comprising 19 significant economic deposits, known as the Streltsovsky mineralised district. In total, these deposits contain ~250 kt U. This ore cluster is in a large volcanic–tectonic caldera formed in the Late Mesozoic (Jurassic–Cretaceous) over heterogeneous Proterozoic–Paleozoic basement. The thickness of the Mesozoic formations is typically 500–900 m but up to 1400 m in peripheral parts of the caldera.

The Streltsovskoe deposit accounts for ~20% of the U reserves in the mineralised district. The deposit occupies about 10 km^2 and extends as a north–south-trending belt about 4 × 25 km. There are two structural levels: (i) a lower level composed of leucocratic granite porphyry; and (ii) an upper level composed of Upper Jurassic and Lower Cretaceous sequences about 1000 m thick forming a shallow-dipping (5–10°) monocline (Ischukova 1995). The Upper Jurassic sequence is represented by conglomerates, basalts and trachydacites, whereas the Lower Cretaceous rocks include conglomerates, basalts and felsic lavas. The mineralisation is controlled by numerous subvertical zones of intense faulting, fracturing and brecciation, and has a vertical extent of about 480 m. The majority of U reserves are concentrated at a depth of 300–550 m below the surface. The U mineralisation forms large subvertical stockworks and veins, with grades typically of about 0.20–0.30 wt% U, but locally up to 2 wt% and more (Ischukova 1995). Notably, U mineralisation occurs also in the underlying leucogranites (the most significant deposit of this style is referred to as the Antei deposit that underlies the Streltsovskoe deposit).

The mineralisation was formed in the Early Cretaceous (140–125 Ma) during several mineralising stages. The early stage is represented by hydrothermal alteration of the host volcanic rocks, with formation of hydromicas, carbonates (siderite, ankerite, calcite), chlorite, quartz and locally kaolinite. Brecciated veins were formed, with their cement composed of fine-grained quartz containing fine-disseminated iordizite and low-Fe sphalerite. The next, major U-bearing, stage

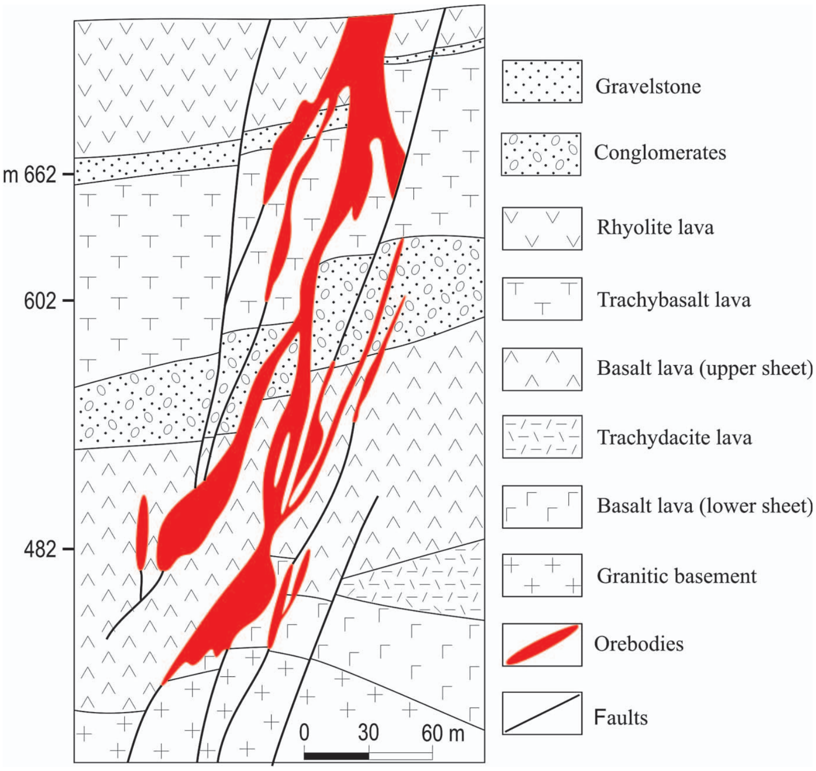

Figure 13 Schematic cross-section through the Streltzovskoe U deposits (modified after Ischukova 1995).

included formation of pitchblende, with variable amounts of brannerite and coffinite, with local occurrence of uraninite (Ischukova 1995; Aleshin *et al*. 2007). This mineralisation is accompanied by abundant dark-purple fluorite, and by intense albitisation and hematitisation of the country rocks. Formation of abundant fluorite continued in the later stages, together with carbonate, chlorite, hydromicas and sulfides (pyrite, galena, chalcopyrite, pyrrhotite, tennantite–tetrahedrite).

Granite-related Sn, W, Mo greisen, vein and stockwork deposits

This group incorporates a broad variety of pluton-related Sn, W, Mo and other deposits in close proximity to the parental plutons and represented by greisens, veins and stockworks. There are two principal varieties of these deposits: (i) Sn–W; and (ii) Mo–W. This reflects the common occurrence of Sn and Mo deposits in different metallogenic belts that differ by tectonic environments and type of productive granitic magmatism, generally corresponding to S- and I-type granitoids. The geodynamic evolution of the respective terranes, caused emplacement of A-type granitoids which were accompanied by more complex Sn- or Mo–W–rare metal (Be, Ta) mineralisation. The Sn–sulfide deposits are also included in this group due to their relationships to some Sn–W deposits.

The *Iultin Sn–W deposit* in Chukotka is localised in the exocontact zone of a large S-type granite pluton intruded into a metamorphosed Triassic sandstone–shale sequence. The deposit consists of numerous quartz veins set in a zone about 150–200 m thick, which can be traced for several kilometres. All productive mineralisation is localised above the granite contact, although some Sn–W-bearing veins extend into the granite. Thickness of individual veins varies from a few centimetres to 3.5 m, whereas strike and dip extent range from few metres to 500 m. At depth, the quartz veins merge and form stockwork-like zones 20–30 m thick. The veins are composed of quartz (90–95 vol%), with minor muscovite, albite, topaz, fluorite and carbonate. The ore minerals comprise cassiterite and wolframite with lesser chalcopyrite, pyrite, pyrrhotite, arsenopyrite and scheelite.

The *Pyrkakai Sn deposit* in Chukotka is also related to a large pluton of S-type granitoids. The deposit, containing 260 kt of Sn (Russian B+C1 reserve categories), with an average grade of 0.23 wt% Sn, consists of a quartz–cassiterite stockwork system, sited above a series of intrusive cupolas.

The *Pravo–Urmiiskoe Sn deposit* in the Khabarovsk region (eastern Siberia: Figure 1) has reserves of 93 kt Sn, with an average grade of 0.84 wt% Sn. The mineralisation is characterised by stockworks above a flat-lying granite porphyry dyke and hosted in rhyolite ignimbrites. The stockwork is not very thick (4–17 m), but extends for a significant strike length ($>$2400 m) and width (950 m), and is composed of quartz–topaz–cassiterite greisens contained in thin veinlets.

The *Dzhida group of W and Mo deposits* (Figure 14) is situated in Western Transbaikalia (Figure 1), and was formed during Mesozoic anorogenic tectonic and magmatic processes that affected Caledonian orogenic terranes of the Mongol–Okhotsk orogenic belt. In addition, there are also several other significant W and Mo deposits in this region. Tungsten mineralisation typically was formed after Mo ores, and in many cases is much more concentrated than the latter. Some deposits are characterised by a close association of W with base-metal mineralisation that was generally formed together, but more typically overprints the most intense W mineralisation. In this type of deposits, W mineralisation is accompanied by fluorite associated with chalcedony-like quartz. Another common feature is close association of W with Mn that is expressed both in formation of huebnerite and rhodochrosite.

The three most significant deposits of the Dzhida group (Figure 14) are the: (i) Pervomaiskoe stockwork Mo deposit; (ii) Kholtoson vein W deposit; and (iii) Inkur stockwork W deposit. The Pervomaiskoe deposit is a mushroom-shaped Mo stockwork about 550 × 600 m across and 250 m thick, grading 0.1–0.15 wt% Mo. The stockwork is composed of early quartz–microcline veinlets, with minor muscovite, fluorite, oligoclase, hematite, chalcopyrite, magnetite and pyrite. The main productive quartz–molybdenite veinlets are in the uppermost part of the pluton and also containing muscovite, fluorite, pyrite and pyrrhotite. The late mineralising stage is represented by quartz–pyrite veinlets, mostly in exocontacts of the pluton.

The Kholtoson deposit is represented by quartz–huebnerite–sulfide veins $\sim$1–4 m thick (occasionally up to 12–15 m) extending for up to 0.5–2.0 km and 500–600 m downdip (Shcheglov 1966). Several varieties of veins are present, such as barren microcline veins, the ore-bearing quartz–huebnerite–pyrite, quartz–huebnerite–sulfide veins, quartz–rhodochrosite–huebnerite–sulfide veins, and late barren quartz–fluorite veins. The veins are associated with fine-grained sericite–carbonate–fluorite–quartz–pyrite alteration zones, some huebnerite–pyrite veins and also by coarse-grained muscovite–fluorite–pyrite rims. The quartz–huebnerite–sulfide veins include those with or without abundant tetrahedrite–tennantite. Other ore minerals include galena, chalcopyrite, pyrite, sphalerite, locally scheelite, and trace apatite, topaz, Bi-minerals and stannite. The quartz–rhodochrosite–huebnerite–sulfide veins also contain abundant fluorite, pyrite, galena, sphalerite, chalcopyrite, and minor ankerite, sericite, tetrahedrite–tennantite, beryl and scheelite.

Finally, the Inkur deposit is represented by quartz–huebnerite stockworks, averaging 0.15 wt% WO_3. The stockwork is 0.8 × 2.3 km across, but three sectors of denser quartz–huebnerite veining 60–250 m thick can be distinguished. Besides quartz and huebnerite, the veinlets also contain scheelite and sulfides (pyrite, galena, sphalerite, chalcopyrite, tennantite–tetrahedrite).

The *Kalguty (also spelled Kalguta) Mo–W–Bi–Be deposit* (Figure 15) is situated in the Altai–Sayan orogenic belt (southwest Siberia: Figure 1); it is related to Triassic–Jurassic anorogenic magmatism that affected this Caledonian–Hercynian orogenic belt (Vladimirov *et al*. 1998; Annikova *et al*. 2006, 2007). The deposit

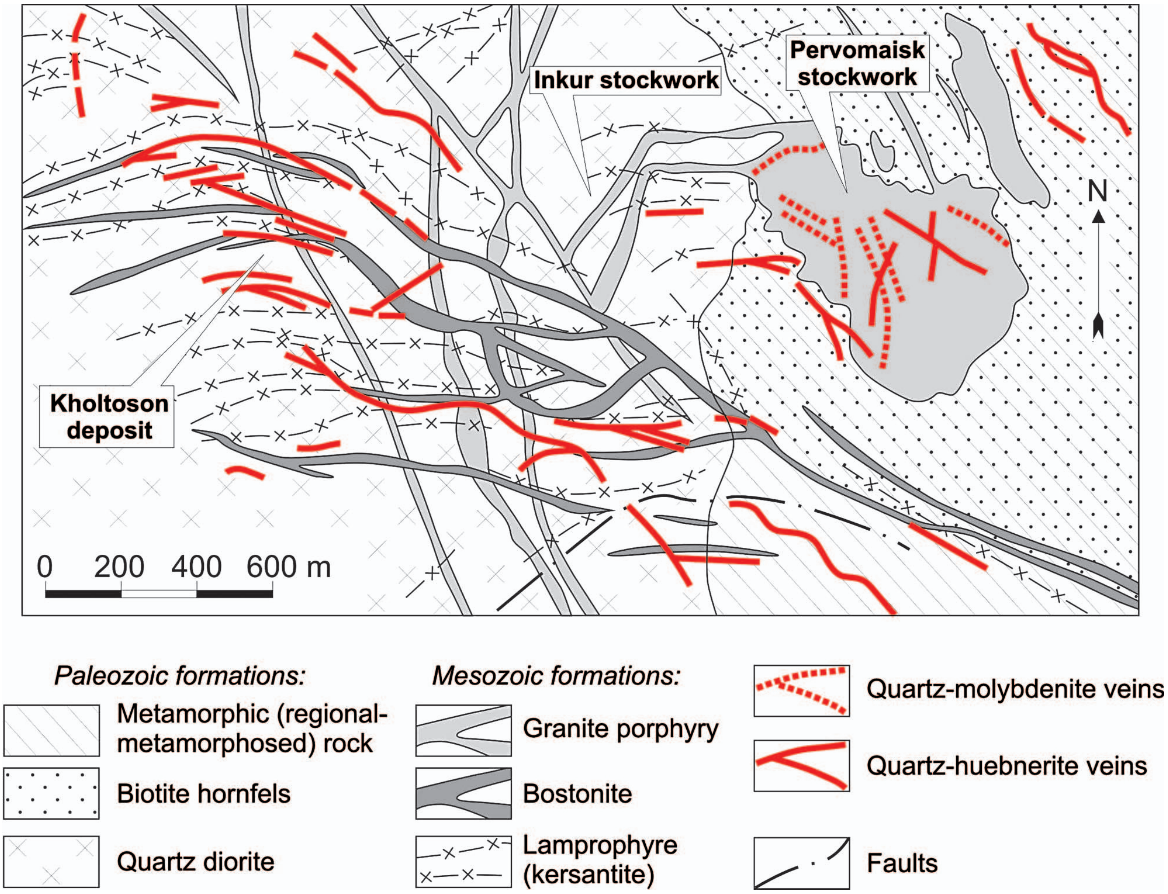

Figure 14 Geological map of the Dzhida W–Mo mineralised district (modified after Shcheglov 1966).

had pre-production reserves of 50 t WO$_3$ and 10 t Mo, with average grades of 1.9 wt% WO$_3$, 0.36 wt% Mo, 0.11 wt% Bi and 0.35 wt% Be.

The Kalguty greisen deposit is associated with a multiphase granitoid pluton 70 km^2 in area intruding Lower–Middle Devonian volcanic–sedimentary sequences. The pluton comprises older leucogranite and a younger dyke suite. The granitic rocks of the pluton are ($\sim$90%) composed of biotite granite porphyry and biotite–muscovite to muscovite leucogranite. The younger dykes are ongonites and other Li–F-rich rocks, which form a belt about 10 km long. These include a granitic rock strongly enriched in Cs (up to 1800 g/t) and P (up to 0.96 wt%).

The deposit is characterised by W and/or Mo mineralised greisens, veins and stockworks, and also substantial Be, Cu and Bi mineralisation. The veins are usually $<$1 m thick but can attain 1000 m in strike length. The vertical extent exceeds 500 m. The greisens form mushroom-shaped and pipe-like bodies close to intrusive contacts and locally overprint intrusive breccias. Quartz–tourmaline–wolframite veins are closely related to the biotite granite porphyry, whereas Mo-bearing greisens are associated with the muscovite granite porphyry. Quartz–huebnerite–beryl and quartz–sulfide–sulfosalt mineralisation is associated with Li–F-enriched dykes and generally occurs in the same controlling structures. Fluorite, topaz and scheelite are also present in the alteration assemblages (Pozeluev *et al.* 2006).

The sequence of magmatism, metasomatism and mineralisation is as follows (Vladimirov *et al.* 1998 and references therein; Annikova *et al.* 2007). The emplacement of the main phase biotite granite was accompanied by quartz–tourmaline–wolframite veins and the formation of quartz–molybdenite veins. This was followed by the granitoid intrusions associated with greisen and magmatic–hydrothermal breccias containing disseminated pyrite, molybdenite, chalcopyrite and wolframite with a molybdenite Re–Os age of about 213 Ma. Emplacement of ongonite, dykes and stocks followed at 204–202 Ma. Roughly coeval or post-dating the ongonites are rare-metal quartz veins with wolframite, molybdenite, beryl, bismutite and chalcopyrite. Melt inclusions in quartz from dykes show temperatures ranging from 610 to 580°C. Sm–Nd isotopic data of the Kalguty igneous rocks show negative ϵ_{Nd}(T) ranging from –3.7 to –9.9 and low radiogenic Pb isotopic ratios (^{206}Pb/^{204}Pb = 18.305–18.831; ^{207}Pb/^{206}Pb = 15.527–15.571), which Annikova *et al.* (2006, 2007) interpreted as mantle derived. The Kalguty

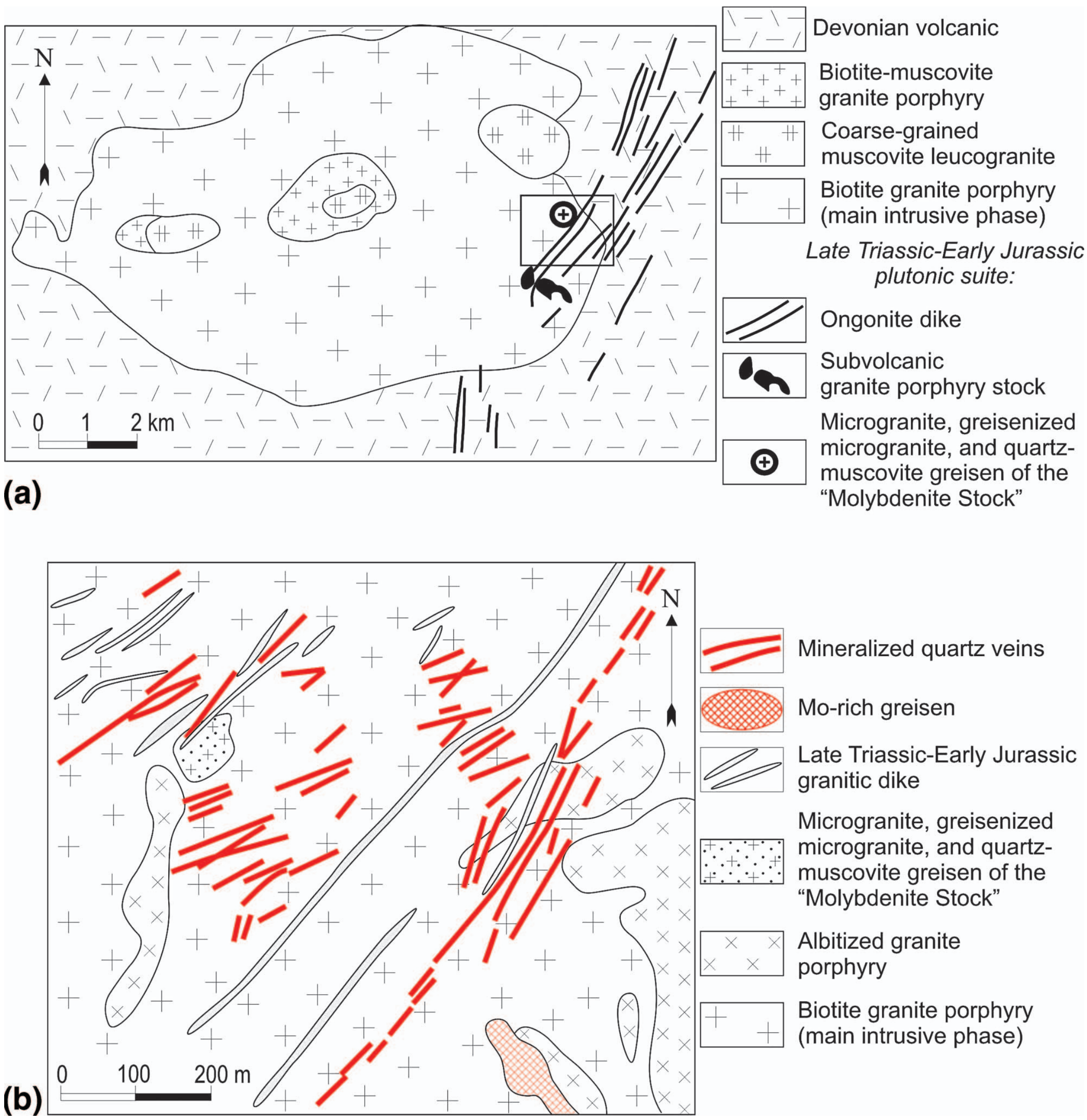

Figure 15 Simplified geology of (a) the Kalguty granitic pluton and (b) the Kalguty deposit (both modified after B. Sementzov unpubl. data).

magmatic–ore system is therefore considered as the result of a fractionation processes in a deep crustal magma chamber.

The *Deputatskoe Sn deposit* is situated in the northern Yana–Kolyma orogenic belt (Figure 1) and has reserves of 200 kt Sn (Russian B+C1 reserve categories), with an average grade of 1.15 wt% Sn. This deposit is considered to represent a Sn–(Ag)–porphyry style of mineralisation (Sillitoe *et al*. 1975), with transitions to Ag–sulfide mineralisation (Pavlova & Borovikov 2010). The deposit is associated with unexposed Late Cretaceous granite stock, which was encountered during drilling at a depth of 380 m intruding Middle Jurassic shales. The stock is accompanied by numerous mafic, intermediate and felsic dykes.

The deposit is part of a mineralised district comprising early As–Sn–W mineralisation, followed by predominating B–Sn mineralisation and then by distal late Ag–Pb–Zn mineralisation. The early mineralisation consists of flat-lying zones of apical quartz–topaz greisens, bearing cassiterite and wolframite, spatially and ?genetically related to a granite stock. On higher levels, the deposit comprises 150 orebodies which consist of shear-zone-controlled veins or linear stockworks (Smirnov 1977). The veins attain 18 m in thickness and 1400 m in strike length. They are composed of

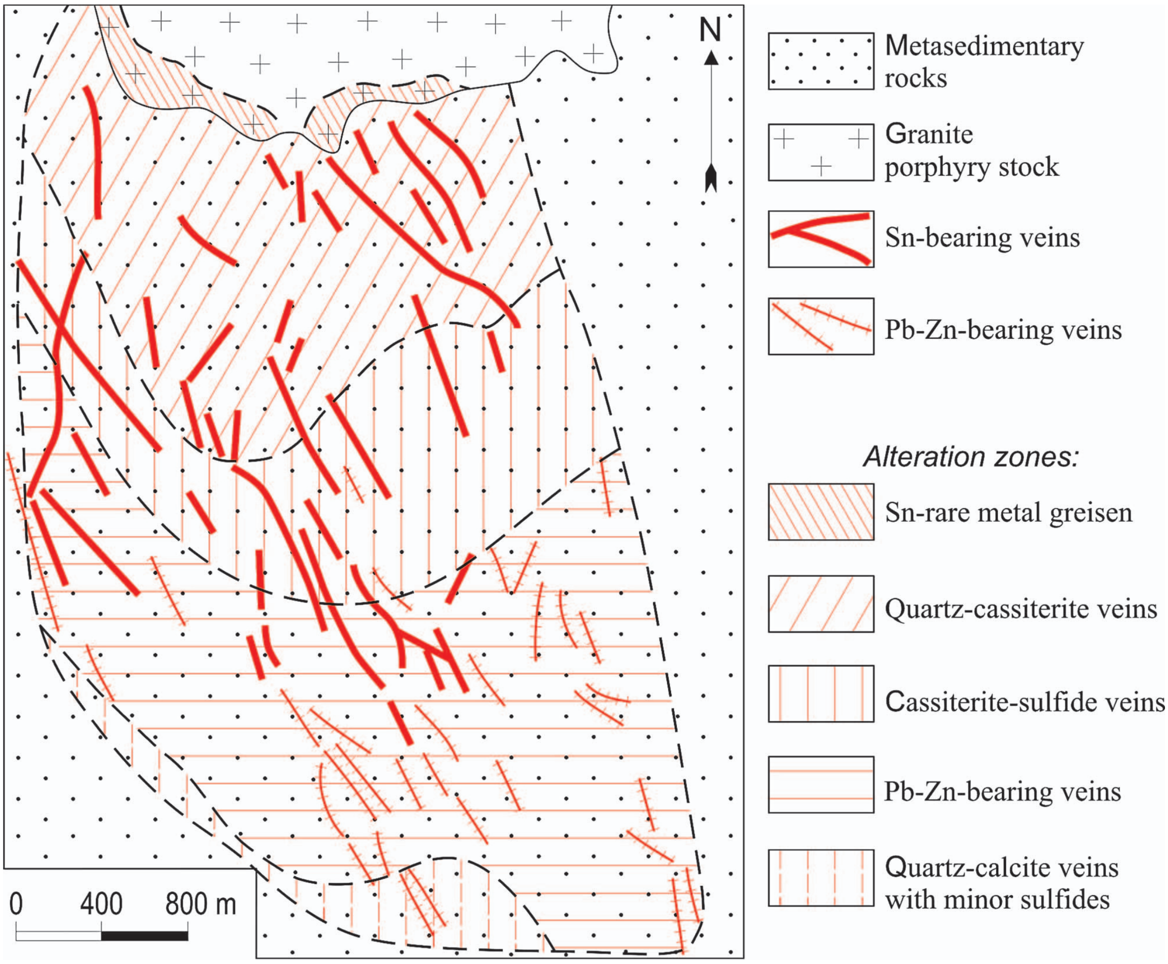

Figure 16 Simplified geology of the Khapcheranga Sn deposit (modified after Gongalskyi & Sergeev 1995).

quartz, tourmaline, chlorite, axinite, fluorite, siderite and ankerite, and contain a variety of ore minerals including cassiterite, arsenopyrite, pyrrhotite, chalcopyrite, pyrite, sphalerite, galena, stannite, boulangerite, Bi minerals, scheelite and sulfosalts. The veins are accompanied by wall-rock alterations represented by greisen, quartz–tourmaline or quartz–chlorite assemblages.

The *Khapcheranga Sn–sulfide deposit* (Figure 16) is situated in Eastern Transbaikalia and is related to a Middle Jurassic 2 km^2 granite porphyry stock, intruding a Permian–Triassic sandstone–shale sequence. The stock is accompanied by apical Sn–W-bearing quartz–muscovite–topaz greisen and by numerous steeply dipping quartz–cassiterite–sulfide veins, with the largest 20 extending for up to 1.1 km along strike and varying in thickness from 0.5 to 2 m. There are also more than 50 smaller veins (Gongalskyi & Sergeev 1995).

In general, the deposit is remarkable by its well-displayed intrusive-centred zonation, with a transition from Sn–W-bearing (cassiterite–ferberite) apical greisens and proximal quartz–cassiterite veins to sulfide–cassiterite veins and to distal Pb–Zn sulfide veins, with minor cinnabar and stibnite. Sulfides are represented mostly by pyrrhotite and arsenopyrite, and minor sphalerite, galena, chalcopyrite, pyrite and stannite. Besides veins, cassiterite-rich chlorite–calcite–quartz are present in zones of intense brecciation and hydrothermal alteration. Total vertical and lateral extent of mineralisation is from 1500 to 2000 m. Grades vary from 0.08 to 1 wt% Sn, averaging 0.75 wt%. In addition, the ores contain 0.3–25 wt% Pb, 1–25 wt% Zn, 11–600 g/t Ag and 0.01–0.17 wt% Cd. The deposit has produced >10 kt Sn.

The *Ermakovskoe Be deposit* is situated in Western Transbaikalia (Mongol–Transbaikalian metallogenic belt, southeast Siberia) and is related to Mesozoic intrusives. The ores contain in average 1.2–1.3 wt% BeO and 22.5 wt% fluorite (Kuprianova *et al.* 2006).

The Mesozoic igneous rocks include quartz syenite, granosyenite, subalkaline granite, and dykes of syenite porphyry, granite porphyry and diorite porphyry. These rocks intrude a large roof pendant composed of Neoproterozoic carbonate rocks (limestone, dolomite) intercalated with minor sandstones and shales and forming a synclinal fold and also intruded by older (Paleozoic) diorites, granodiorites and granites. The mineralisation is hosted in carbonate rocks and is represented by tabular and lens-like zones up to several tens of metres thick and extending for tens to hundreds of metres along strike and downdip. Magnesian and calcic skarns are abundant and are replaced by ore-bearing assemblages. The ores include bertrandite–phenakite–fluorite, phenakite–bertrandite (with minor fluorite, quartz, microcline, sulfides), fluorite, fluorite–quartz (with low Be content), phenakite–bertrandite–fluorite–phlogopite, and phenakite–fluorite–carbonate–phlogopite. Phenakite and bertrandite predominate, with the amount of bertrandite decreasing with depth. Minor Be minerals include melanophane, leucophane, eudidimite, bavenite, milarite and helvite. Locally, veining and brecciation zones are present; they are composed of coarse-crystalline microcline, quartz, carbonates, phenakite and pyrite, with relicts of country rocks and minor fluorite. A late carbonate–sulfide stage caused replacement of phenakite, melanophane and bertrandite by milarite and bavenite.

The *Khovu–Aksy Co–Ni deposit* is situated in the Altai–Sayan orogenic belt (Central Tuva region: Figure 1) and represents intrusive-related polymetallic (As–Ni–Co–Ag–Bi ± U) mineralisation. The deposit has 0.7 Mt of ore containing about 13 kt Co and 17 kt Ni, with accompanying Bi, Cu, Ag and As (Lebedev 1998, 2003).

According to Lebedev (1998, 2003), the deposit is in a cluster of Ni–Co–As and Cu–Co–As deposits and occurrences, and is related to a Late Carboniferous–Early Permian plutonic suite, represented by gabbro, gabbro–dolerite, granosyenite, granite stocks and dykes, intruding Silurian–Devonian clastic, carbonate and volcanic sequences. The host rocks are replaced by pyroxene, pyroxene–garnet and scapolite–pyroxene skarns, forming a complex-shaped tabular skarn body. In turn, the skarns are replaced by albite–orthoclase–prehnite, followed by minor sulfide and sulfoarsenide veins (chalcopyrite, bornite, pentlandite, pyrrhotite, Co-pyrite, arsenopyrite, cobaltite, sphalerite, galena) associated with quartz, carbonate and chlorite. This mineralisation was developed before emplacement of lamprophyre dykes.

The emplacement of these dykes was accompanied by multiple brecciation of the skarns and adjacent host rocks, followed by multiple mineralising episodes that resulted in the major productive assemblages of Ni, Co and Fe arsenides, with minor sulfides, sulfosalts and native elements (Bi, Ag, Au, As). This mineralisation is accompanied by abundant calcite and dolomite and minor ankerite, quartz, barite and siderite At least three mineralising stages dominated by arsenides are distinguished. The major ore minerals include rammelsbergite, chloantite, schmaltite, scutterudite and safflorite associated with fahlores, chalcopyrite and sphalerite. A late stage included formation of quartz and carbonates associated with tennantite–bornite–chalcopyrite mineralisation, with minor hersdorfite and safflorite, and also late quartz–carbonate veinlets containing Ag-rich galena. The mineralisation forms numerous but narrow (< 2 m) veins attaining 1–2 km in length.

Ta-bearing peraluminous Be, Li–F–granite deposits

In Siberia, there are two large deposits of this type with established Ta resources (Orlovskoe and Etykinskoe). There is furthermore one underexplored, but potentially large Li–Ta deposit (Alakhinskoe), and a cluster of deposits (Pogranichnoe, Voznesenskoe), where Ta is a possible by-product.

The *Orlovskoe (Orlovka) deposit* (Figure 17) is situated in the Mongol–Transbaikalia orogenic belt of southeast Siberia (Chita region). The deposit is a part of a mineralised cluster outlining a composite granite pluton (Khangilay pluton) and incorporating several Ta–Li, Sn and W deposits and occurrences—in particular, the large Spokoininskoe W greisen deposit, which is situated 8 km from the Orlovskoe deposit.

In the deposit area, various granitic rocks can be subdivided into three successive types: (i) biotite granite; (ii) leucogranite–alaskite; and (iii) microcline–albite Li–F granite (Beskin *et al.* 1994a; Reyf *et al.* 2000; Dolgopolova *et al.* 2004). The albite–microcline Li–F granite is characterised by zoned compositional variations. Its lower part is composed of porphyroblastic quartz–microcline–albite–muscovite granite, containing accessory topaz (0.1%). This granite is 'overlain' by equigranular albite–microcline–amazonite granite with muscovite (in its lower part) or muscovite and zinnwaldite (in its upper part), as well as topaz (0.5%). The uppermost part of the intrusive is composed of medium-grained albite–microcline–zinnwaldite–muscovite–amazonite granite and fine-grained albite–lepidolite granite. There are also vertical dykes of younger fine-grained albitic aplite, transitional to albitite, quartz–lepidolite to quartz–muscovite greisens, comprising a Li–F granite–metasomatite association with sporadic wolframite, scheelite and beryl. The granites also contain rare spodumene and aegirine.

Ta–Nb mineralisation is hosted in the albite–microcline–quartz (± amazonite) rocks that are highly variable in texture and mineral composition and contain Li micas, topaz, fluorite and rare-metal minerals. The granites are enriched in Li micas (e.g. albite–lepidolite granite), which host the most significant Ta–Nb mineralisation. The flat-lying orebody has lens- to manto-like shape and extends for about 1200 m along strike; it is 250 m wide and 80–100 m thick. Tantalum and Nb are concentrated mostly in columbite–tantalite and, to a lesser extent, in pyrochlore–microlite and cassiterite forming very finely disseminated grains (Beskin *et al.* 1994a). Average Ta_2O_5 grade is 0.0129% (0.008% cutoff) (Kudrin & Chistov 1997; Ryabstev *et al.* 2006a,b).

The *Etykinskoe (Etyka) deposit* is also situated in southeast Siberia (Chita region). It is related to Mesozoic (155–130 Ma) multiphase granite pluton intruded into a terrigenous Jurassic sequence. The first intrusive phase is represented by biotite and hornblende granodiorite and plagiogranite that are intersected by biotite granite of the second intrusive phase and related cassiterite/wolframite veins, with gangue topaz, fluorite, amazonite, albite, quartz, sulfides. Ta mineralisation is related to smaller plutons of the third intrusive

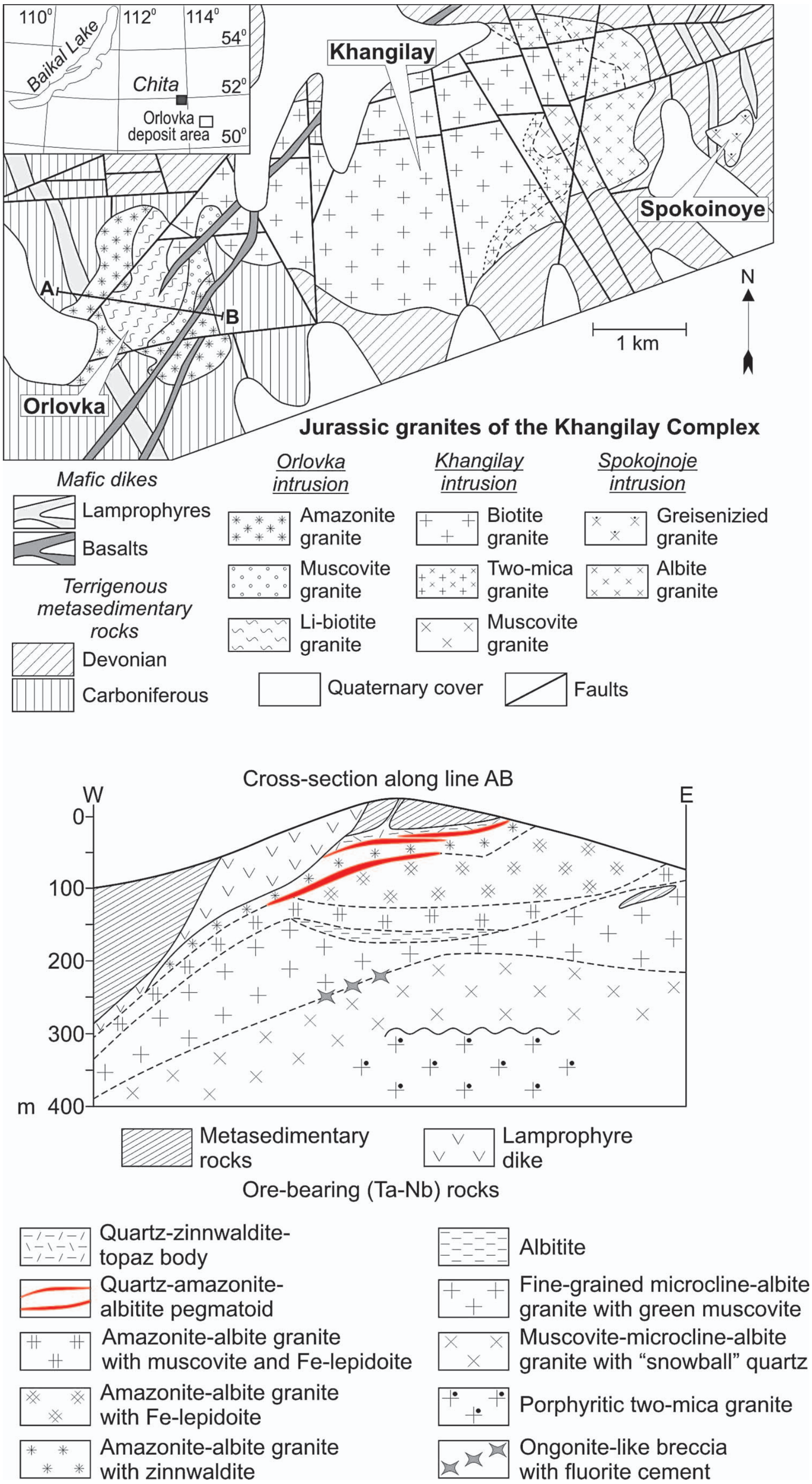

Figure 17 Simplified geology of the Orlovka deposit area (modified after Beskin *et al.* 1994a).

phase, represented by amazonite granites (Beskin *et al.* 1994b).

The Ta-bearing zone is located in the apical part of small dome-like body of quartz–albite–microcline (amazonite) granite outcropping over an area of 1.3 × 1.0 km. The internal structure of the pluton and its textures are extremely irregular due to the multiphase intrusion and broad occurrence of late magmatic and post-magmatic metasomatism. In general, the rocks are composed of microcline (usually amazonite), albite, quartz and Li micas (zinnwaldite, lepidolite and Fe-lepidolite or cryophyllite), with minor topaz, Ta–Nb minerals, cassiterite, galena, zircon and monazite.

The Ta-bearing zone outlines contours of the granite dome, extending for 3 km and 120–700 m wide. From the external side it is limited by the geological boundary of the intrusive, and from the internal side by the cutoff grade of 0.009% Ta_2O_5. Higher Ta grades are in the uppermost part of this mineralised zone, but they rapidly decrease with depth. Vertical thickness of the mineralised zone is ~50–60 m. Columbite–tantalite (7–28% Ta_2O_5) and microlite (36–46% Ta_2O_5) are the main Ta-bearing minerals; struverite–ilmenorutile and loparite are rare and sporadic. Some portion of Ta is related to cassiterite, containing 1.5–4% Ta_2O_5. As a result, 30–40% of Ta is concentrated in microlite, 40–60% in columbite–tantalite, and 10–15% in cassiterite. Average grades are 0.0131% Ta_2O_5 (0.008% cutoff), 0.019% Nb_2O_5, 0.02% Sn and 0.110% Li_2O (Beskin *et al.* 1994b).

The *Pogranichnoe* and the nearby *Voznesenskoe deposits* (Russian Far East: Figure 1) are large fluorite and Be, Li, Cs deposits, accompanied by smaller deposits of similar type as well as by small Sn, W, Ta and Pb–Zn deposits, forming a cluster or large mineralised district (Kuprianova & Shpanov 1997). The mineralisation is related to the Late Silurian albite–topaz-protolithionite Li–F-type granite forming small (up to a few square kilometres) hypabyssal bodies enriched in Li, Rb, Cs and other rare elements. The Voznesenskoe deposit is related to a ridge-shaped granite intrusive emplaced in axial part of anticline, within a limb of a larger syncline, comprising limestone and phyllite. The limestone was subjected to intense metasomatic replacement, which produced various skarns and overprinting greisens. This led to the formation of a large body of fluorite–Be ore located above the pluton. The orebody extends for about 1200 m along strike and is up to 500 m wide. There are several mineralogical types of ores including fluorite–phenakite and fluorite–albite–quartz–micaceous ones, with beryl content increasing toward the deeper levels. The deposit, characterised by explosive breccias has average grades of 0.45% Li_2O, 0.26% Rb_2O, 0.02% Cs_2O, 0.075% BeO, an average fluorite content in the low-grade ores of 20% and in high-grade ores 30% (Rub *et al.* 1998).

The Pogranichnoe deposit is represented by several large fluorite–Be orebodies, located above an irregularly shaped upper contact of the parental pluton, with the largest traced down to 800 m. Similarly to the Voznesenskoe deposit, there are several types of ores including 'apo-carbonate' fluorite–chrysoberyl ore and breccia-like fluorite–euclase ore. However, in contrast to the Voznesenskoe deposit, the ores contain lower fluorite, but higher (2–3×) Be grades. Average metal grades are 0.17% Li_2O, 0.14% Rb_2O, 0.247% BeO (Rub *et al.* 1998), with average fluorite content similar to that at the Voznesenskoe deposit. There are also Be-free fluorite–diaspore–topaz and fluorite–topaz ores.

Rare-metal (Ta, Li, Cs) pegmatite deposits

Rare-metal pegmatites are numerous in the Altai–Sayan and Mongol–Okhotsk orogenic belts, with the Goltzovoe and Vishnyakovskoe deposits in the Eastern Sayan (South Siberia) being the largest.

The *Goltzovoe pegmatite deposit* is situated in the southeastern part of a Mesoproterozoic (1.80–1.75 Ga) pegmatite belt contained in a rift system, aligned along the southern margin of the Siberian craton. The deposit is represented by large pegmatite bodies hosted in Precambrian metasedimentary and intrusive rocks and surrounded by thick zones of Cs-bearing micaceous metasomatites and biotite schists. Pegmatites occupy ~10% of the area and are both concordant and cross-cutting. Several compositional varieties of the pegmatites are distinguished, such as Ta–Li–Cs-bearing spodumene–microcline–albite (with pollucite and montebrasite), Li–Ta-bearing spodumene–microcline–albite (with tourmaline), Li-bearing spodumene–microcline–albite (with tourmaline and garnet), and Ta-bearing albite and muscovite–albite (with microlite and spodumene) pegmatites. As a result, besides Ta, the deposit contains resources of Li and Cs. The average grades in the pegmatite ores are 0.0138% Ta_2O_5, 0.79% Li_2O and 0.122% Cs_2O (Ryabtsev *et al.* 2006a, b).

The *Vishnyakovskoe deposit* is situated in the northwestern part of the above-mentioned rift system. The deposit is hosted in a thick orthoamphibolite unit, within biotite–muscovite and mica–andalusite crystalline schists that are 0.8–1.0 km away from a biotite–amphibole and biotite granite pluton considered to be the parental intrusion. The deposit is represented by a system of gently dipping (10–25°) lode-like pegmatitic bodies forming three main swarms and extending for up to several kilometres in length and forming packages up to 1–3 km in width. These pegmatitic swarms occupy a vertical section about 500 m thick, with selected swarms varying from 20 to 100 m. The distance between swarms is from 40 to 120 m. Thickness of individual pegmatitic bodies within the swarms is <12 m. The deposit contains inferred resources of 42 Mt averaging 1.06 wt% Li_2O and 0.012 wt% Ta_2O_5 (Odintsova & Syzykh 2007).

These gently dipping pegmatites consist of several zones: (i) an uppermost zone of muscovite–quartz or albite–muscovite–quartz; (ii) a microcline–petalite zone, partially replaced by feldspar–quartz–spodumene (eucryptite) assemblage; (iii) a central quartz–Rb-muscovite–microcline zone (this zone formed in the uppermost swarm contains abundant wodginite); (iv) a K-feldspar–quartz-altered petalite zone; and (v) a lower albite zone. Tantalum grades decrease gradually toward the lower pegmatite swarms (from 0.026% Ta_2O_5 to 0.014% Ta_2O_5). Therefore, Ta mineralisation is abundant in the uppermost (first) swarm, whereas Li mineralisation predominates in the deepest (third) swarm. Tantalum ore minerals are columbite–tantalite and mangantantalite (35–65% Ta_2O_5, 0.9–3.0% SnO_2), wodginite (57–80% Ta_2O_5, 6–17% SnO_2), ixiolite and microlite.

Porphyry deposits

Porphyry (locally associated with skarn) deposits are numerous in the Altaid and Circum-Pacific terranes. They are mainly represented by Cu, Cu–Mo, Mo–Cu, Cu–Au, Cu–Mo–Au, Mo and Mo–W metal associations. The most significant examples include the Sorskoe Mo–Cu porphyry, Aksug Cu–Mo–Au porphyry, Peschanka Cu–Au–Mo porphyry, Shakhtama and Zhireken Mo porphyry, Bugdaya Mo–Au porphyry and Ryabinovoe Cu–Au porphyry.

The *Sorskoe (Sora) Mo–Cu deposit* is situated in the Khakassia region of southwestern Siberia. After several decades of mining activity reserves of 135 kt Mo still remain, grading 0.058% Mo. Other metals include Cu (average grade 0.055%), Ag (average grade 2.3 g/t) and Au.

According to Pokalov (1992) and Sotnikov *et al.* (2001), the deposit is characterised by multiphase granitoid magmatism, with some granitic phases accompanied by intense potassic alteration with disseminated molybdenite and chalcopyrite. The deposit is associated with Cambrian–Ordovician to Devonian composite intrusive complexes composed of: (i) an early suite of gabbro, monzogabbro and monzonite; (ii) an intermediate suite of monzonite, syenite, granodiorite, granosyenite and diorite; and (iii) a late suite of leucogranite and aplitic granite. Two series of granite porphyries belong to the intermediate and late suites. Two major mineralising events are recognised. An early event characterised by quartz–biotite–K-feldspar alteration and overprinting stockwork and Mo mineralisation, formed after emplacement of the early porphyry phases. Vertical extent of Mo mineralisation varies from >1000 m in the deposit centre to 300–500 m on its flanks. The stockwork Mo–Cu ores are most abundant, whereas the mineralised breccias have the highest Mo grades. The breccias are composed of angular fragments of the host rocks cemented by fine-grained quartz–fluorite matrix containing molybdenite, pyrite and chalcopyrite. Mo grades in the breccia attain 0.5–1.0%. This was followed by a second mineralisation event of quartz–fluorite–galena–sphalerite veins surrounded by haloes of sericitisation and pyritisation. Finally, late quartz–fluorite–pyrite and quartz–molybdenite veinlets of minor economic importance were formed after emplacement of the late porphyry phases. The peak Mo–Cu mineralisation occurs at 389–388 Ma, followed by the intrusion of separate porphyry phases (Sotnikov *et al.* 2001). It is likely that the suites of both intrusive complexes contributed to the mineralisation and that the initial porphyry system was overprinted by later events, which caused redistribution of the original porphyry mineralisation. This may explain why the formation of this deposit spans a period of about 130 Ma (481–356 Ma).

The *Aksug Cu–Mo–Au porphyry deposit* is situated in the Tuva region (southwest Siberia: Sotnikov & Berzina 2000) and contains 4.2 Mt Cu (average 0.52% Cu), 115 kt Mo, 126 t Au and 795 t Ag. It is related to a Silurian–Devonian multiphase pluton located near a regional fault zone and consisting of at least two different intrusive suites: Early (Silurian?) diorite–monzonite, granodiorite and granodiorite porphyries, with dykes of leucocratic granite and granosyenite, intruded by Late Devonian equigranular and porphyritic tonalite and trondjhemite. At the more local scale, the deposit is related to a small cupola-shaped plagiogranite porphyry stock, with steeply dipping (70°) contacts. The stock was pervasively hydrothermally altered, with barren quartz stockwork in its central part, and an outer zone of quartz–sericite–carbonate–pyrite alteration. The latter hosts most of the sulfide mineralisation, which was formed during three stages: (i) quartz–molybdenite; (ii) predominating quartz–carbonate–pyrite–chalcopyrite–bornite (with minor sphalerite and molybdenite); and (iii) carbonate–bornite–chalcopyrite (with minor hematite). This mineralisation overprints and surrounds the alteration halo.

A cluster of Cu–Au porphyry deposits was recently discovered in southeastern Siberia; it includes the Bystrinskoe, Lugokanskoe, Kultuminskoe and other Cu–Au porphyry deposits related to small alkaline (monzonitic) porphyry intrusions of a Jurassic plutonic–volcanic suite in Eastern Transbaikalia. The plutons intrude Lower Cambrian limestones and dolomites and are commonly accompanied by skarns, including Cu-bearing magnetite. Later stages produced disseminated quartz–pyrite–chalcopyrite mineralisation that overprints the skarns.

The *Bystrinskoe Cu–Au porphyry deposit* contains resources of at least 2.4 Mt of contained Cu, with an average grade of 0.74% Cu and 270 t of contained Au, with an average grade of 0.85 g/t Au, and 1800 t of contained Ag, with an average grade of 5 g/t Ag. The mineralisation forms wide tabular stockwork zones, extending for over 1 km traceable for at least 300–500 m downdip. The ore minerals are chalcopyrite, with minor arsenopyrite containing finely dispersed gold. Magnetite skarns locally enriched with boron are common; weak tungsten (0.14–0.42% WO_3) and molybdenum (0.054–0.23% Mo) mineralisation is locally present. An important feature is the presence of the large Novo–Shirokinskoe Au–sulfide deposit 15 km from the Bystrinskoe deposit. All these deposits represent parts of a large (regional- to district-scale) Jurassic shoshonite-related mineralised system.

An important variety of mineralised porphyry systems in Eastern Transbaikalia is represented by the *Bugdaya Mo–W–Au porphyry deposit*. This deposit is related to a small Late Jurassic hypabyssal granite porphyry stock located within a volcanic caldera 3.5 km across (Kovalenker *et al.* 2006). The mineralisation consists of an early Mo stockwork ore, partially overprinted by late Au–Pb–Zn mineralisation which extends well outside the Mo stockwork. The mineralised stockwork is 1100 × 800 m across and contains significant resources: >100 t Au, 800 t Ag, 400 kt Mo, 200 kt WO_3, 40 kt Cu, 55 kt Bi, >500 kt Pb and 650 kt Zn. Average grades are 0.034% Mo, 0.28 g/t Au, 2.9 g/t Ag, 0.02% Cu; the average Au grades in the Au–Pb–Zn mineralisation are 10 g/t Au.

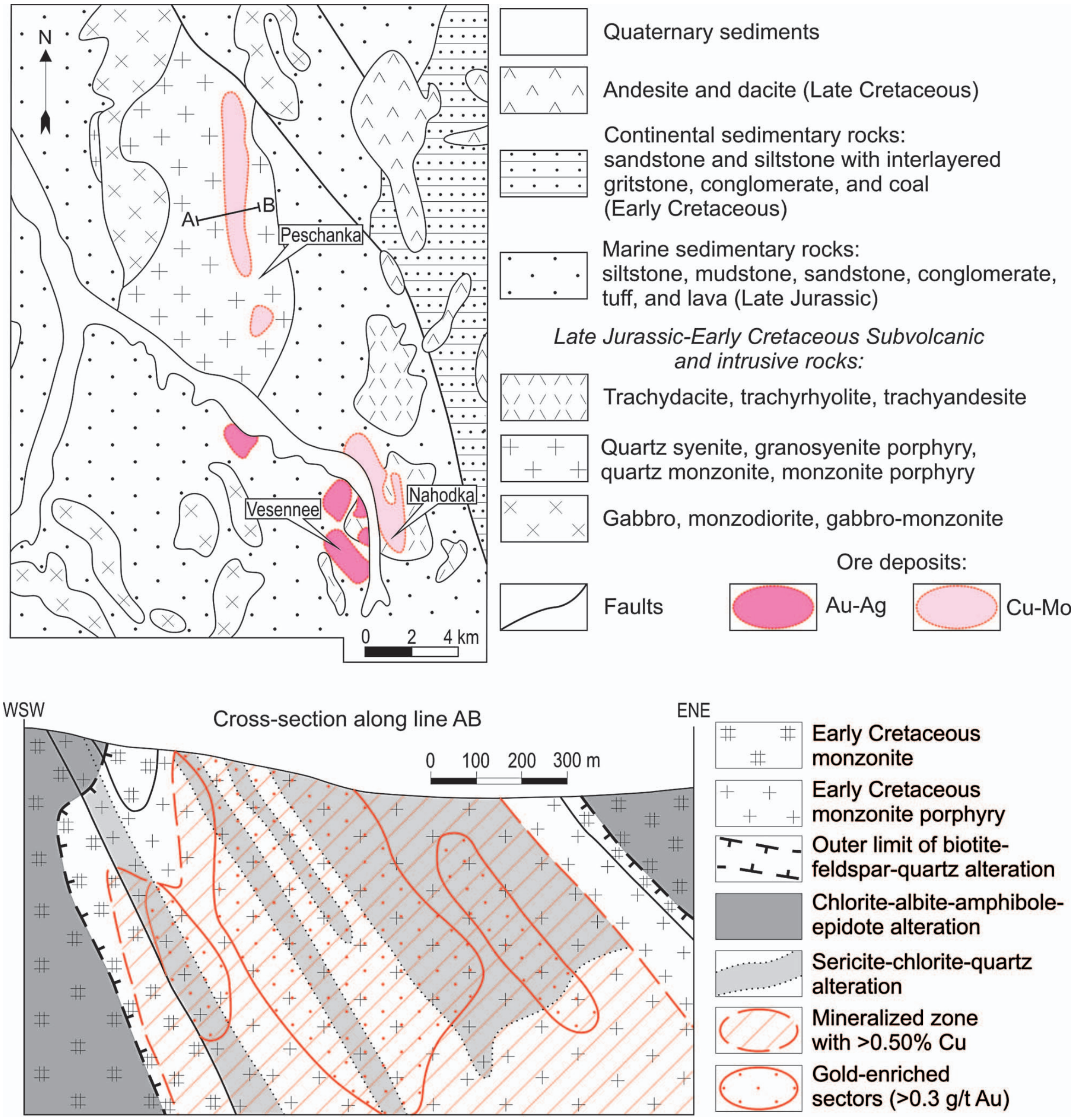

Figure 18 Schematic section through the Peschanka Cu–Au–Mo deposit (modified after Migachev *et al.* 1995).

The *Peschanka (Baimskoe) Cu–Au–Mo porphyry deposit* (Figure 18) (Migachev *et al.* 1995) contains resources of 1350 Mt of ore grading 0.61% Cu, 0.015% Mo, 0.32 g/t Au and 3.7 g/t Ag and contains 8.3 Mt Cu, 200 kt Mo, 425 t Au and 5 kt Ag. The deposit is situated in the Circum-Pacific orogen (Chukotka Peninsula), close to the western margin of the Okhotsk–Chukotka volcanic–plutonic belt, where this belt is superimposed on the Omolon microcontinent. The belt contains multiphase diorite–monzonite–syenite–granite intrusions, located within the Baym metallogenic zone. This metallogenic zone forms a linear structure traceable for over 200 km, with a width of 20–25 km, and hosts a number of porphyry deposits. Monzodiorite and quartz monzodiorite intruded by younger granodiorite porphyry stocks are present in the deposit area. Hydrothermal alteration has an innermost zone represented by quartz–sericite–carbonate assemblage, an intermediate zone composed of K-feldspar and biotite, and an outermost zone composed of propylitic (hydrosilicate) assemblages (Figure 18). The Cu porphyry mineralisation is coincident with the zone of quartz–sericite–carbonate alteration replacing the entire granodiorite porphyry body, whereas Mo mineralisation is confined to a narrower area inside the Cu halo, generally associated with a dense quartz stockwork. The mineralisation formed during four stages (from earlier to later): (i) molybdenite; (ii) chalcopyrite–pyrite; (iii) bornite–chalcopyrite–tennantite; and (iv) chalcopyrite–sphalerite–galena stages. The chalcopyrite–pyrite mineralisation is most widespread, but the higher-grade ores are associated with the bornite–chalcopyrite–tennantite assemblage.

Skarn deposits

Siberia has many economically significant skarn deposits including Fe, W, Au, Cu–Au, Pb–Zn and boron. Skarn deposits are mostly in the Altai–Sayan and Mongol–Okhotsk orogenic systems, and in the Mesozoic–Tertiary terranes of the Circum-Pacific orogenic belt.

Large Fe skarn deposits are present in southwest Siberia (Khakassia, Tuva, Shoria and other regions) (Figure 1). The large *Abakan Fe deposit* is part of an ore cluster in Khakassia (Borisenko & Lebedev 2009) in Lower Cambrian volcanic–sedimentary rocks (basalt and andesite tuffs, shales, limestones, with minor sandstones), intruded by Cambrian monzonite plutons and younger (Devonian?) diorite and granite stocks and dykes. The volcanic–sedimentary sequence hosts several bedding-parallel subvertical orebodies composed of massive magnetite skarn, accompanied by haloes of intense propylitic and sodic (albitic) alteration. Total strike extent of the mineralised package is 1.3 km, with thicknesses of 300–400 m. The magnetite bodies are overprinted by hydrosilicates (epidote, amphibole, chlorite), ankerite–quartz, quartz–hematite and sulfide–arsenide assemblages, and contain Co-pyrite other minor sulfides (chalcopyrite, pyrrhotite), hematite and apatite. The deposit has about 300 Mt of ore averaging 45 wt% Fe (Smirnov 1977).

Gold skarn deposits are also present in southwest Siberia, where the well-known *Sinyukha Au skarn deposit* had pre-production reserves of ~50 t Au and additional resources of ~30 t Au (Ettlinger & Meinert 1991). Copper mineralisation is also significant although not mined. The deposit is associated with a multiphase Devonian diorite–tonalite pluton. The skarn consists of complex-shaped tabular flat-lying to pillar-like subvertical bodies in both proximal (near intrusive contacts) and distal (in the host rocks, along contacts of limestones and volcanics) settings. Thickness of individual orebodies varies from 1 m to 20 m, their strike length attains 400 m, and downdip extent is about 200 m (locally up to 500 m). Average grades for these orebodies vary from 3–4 g/t Au to >36 g/t Au, whereas some narrow intervals contain up to 200–400 g/t Au. The skarns are composed mostly of andradite garnet and wollastonite, with minor pyroxene. Economic Au concentrations are associated with Cu sulfide (bornite, chalcocite, lesser chalcopyrite), with admixture of Bi–, Te–, and Sb–Pb–As. Mineral zonation shows a transition from chalcopyrite–magnetite within the pluton and its endocontacts, towards bornite–chalcocite–pyrite in the exocontacts and more distal settings. Different generations of native Au are present; they vary in fineness from early low-fineness (600–650) associated with pyrrhotite and chalcopyrite to a late high-fineness (900–1000) variety, associated with bornite, chalcocite, Bi–Ag–Pb and other sulfides (Gusev 1998).

Large Pb–Zn skarn deposits are known in several regions. In particular, in Eastern Transbaikalia, the *Savinskoe Pb–Zn deposit* is related to a Late Jurassic granitic suite, also containing Sn, Sn–Pb–Zn and fluorite mineralisation (Sanin & Zorina 1978). The deposit is in a large roof pendant, surrounded by Paleozoic diorite plutons. A Late Jurassic smoky quartz-bearing leucocratic granite pluton, which outcrops 4–5 km east of the deposit, underlies the general area of the deposit. The roof pendant is composed of intercalating limestone and shales, intensely replaced by garnet, garnet–pyroxene, and axinite skarns. In turn, the skarns are replaced by sphalerite–pyrrhotite, sphalerite–galena–pyrrhotite, sphalerite–galena–pyrrhotite–arsenopyrite–pyrite and fluorite, which constitute economic orebodies.

The *Dalnegorsk group of Pb–Zn skarn deposits* of the Russian Far East (e.g. Nikolaevskoe, Verkhnee, Sadovoe, 1st Sovetskoe and Partizan) are situated in the Sikhote–Alin orogen, which is part of the Circum-Pacific orogenic belt (Figure 1). The mineralised district comprises folded and faulted Carboniferous to Lower Cretaceous sequences (cherts, siltstone, sandstones, siltstones), overlain by Upper Cretaceous–Tertiary intermediate to felsic volcanics (lavas, ignimbrites, volcanic breccias, tuffs). These volcanic rocks are associated with graben-like structures and are accompanied by subvolcanic diorite, granite porphyry, rhyolite, syenite porphyry, dolerite, stocks and dykes. Most Pb–Zn skarn bodies are formed from Triassic limestones.

The *Nikolaevskoe deposit* (Figure 19) (Nokleberg 2010; Nokleberg *et al*. 1996) is within a downthrown block of Upper Triassic limestone, overlain by Upper Cretaceous rhyolite, volcanic breccias and tuffs, and Paleocene andesite lavas and pyroclastics. All these rocks are intruded by gabbro–diorite, diorite, granite, rhyolite and dolerite stocks and dykes, representing parts of the local volcanic–plutonic centre. The major orebody is flat-lying and tabular-shaped, and is in the uppermost part of the limestone, immediately below the overlying volcanics at a depth of 700–1200 m below the surface. The mineralisation overprints pyroxene skarn (with minor garnet and wollastonite) and includes galena, sphalerite and pyrrhotite, with minor arsenopyrite, chalcopyrite, magnetite and trace Ag–Bi–Te minerals and cassiterite. Other gangue minerals include ilvaite, axinite, tourmaline, epidote, fluorite, barite and amphibole. The overlying volcanic rocks contain quartz–sulfide veins, associated with silicification and phyllic alteration overprinting haloes of propylite-like alteration. An interesting feature of this and other Dalnegorsk Pb–Zn skarn deposits, is the presence of large (metres across) cavities filled by large crystals of sulfides and gangue minerals.

The large *Dalnegorsk boron skarn deposit* is situated near the Nikolaevskoe deposit, in a ~3.5 km long and 600 m thick Upper Triassic limestone lens enclosed in terrigenous–cherty rocks (Nokleberg 2010 and references therein). A multiphase pluton of amphibole–biotite granitoids was encountered between 1100 and 1400 m below this limestone. The limestone and adjacent terrigenous–cherty rocks were replaced by pyroxene, garnet and wollastonite skarns, overprinted by retrograde hydrosilicate assemblages containing quartz,

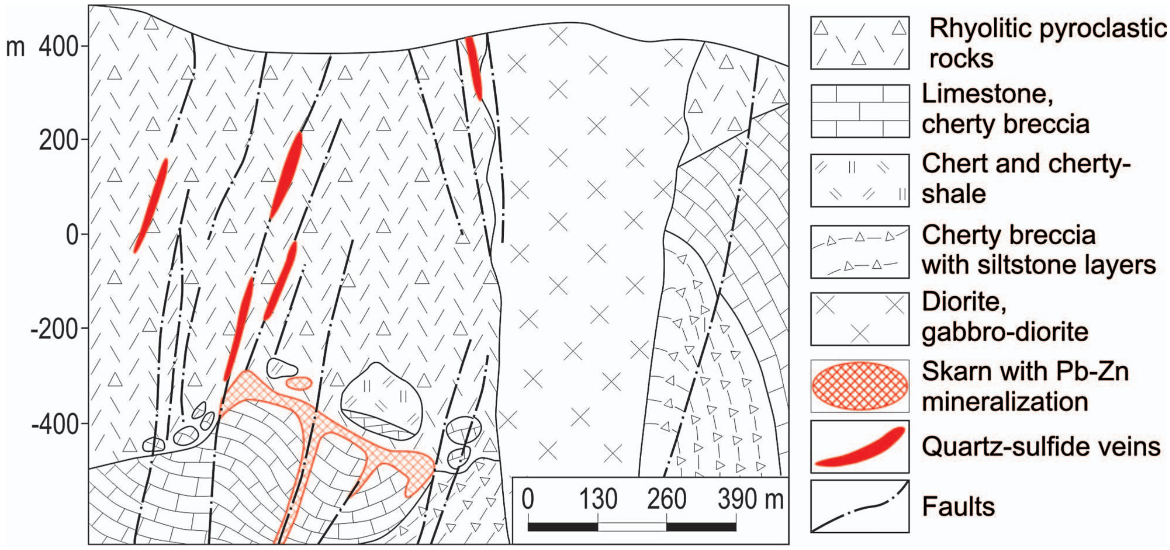

Figure 19 Geological section through the Nikolaevskoe Pb–Zn skarn deposit (modified after A.Sedykh & A.Natarov unpubl. data and Rogulina & Sveshnikova 2008).

calcite, B-bearing minerals (datolite, danburite, axinite, ilvaite), epidote, chlorite, albite, sericite and various sulfides. Three types of boron ores are present: datolite, danburite+datolite and axinite+datolite. These ores have massive, spotty, banded, brecciated and especially notable concentric textures; the latter caused by rhythmically alternating bands of wollastonite, pyroxene, garnet, datolite and other minerals. Datolite is the most abundant boron mineral in the deposit; it is present mostly on the upper levels, where it forms monomineralic lenses and patches. At greater depths, datolite forms thin-banded aggregations together with pyroxene and wollastonite.

Tungsten skarn deposits are present in the Sikhote–Alin orogenic belt on the Russian Far East (Vostok-2 and Lermontovskoe deposits) and in the Yana–Kolyma orogenic belt in Yakutia (Agylky deposit). On the basis of their settings and mineral composition, these deposits are similar to the large 'reduced type' Canadian W skarn deposits (Einaudi *et al.* 1981) such as MacTung and CanTung (Dick & Hodgson 1982).

The *Vostok-2 deposit* (Figure 20) contained pre-production reserves in excess of 180 kt contained WO_3, with the deposit average of 1–2 wt% WO_3 (Gvozdev & Tsepin 2005). The deposit is related to a Late Cretaceous multiphase monzodiorite–granodiorite–granite pluton of the ilmenite series intruded into a Jurassic–Cretaceous carbonaceous terrigenous–volcanic-carbonate sequence. The mineralisation is located in a thrust-fault zone in the sedimentary sequence. The fault zone is characterised by tectonic slabs, fragments and boudins of carbonate rocks, enclosed in fine-grained cherty material. The zone includes several mineralised skarn bodies, with the largest tabular steeply dipping skarn body about 30–35 m thick, extending for 700–800 m along strike and downdip. The skarns have pyroxene replaced by hydrosilicate assemblages dominated by amphibole, chlorite and epidote associated with quartz, albite, carbonate, associated with abundant pyrrhotite, scheelite and chalcopyrite. This assemblage was followed by quartz–sericite (quartz–muscovite), further contributing to the abundance of scheelite and sulfides, and with the formation of high-grade (locally >10 wt% WO_3) scheelite–sulfide ores. Sulfide assemblages include Bi, Ag–Au and Sb mineralisation.

Iron oxide–copper–gold (–uranium) and related deposits

Iron oxide–copper–gold (IOCG) and related deposits are represented by several subtypes including IOCG in ultrametamorphic rocks, skarn and carbonatite (Williams *et al.* 2005). There are also some IOCG-like deposits in Siberia that have not been allocated to any of the known subtypes of the IOCG deposits.

Fe oxide (±Cu) deposits present in Precambrian (Archean) ultrametamorphic sequences, similar to those of the Brazilian Shield (Salobo), include Taezhnoe, Des, Sivagli and associated deposits in the Aldan Shield (Soloviev in press a). The *Sivagli deposit* is the most remarkable, due to its significant Cu, Co and Fe oxides mineralisation. The deposit has 81 kt of contained Cu, with an average grade of 0.83% Cu. Measured, indicated and inferred resources (Russian $B+C_1+C_2+P_1$ reserve and resource categories) of iron ores are 173 Mt grading 22–32% $Fe_{tot.}$ In some reserve blocks, average Cu grades attain 1.63–1.73%. The diopside–magnetite ores contains 0.01–0.017% Co (Orlov & Malich 2002). Sivagli is located in an Archean metamorphic sequence, which is the same to that hosting the Taezhnoe and other deposits found in the area, and is composed of dolomite marbles and diopside–phlogopite–amphibole–scapolite skarns, with minor gneisses and crystalline schists. The productive units have a moderately steep dip; however, their extent at depth is cut by intrusions of Paleoproterozoic granites and Mesozoic (post-Jurassic) monzonites.

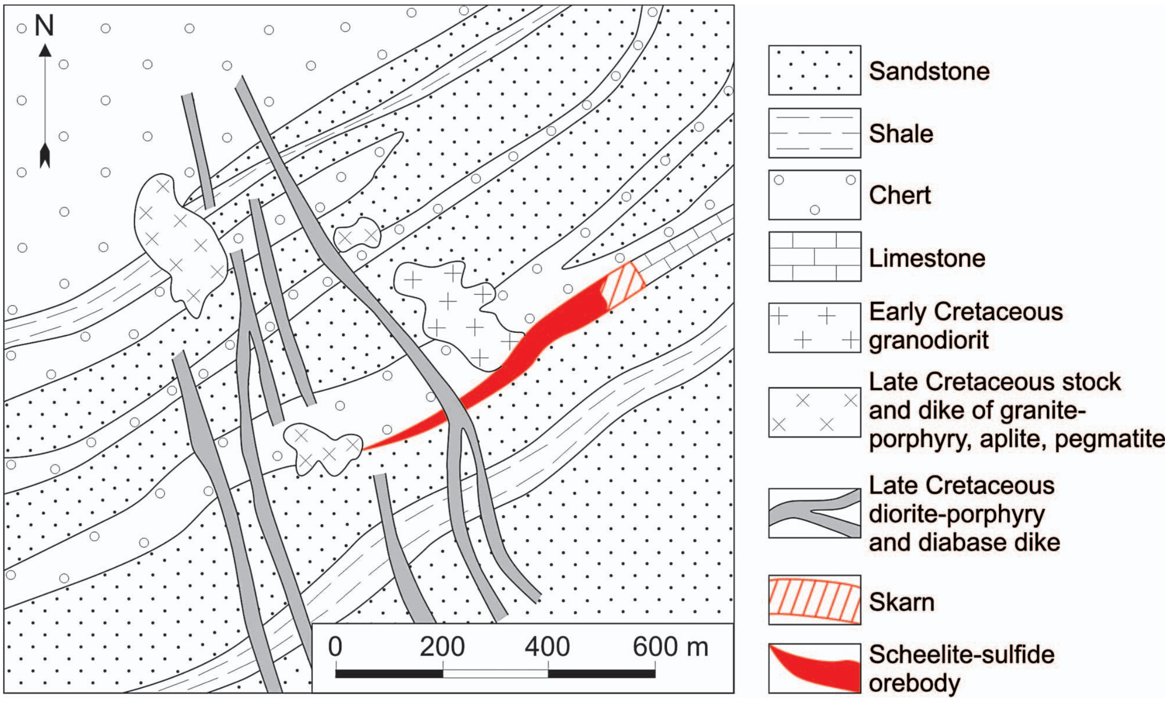

Figure 20 Geological map of the Vostok-2 tungsten skarn deposit (modified after Gvozdev & Tsepin 2005).

The deposit consists of four lens-like and tabular orebodies, lying concordantly with the host rocks. The largest orebody has surface dimensions of 540 × 200 m and pinches out at a depth of 250–510 m; two others were traced for 400 m along strike and are up to 10 m thick. The mineralisation consists of primary magnetite and secondary martite ores, massive, banded and disseminated, less often brecciated. The primary ores contain magnetite and minor pyrite; the Cu-bearing varieties contain also chalcopyrite, chalcocite and bornite.

The IOCG deposits of the skarn subtype may include the Abakan deposit described in the skarn section, as well as other Fe–Cu–Au skarn deposits of the Altai–Sayan orogenic belt (Soloviev in press c). Gusev *et al.* (2006) and Soloviev (in press c) suggested an IOCG nature for the Kholzunskoe Fe oxide deposit in Russian Altai and the Karasug hematite–apatite–REE carbonatite deposit in the Tuva region (southwest Siberia), discussed below. The *Seligdar and other apatite–REE–Fe oxide deposits* of the Aldan Shield also bear similarities to IOCG deposits (Soloviev in press a).

In addition, the Angara and Ilim River Basins in the southern Siberian craton contain several tens of very unusual large Fe oxide deposits, known as the Angara–Ilim type (Soloviev in press b). Currently, over 50 iron deposits of this type are known in the region. Total mineable Fe ore reserves (Russian $B+C_1+C_2$ reserve categories) of 11 of these deposits have 18 Gt, with individual deposits having around 0.5–1.0 Gt that are represented by mineralised subvertical breccia pipes, probably diatremes–maars. The breccia pipes cut through tholeiitic calc-alkaline mafic (dolerite) sills of the Permian–Triassic Siberian traps as well as younger basaltic dykes and stocks, which are possibly alkaline and exhibit shoshonitic affinity. Massive magnetite mineralisation on some deposits was intersected by drilling on a depth of 2 km, but geophysical (magnetic) surveys show that it may extend to a depth of 4.2 km, suggesting that the mineralisation is not limited to the sedimentary cover, but possibly extends further down into the Precambrian basement. The *Korshunovskoe deposit*, consists of a mineralised breccia pipe, incorporating fragments and larger blocks of sedimentary (sandstone, siltstone, limestone, argillite) (60–80%) and igneous (gabbro–dolerites, dolerites, basalts) (10–40%) rocks, cemented by chloritic material and fine-grained carbonate. Its central part is characterised by multiple brecciation episodes, with rock fragments represented by variably altered dolerites and cemented by a fine-dispersed matrix completely replaced by skarns, post-skarn alteration assemblages and iron oxides. In the *Rudnogorskoe deposit*, the pipes have a wide, funnel shape, containing chaotically mixed fragments of sedimentary rocks and relatively minor dolerite, varying in size from fractions of centimetre to few metres across. They are cemented by fine-grained chloritic and carbonate matrix. The breccias were intensely altered and almost entirely converted to pyroxene and pyroxene–garnet skarns, later replaced by a calcite–serpentine–chlorite assemblage.

In general, two episodes of brecciation, hydrothermal alteration and mineralisation separated by emplacement of basaltic dykes are distinguished. The first (early) episode is manifested by brecciation of dolerites and sedimentary host rocks followed by hydrothermal alteration of the breccias (prograde magnesian and calcic skarn to retrograde and hydrosilicate alteration) and mineralisation including abundant magnetite. The second (late) episode occurred after or contemporaneously with the emplacement of basaltic dykes and intense re-brecciation including the formation of numerous massive magnetite, magnetite–apatite and magnetite–calcite veins. The deposit consists of magnetite orebodies of various structural types, including steeply dipping, columnar, veins contained in zones of intense brecciation and skarn replacement. Also, subhorizontal orebodies are present to a depth of 600–1500 m below the surface. The mineralisation is represented mostly by magnetite (~82% of Fe resources) and minor magnomagnetite, hematite and martite.

The deposits are characterised by varying pyroxene/garnet ratios in the magnesian and calcareous skarns, with intense retrograde and hydrosilicate (mostly chlorite–serpentine) alteration. All these assemblages include magnetite, which is especially abundant in association with chlorite and serpentine, forming brecciated, disseminated and massive ores. Late massive magnetite (±apatite, calcite) veins cross-cut the early assemblages and often contain 'oolite' (concentric, spherulitic, ball-like) magnetite aggregates and magnetite–halite accumulations. Enrichment in sulfides (chalcopyrite, pyrite) is observed in the uppermost parts of some deposits.

Peralkaline granite-associated deposits

There are several large Nb–Ta (±REE, Y, Zr, cryolite) deposits in Siberia (e.g. Katugin, Zashikhinskoe, Ulug–Tanzek, Aryskan) that have similarities to peralkaline granite-related deposits worldwide (Strange Lake/Lac

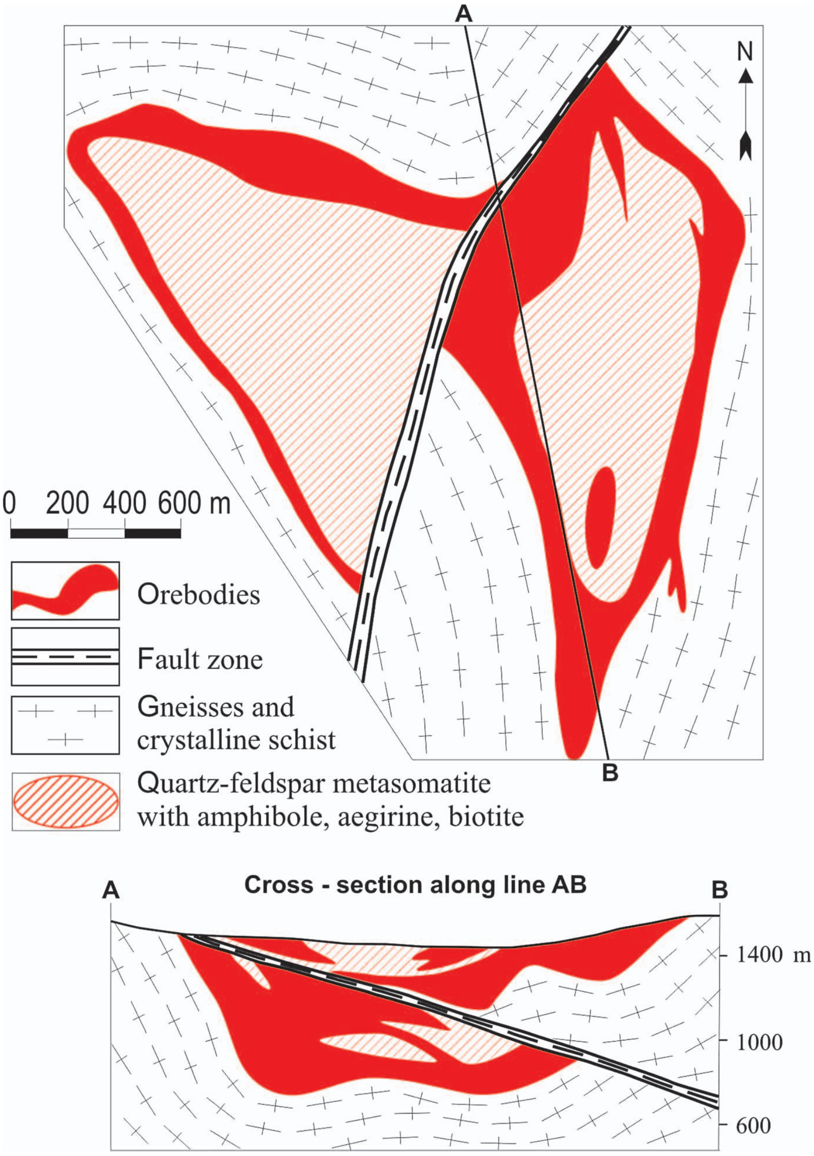

Figure 21 Simplified geology and section through the Katugin Ta–Nb–REE deposit (modified after Bykov & Arkhangel'skaya 1995).

Brisson, Kipawa, Thor Lake deposits in Canada, Ghurayyah in Saudi Arabia: Kovalenko *et al.* 1995; Markl 2006).

Katugin (Chita region in southeast Siberia: Figure 21) represents a special type of Nb–Ta deposit, related to peralkaline quartz–albite–microcline metasomatites and granites, hosted in zones of deep-seated faults (Arkhangel'skaya *et al.* 1993). The deposit was formed during fault-related regional metamorphism (low-pressure amphibolite facies) and partial melting of metasedimentary rocks. Katugin is situated in the western sector of Archean Aldan shield, overlain by Paleoproterozoic terrigenous rocks of the Kalar rift system, metamorphosed to greenschist (to amphibolite?) facies. The rift is controlled by regional-scale deep faults of Archean age, activated many times during the Proterozoic and Phanerozoic. The ore-bearing sequence of the deposit is represented by Paleoproterozoic high-grade metamorphic rocks (migmatitic gneisses and biotite, biotite–muscovite, biotite–garnet–amphibole, staurolite–kyanite, crystalline schists), lying subconcordantly on Archean crystalline schists and gneisses and metasomatically altered in the Paleoproterozoic–Mesoproterozoic ($\sim$1.8–1.6 Ga).

The peralkaline quartz–albite–microcline metasomatites were formed after biotite gneiss and crystalline schists and consists of a large concordant lens- to tabular-shaped steeply dipping mineralised zone. Surface outcrops can be traced for 14 km along strike, with the width of this mineralised strip varying from 0.5 km to 2 km. The mineralised zone exhibits a complex internal zonation shown by alternations of tabular and lens-like metasomatic bodies of two major types. The first type is represented by apo-gneiss and apo-schist metasomatite, exhibiting a gneissic texture and enriched in finely disseminated REE–Ta pyrochlore, zircon, gagarinite and cryolite. The second type is represented by apo-granite–gneiss metasomatite with a weakly gneissic texture, depleted in pyrochlore but enriched in zircon and Y-fluorite. The complex Ta–Nb–REE–Zr mineralisation is associated with amphibole–aegirine quartz–albite–microcline. The major orebody extends for 4 km along strike, for 800 m downdip, and is 6–300 m in thickness. The main Ta–Nb minerals are REE- and Ta-bearing pyrochlore, gagarinite and zircon. In contrast, the REE–Zr mineralisation contains less pyrochlore but is enriched in yttrofluorite, gagarinite and zircon. The deposit has average ore grades of 0.02% Ta_2O_5, 0.36% Nb_2O_5, 1.72% Zr_2O, 0.386% $(REE)_2O_3$ and 0.164% Y_2O_3 and contains also in average 0.0078% U and 1.8% cryolite (Arkhangel'skaya *et al.* 1998, Ryabtsev *et al.* 2006a, b).

The *Zaschikhinskoe deposit* (Irkutsk region, southeast Siberia, Eastern Sayan orogenic belt) is associated with a Late Paleozoic pluton of peralkaline granite, intruded into a rift system, developed along the southern uplift of the Archean basement of the Siberian Craton. The Late Paleozoic peralkaline granite pluton intrudes Proterozoic granites, granite gneisses and metamorphic rocks (plagiogneisses, amphibolites, crystalline schists).

The deposit is in the apical part of a small (1.3 km^2) peralkaline granite pluton (Arkhangel'skaya & Shuriga 1997). The mineralised zone is represented by quartz–albite–microcline, quartz–albite, albite rocks, formed by fenitic alteration of peralkaline granite and containing riebeckite–arfvedsonite, aegirine and Li–Fe micas (protolithionite, zinnwaldite, polylithionite, Li–Fe muscovite). The mineralised zone incorporates a number of alternating lens- and manto-like subconcordant strips composed of various types of Ta–Nb mineralisation, striking east–west and moderately–steeply (40–45°) dipping north. Three main types of Ta–Nb mineralisation are present: (i) high-grade columbite–malacon (hydrated zircon) mineralisation in albitite and quartz–albite rock enriched in Li micas (average grades are 0.038% Ta_2O_5, 0.334% Nb_2O_5, 0.4% ZrO_2, 0.2% $(REE)_2O_3$, 0.2% Sn using 0.02% Ta_2O_5 cutoff); (ii) columbite–malacon mineralisation in quartz–albite–microcline metasomatite containing Li micas, riebeckite–arfvedsonite, occasionally aegirine (average grades are 0.02% Ta_2O_5, 0.19% Nb_2O_5); and (iii) low-grade pyrochlore–columbite–zirtolite mineralisation in a quartz–albite–microcline rock containing riebeckite–arfvedsonite and protolithionite (average grades are 0.01% Ta_2O_5, 0.1% Nb_2O_5). The mineralised zones contain several generations of finely disseminated columbite–tantalite, Ta-bearing pyrochlore, zircon, cassiterite; ilmenorutile–struverite, fergusonite, gagarinite, monazite, xenotime, fluocerite, thorite, cryolite and topaz. The mineralisation is characterised by elevated radioactivity. The deposit remains underexplored, but is known to have inferred resources (Russian P_1 category) of 86 kt Ta_2O_5, with the average grade of 0.033 wt% Ta_2O_5 and 25 kt of Nb_2O_5 (Odintsova & Syzykh 2007).

Carbonatite-related deposits

Carbonatite deposits of several types are present in Siberia including those bearing significant Fe, Fe–apatite, Nb–Ta, Nb–REE and REE (e.g. Arbarastakh, Tomtor, Bolshaya Tagna, Belaya Zima, Karasug). They are present in the Siberian craton and in the adjacent Altaid and Transbaikalia–Mongol orogenic belts (Figure 1). The most recent and comprehensive review of carbonatite deposits in Russia is in Frolov *et al.* (2003) and a full listing of carbonatite occurrences in Russia can be found in Woolley & Kjarsgaard (2008).

The *Tomtor Nb–REE deposit* is one of the world's largest Nb deposits; it is situated in Northern Siberia (Northern Yakutia) on the northeast side of the Anabar crystalline shield (Epshtein *et al.* 1994; Kravchenko & Pokrovsky 1995). The deposit is related to a large (about 250 km^2 in surface area) pluton composed mainly of nepheline syenites with carbonatites in its central sector (Figure 22). There are three types of Nb–REE ores in this deposit. The first type is represented by primary carbonatite in the central part of the pluton and enriched in pyrochlore, florensite and bastnaesite with average grades 0.2–0.3% Nb_2O_5 (up to 0.5%) and 0.6–0.8% $(REE)_2O_3$. The second type is represented by frankolite and hetite-bearing paleoregolith material formed during the Carboniferous, over pyrochlore- and monazite-bearing carbonatites with a roughly elliptical area of about 6 x 8 km. These paleoregolith materials have average thickness of 110 m (up to 300 m in fault zones) and

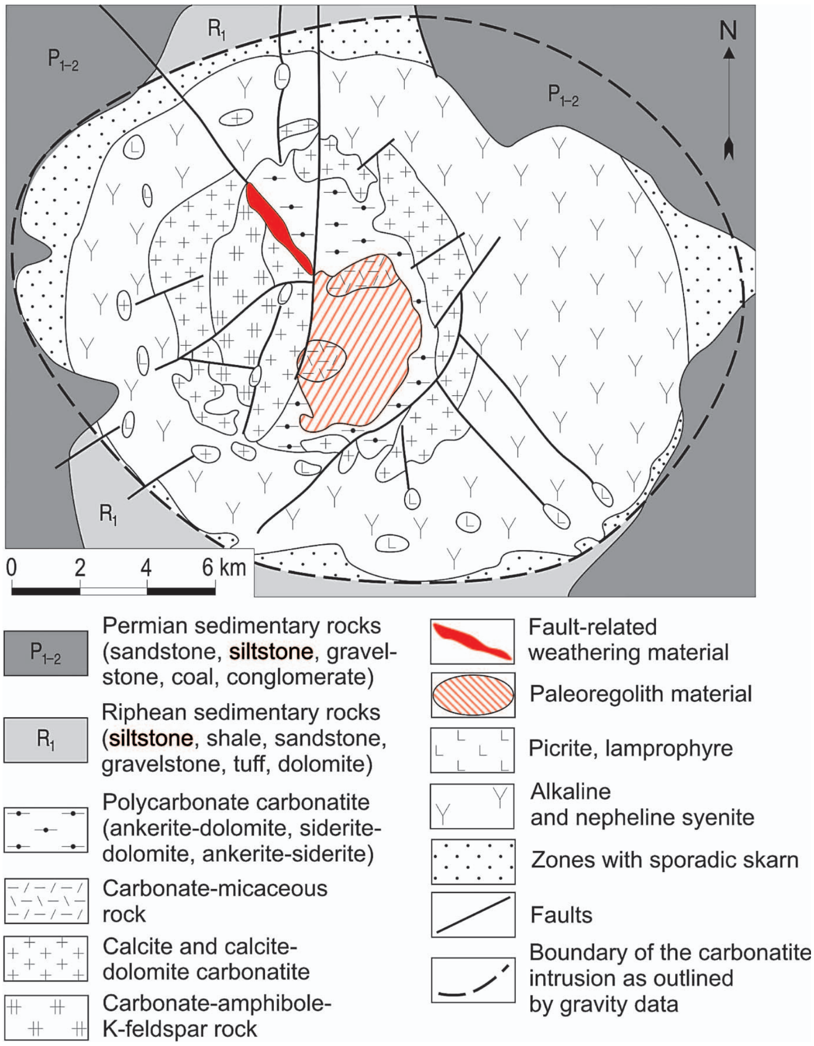

Figure 22 Geological map of the Tomtor Nb–REE deposit (modified after Frolov *et al.* 2003).

contain a frankolite zone with 0.03–2.46% Nb_2O_5 (average 0.81%), 0.55–1.64% $(REE)_2O_3$ (average 1.00%) and 3.8–33.9% P_2O_5 (average 18.0%), and a zone containing 0.19–2.07% Nb_2O_5 (average 0.84%), 2.10–7.60% $(REE)_2O_3$ (average 4.7%) and 0.6–19.6% P_2O_5 (average 4.2%). The third type of ore is represented by a talus of paleoregolith material deposited in several depressions. This redeposited paleoregolith material includes the highest-grade orebody that is 0.2–35 m (average 8–10 m) thick and is composed mostly of pyrochlore, phosphates and alumophosphates of REE, Sr, and Ba (florencite, monazite, gorceixite, goyazite), rutile and pyrite. These ores contain high grades of Nb_2O_5 (2.18–12.42%, average 6.34%), $(REE)_2O_3$ (6.93–22.67%, average 12.7%), Y_2O_3 (0.18–1.04%) and Sc_2O_3 (0.015–0.089%, average 0.05%) (Epshtein *et al.* 1994).

The *Beloziminskoe (Belaya Zima) Ta–Nb–REE–apatite deposit* (Figure 23) is situated in the Eastern Sayan orogenic belt of the southern Siberia (Irkutsk region) (Frolov *et al.* 2003) at the intersection between a graben structure and a regional-scale fault, extending along the southern margin of Siberian craton. The deposit is related to a large (~12 km^2) Mesoproterozoic (650–600 Ma) ring complex of ultramafic alkaline rocks and carbonatites. This complex intrudes a Neoproterozoic metamorphic sequence comprising sericite–quartz schist, phyllite, sandstone, conglomerate and metadolerite. The ultramafic alkaline rocks represent 40–45% of the complex, including predominating ijolite and minor melteigites, urtites (ijiolite series) and pyroxenite, which form the outer zone of the ring structure. There are also several dykes of nepheline and alkaline syenites and several tens of small pipes of picrite porphyries. The core of the complex (~9 km^2) is formed by carbonatites surrounded by ring-like vein zones. The carbonatite hosts primary (hypogene) ores of three types: (i) Nb–Ta ores (0.012–0.04% Ta_2O_5) represented mainly by gattchetolite-bearing calcite–forsterite carbonatites; (ii) Nb ores represented by pyrochlore-bearing calcite–forsterite and calcite–diopside carbonatites, with average 0.2–0.3% Nb_2O_5 and high (1–2.5% Nb_2O_5) grades; and (iii) LREE ores represented by parisite–monazite-bearing late carbonatites. All ores contain apatite (average P_2O_5 grade for the deposit is 4.48%). Average Nb_2O_5 grade for the deposit is 0.25% whereas Ta_2O_5 grade is 0.01–0.04%. A thick paleoregolith contains pyrochlore, columbite, francolite and apatite averaging 0.5 wt% Nb_2O_5 and 13.6 wt% P_2O_5 (Frolov *et al.* 2003).

The *Karasug REE carbonatite deposit* is situated in the Altai–Sayan orogenic belt (southwest Siberia, Tuva region) (Figure 1), and is represented by steeply dipping breccia pipes and vein-like bodies of carbonatites associated with syenitic stocks. These intrude Lower Paleozoic terrigenous–carbonate and volcanic rocks and are believed to be Devonian in age, although other data suggest a Late Mesozoic age (Borisenko & Lebedev 2009). The carbonatites include an early calcite variety containing fluorite, monazite, thorite, stronzianite, celestite, barite, hematite and sulfides. A later siderite–carbonatite is predominant and forms veins and stockworks, enriched in bastnaesite, pyrite, apatite and rutile. The final mineralising stage included intense hematisation of the rocks. The orebodies contain 20 vol% barite, 9–12 vol% fluorite, 3 vol% pyrite, 1.5 vol% bastnaesite and 0.5 vol% apatite. Of the two largest pipe-like orebodies, one is about 670 × 750 m across and the other is 400 × 550 m across. Linear orebodies extend for 300–1400 m along strike and are 100–160 m thick; they can be traced downdip for 300–550 m. According to Frolov *et al.* (2003), the deposit reserves are estimated at 100 Mt Fe, 50 Mt barite, 4.5 Mt Sr and 4 Mt REE_2O_3, with the following average concentrations: Fe 28 wt%, REE 0.7–1.62 wt%, Y 0.016 wt%, U 0.17 wt% and Sr 0.18 wt%.

Kimberlite/lamproite-hosted diamond deposits

World-class diamondiferous kimberlite deposits represent another well-known feature of Siberia (Yakubchuk 2009). Most of these kimberlites are located in the northeast part of Siberian craton (northeast Yakutia) (Figure 1). In total, about 1200 diamondiferous and barren kimberlite pipes, less commonly veins and dykes, are present in this region. Twelve kimberlite pipes are considered to be economic diamond deposits (Mikhailov 2004). There are at least six events of kimberlite emplacement: (i) Late Ordovician; (ii) Late Silurian; (iii) Late Devonian; (iv) Late Permian; (v) Early Triassic; and (vi) Late Jurassic (Davis *et al.* 1980). The Devonian kimberlites are the most productive for diamonds; they intrude platformal carbonate rocks and are often parts of subvolcanic systems incorporating several kimberlite pipes, veins and dykes. The pipes attain few hundred metres in diameter; some of them are overlain by Jurassic and Permian sedimentary rocks.

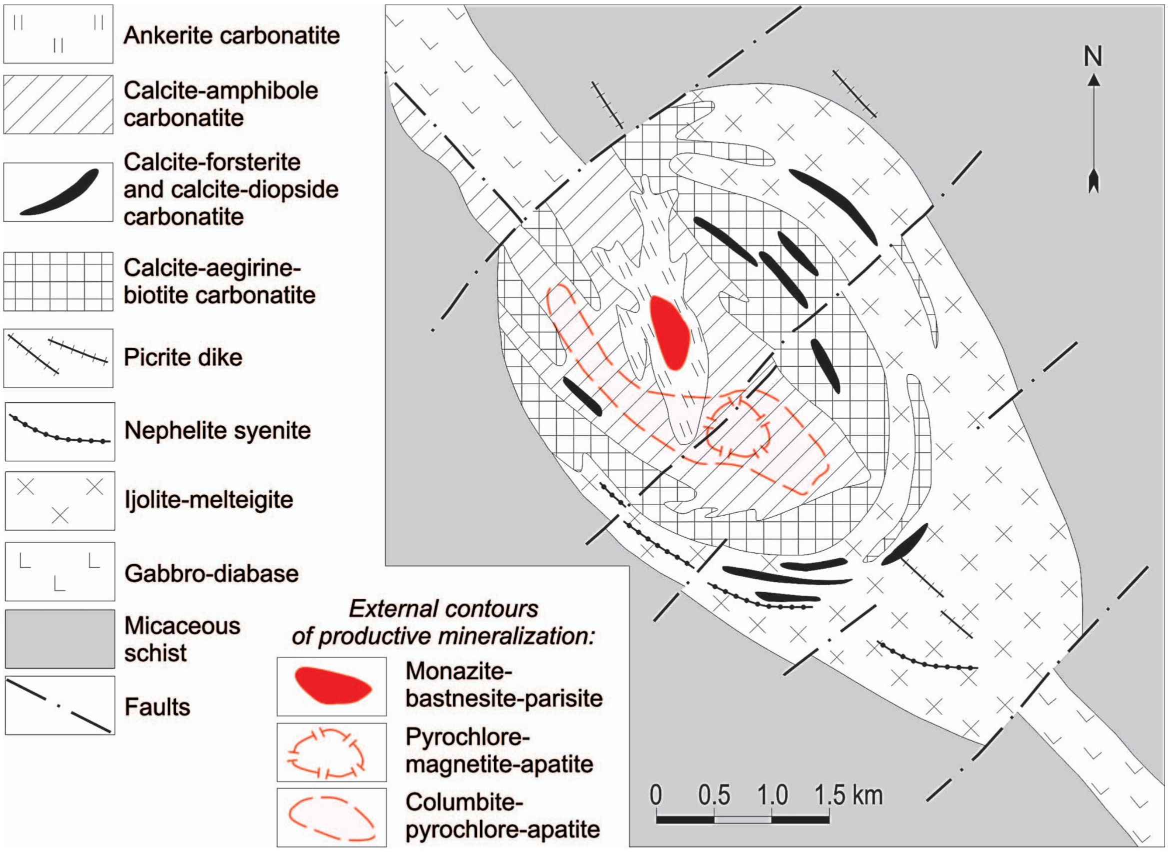

Figure 23 Geological map of the Belaya Zima Nb–Ta–REE carbonatite deposit (modified after Frolov *et al.* 2003).

The world famous *Mir pipe* is of Late Devonian age and together with the neighbouring Sputnic pipe and three kimberlite veins, forming a single subvolcanic system. To a depth of 200 m below the surface, the Mir pipe is funnel-shaped, then becomes cylindrical, and finally splits into several kimberlite dykes at greater depth. The diatreme is composed of kimberlite breccia, with up to six recognisable intrusion stages. The pipe intrudes Cambrian and Ordovician carbonate and clastic rocks. Similarly, the large Internatsionalnaya pipe is from funnel-shaped to cylindrical at depth and continues unchanged for at least 1000 m. Foley *et al.* (2009) gave details of a number of Siberian diamondiferous kimberlites in papers by Klein-BenDavid *et al.* (2009), Kurszlaukis *et al.* (2009) and Rubanova *et al.* (2009).

Magmatic Ni–Cu–PGE sulfide deposits

The world-class and famous Noril'sk Ni–Cu–PGE ore cluster is undoubtedly the showcase of magmatic mineral systems in Asia. The Noril'sk ore cluster is situated in the centre of the Siberian continental flood basalt province that covers (according to some estimates: Ivanov *et al.* 2008) about 7×10^6 km^2. The Ni–Cu–PGE sulfide mineralisation is found in olivine-bearing differentiated mafic intrusives emplaced beneath the flood basalts. The Ni–Cu–PGE-bearing intrusions are in the Noril'sk–Kharaelakh trough of the Tunguska continental flood basalt basin and are 0.5–3 km wide, 0–350 m thick and 20 km long. Numerous publications exist on the Noril'sk Ni-Cu-PGE deposits (Smirnov 1977; Naldrett 1992; Stekhin 1994; Naldrett *et al.* 1996; Yakubchuk & Nikishin 2004; see also Naldrett 1997, 2004 for an overview).

The *Noril'sk 1 deposit* is related to a tabular differentiated intrusion extending for 12 km. Its thickness varies from 30 to 350 m averaging about 130 m. The base of the intrusive is characterised by the presence of locally rounded troughs and funnels up to 150 m deep and up to 600–1000 m wide. The intrusive roof is flatter, with shallow cupolas and is complicated by small apophyses. The internal structure of the intrusion is characterised by distinct layering, with alternation of rocks (from top to bottom) of: (i) eruptive breccias, hybrid rocks and taxitic dolerites; (ii) gabbro–diorites, gabbro- and olivine-bearing dolerites; (iii) olivine gabbros and norite–dolerites; (iv) picritic-gabbro- and norite-dolerites; and finally (v) taxitic and contact dolerites. Sulfide mineralisation forms disseminations and patchy aggregations of pyrrhotite, pentlandite and chalcopyrite mainly in the lower olivine-rich differentiates (picritic, taxitic and contact dolerites), and consists of a relatively continuous horizon coincident in plan with the intrusive contours. In the vertical section, layers of disseminated sulfides (20–50%) occur within the background of 10–20% sulfides ores; with up to six sulfide-enriched layers locally present. The greatest (up to 20 m) thickness of the disseminated ores is characterised by deep rounded troughs at the base of the intrusion. Stringer-disseminated ores form a discontinuous exocontact halo of 15 m width around the intrusive, with average thickness of economic ores of 7–8 m. Large (up to $200 \times 100 \times 20$ m) schlierens of massive sulfide occur locally as well as veins of massive sulfides of 3–4 m (up to 7–8 m) thick. The ore-mineral assemblages comprise chalcopyrite–pyrrhotite–pentlandite, chalcopyrite–millerite and chalcopyrite–pyrite. Besides Cu, Ni, Fe and S, the ores also contain variable amounts of Co, PGE (Pt, Pd, Rh, Ru, Os), Au, Ag, Cd, In, Sn, Sb, Te, Pb, Bi and Sn, The major ore-forming minerals are represented by pyrrhotite, chalcopyrite, pentlandite, cubanite, talnakhite, moikhukite and magnetite, associated with a large number (more than 100) of other, mainly sulfide, minerals and native metals. Disseminated ores contain an average 0.4–0.6 wt% Ni and 2–5 g/t PGE; massive ores contain 2–4 wt% Ni, 3–25 wt% Cu and 2–200 g/t PGE.

The *Talnakh and Oktyabrskoe deposits* are related to a differentiated gabbro–dolerite intrusion. The intrusion is characterised by numerous apophyses coming out of the feeder in the northeastern part of the mineralised area. These apophyses are composed of alternating horizons of (from top to bottom): (i) eruptive breccias, contaminated and leucocratic gabbro; (ii) gabbro and quartz dolerite; (iii) olivine-free and olivine-bearing dolerite; (iv) olivine dolerites; (v) picritic dolerite, dunite and troctolite; and (vi) taxitic and contact-facies dolerites. The majority of the sulfide mineralisation is located at or near the base of the intrusive, mainly in picritic, taxitic and contact-facies dolerites. Orebodies consist of disseminated, stringer-disseminated and massive sulfides.

The ore minerals are pyrrhotite, chalcopyrite, cubanite and pentlandite. Massive ores often contain aggregates of talnakhite, moikhukite and troilite. Disseminated sulfides form about 70% of the total reserves, whereas massive ores account for 18%. Their greatest thickness (about 50 m) occurs in trough-like depressions at the base of the intrusion. Locally, the disseminated ores form a series of lensoid bodies of 5–10 m thick separated by weakly mineralised gabbro–dolerites. About 80% of the disseminated ores are composed of chalcopyrite–pyrrhotite and pyrrhotite–chalcopyrite with a Cu:Ni:Co ratio of 45:25:1. Ore minerals include pyrrhotite, chalcopyrite, cubanite, talnakhite and moikhukite. The massive ores of the Talhakh deposit have Cu:Ni:Co ratio of 49:33:1 and those of the Oktyabrskoe deposit 46:24:1. The stringer-disseminated ores are in the exocontact rocks and have minor importance, constituting about 6% of the reserves. They usually are up to 2–3 m thick and surround the massive ores and are composed mostly of pyrrhotite, chalcopyrite and pentlandite, with lesser amounts of millerite, bornite, pyrite and magnetite. Cu:Ni ratio in these ores varies from 1:1 to 20:1.

Recently, another large Ni–Cu–PGE deposit of similar style was discovered and explored in southwest Siberia (Tuva region) (Glazunov & Radomskaya 2010). This is the *Kingash Ni–Cu–PGE deposit* which contains about 100 Mt of ore, with an average grade of 0.6% Ni, 0.4% Cu and 0.8 g/t Pt+Pd. The mineralisation is related to a small mafic–ultramafic (wehrlite–pyroxenite–gabbro) differentiated intrusive in the Eastern Sayan orogenic belt. The intrusion has a lens shape and, at its present level of erosion, covers an area of 2.5 km^2. The mineralised area occupies about 3000×700 m. Three zones are recognised in the intrusive: (i) lower peridotite zone; (ii) intermediate pyroxenite zone; and (iii) upper gabbro zone, with a cumulative thickness of over 1000 m. The peridotite zone is poorly layered and consists of serpentinised dunite and wehrlite. The pyroxenite zone is transitional from ultramafic to gabbroic rocks and is distinctly layered, consisting of alternating rhythmic units represented by pyroxenites, peridotites and gabbros. Cu–Ni mineralisation is hosted in mafic–ultramafic layered rocks and, to lesser degree, near the contacts with gneisses and amphibolites, but Cu–Ni sulfide ores are confined to peridotites. The gabbro zone contains fine dissemination of pyrite and magnetite. The sulfide ores are represented by disseminated, breccia and massive types. The disseminated sulfides predominate and occur in the lower and middle portions of the peridotite zone. Thickness of the orebodies varies from 5 to 270 m; and the sulfide content increases downward from 1–2 vol% to 15–20 vol%. The major ore minerals are pyrrhotite (50%), pentlandite (up to 20%), with subordinate amounts of chalcopyrite and magnetite (up to 10%). Three major ore assemblages are recognised: (i) pyrrhotite–valleriite–pentlandite; (ii) pyrrhotite–pentlandite; and (iii) chalcopyrite–pentlandite–pyrrhotite. The disseminated ores contain 0.3–1.4% Ni, up to 0.7% Cu and 0.005–0.3% Co. The massive ores form veins, with thickness ranging from a few centimetres to 80 cm. The major ore minerals are pentlandite, chalcopyrite and pyrrhotite. The massive ores contain an average 6.05% Ni, 2.46% Cu and 0.14% Co. Breccia–matrix ores occur together with the massive ores, with thickness ranging from 0.8 to 3.1 m These ores contain pyrrhotite (10–35 vol%), pentlandite (15–20 vol%), chalcopyrite and cubanite (10 vol% each). The breccia–matrix ore contain up to 3.95% Ni, 0.95% Cu and 0.094% Co.

Mafic intrusion-hosted Fe–Ti–V deposits

The largest deposit of this style is represented by the *Chiney Fe–Ti–V and associated Cu deposit* situated in southeastern Siberia (Chita region) (Gongalsky *et al.* 1995). This deposit is located in the northeastern part of the mineral district, which also includes the Udokan deposit and is related to Proterozoic gabbroic pluton. The latter is a lopolith-like intrusive and is composed of norite, gabbro–norite with a Ti-magnetite content of 7–10%, pyroxenite, layered gabbro–norite with a Ti-magnetite content of 10–90 vol% and gabbro–diorite with layered bodies of anorthosite and veined Ti-magnetite ores. This pluton hosts two large deposits: (i) the Chiney Fe–Ti–V deposit (reserves exceed several tens of billion tonnes of ore, including openpit reserves (10 Gt; Fe grade varies from 16 to 58 wt%, TiO_2 from 3.35 to 15.4 wt%, V_2O_5 from 0.22 to 1.23 wt%); and (ii) the Chiney deposit of Cu-bearing gabbros. The latter contains reserves of 8.2 Mt Cu, with additional Ni, Co, Pt, Ag and Au, and is represented by lenticular and veined orebodies sited in the exocontact of the Chiney gabbroic pluton; they form mineralised zones up to 5–10 m (usually 2–2.5 m) thick extending for many hundreds of metres to several kilometres. The deposit consists of two economically important sectors. One located in the eastern endocontact of the intrusive and composed of pyrrhotite–chalcopyrite, and the other located in the western endocontact and composed of pyrite–chalcopyrite. The massive and disseminated ores are transitional. Copper contents vary from 0.1 to 2.4%, with Ni and Co contents of about 0.01%. The ore minerals are chalcopyrite, pyrrhotite, pentlandite, bornite and chalcocite, with traces of linneite, nickelite, pyrite and magnetite.

Magmatic PGE deposits

PGE–chromite mineralisation is present in Ural–Alaskan type intrusions (Johan 2002), which are quite common in various Siberian terranes with the *Kondyor PGE deposit* (Figure 24) being the largest. This deposit is situated in the southern part of the Aldan Shield (Figure 1) and is related to a concentrically zoned ultramafic–alkaline pluton about 6 km across, intruded through Archean and Proterozoic sequences. According to Sushkin (1995), the pluton has a dunite core and outer zones composed of clinopyroxenite, peridotite and diorite, with clinopyroxenite locally hosting apatite–magnetite–biotite veins. These rocks were intruded by Mesozoic alkaline rocks, such as nepheline syenites containing eudialite, lamprophyllite, lovozerite, murmanite and ramzaite. These rocks locally contain abundant chrome–diopside. The PGE mineralisation is mostly in dunites, where dense disseminations, schlierens and veinlets of ferrochromite are present, and is represented by monomineralic grains or their aggregations cementing chromespinelides and olivine. Isoferroplatinum (Pt_3Fe) is the major platinum mineral; it often contains a significant admixture of Ir and Os and/or Ir–Os alloys. The deposit bears also sulfide and As mineralisation and is accompanied by a large placer of PGE minerals (Cabri & Laflamme 1997; Shcheka *et al.* 2004).

IMPORTANCE OF SIBERIAN METALLOGENY FROM A GLOBAL PERSPECTIVE AND EXPLORATION POTENTIAL: CONCLUDING REMARKS

The overview of Siberian metallogeny presented in this paper shows the great importance of this region for the improvement and further development of metallogenic concepts. Moreover, this region provides tremendous input in further understanding of the metallogeny of cratons and orogenic belts, orogenic collages and anorogenic intraplate settings. More specifically, the Siberian terranes incorporate a range of mineral deposits in different geological and tectonic settings, from those found in Precambrian craton basement, rift basins to cratonic cover. Many of these deposits are probably related to intraplate anorogenic magmatism (e.g. mantle plumes), which occurred in the Paleoproterozoic, possibly Mesoproterozoic and Mesozoic. Specifically, important large deposits (e.g. Noril'sk Cu–Ni–PGE deposits, and other mafic intrusive-related deposits, carbonatite-related deposits, and possibly IOCG-related deposits) testify to widespread anorogenic mag-

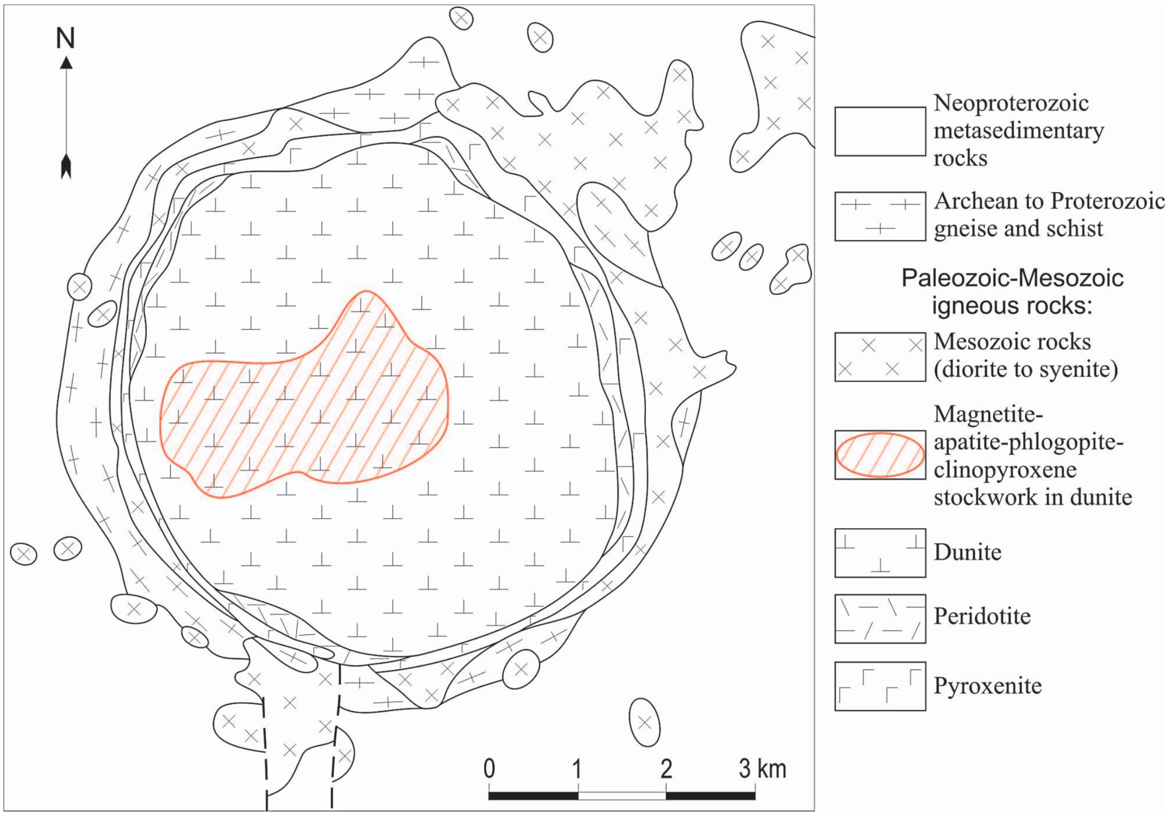

Figure 24 Simplified geology of the Kondyor PGE deposit (modified after Sushkin 1995).

matic activity in Siberia, providing further understanding of metallogenic processes related to mantle plumes (Borisenko *et al.* 2006; Pirajno *et al.* 2009). Yet larger numbers of deposits occur in different orogenic and anorogenic settings in numerous fold belts accreted to the Siberian craton during the Phanerozoic and forming respectively the Altaid, Mongolian–Transbaikalian, Yana–Kolyma, Okhotsk–Chukotka and other orogenic collages. Possible interaction between cratonic and tectono-thermal processes have been studied on Siberian examples, in particular, influence of mantle upwellings, like those that occurred during Mesozoic proximal and distal subduction-related orogenic processes, with the closure of the Paleo-Tethys ocean and subsequent development of the Pacific Ocean. This interaction may have resulted in the occurrence of polychronous mineralisation overprinting within the same long-lasting structures which, in turn, may lead to the formation of large and high-grade deposits. Furthermore, sustainable spatial associations of coeval deposits in various tectonic terrains leads to recognition of the respective 'lateral' genetic assemblages of these deposit styles. On the other hand, the distinct temporal evolution of these assemblages in relation to evolving tectonic settings, magmatic suites etc., shows the possibility of the respective evolutionary trends forming 'vertical' (i.e. evolving in time) stacking (telescoping) of mineral deposits. In particular, the porphyry–epithermal transition related to temporally evolving igneous suites would be an example of telescoping of a mineral system. At the more local scale, the importance of various structures (troughs/grabens and other linear faults, concealed faults, revealed by photolineaments, and ring faults, corresponding to deep-seated magma chambers, plutonic uplift/domes and volcanic depressions) providing controls on mineralisation at the scale of mineralised districts can be observed on many Siberian examples.

Furthermore, the present overview of Siberian mineral deposits also shows the great importance of this region for the improvement of mineral systems genetic models. These would include both: (i) additions to and further development of existing classifications and genetic models of mineral systems; and (ii) new significant examples complementing models of known deposit styles. In particular, the abundance of numerous, and often large, Siberian deposits representing known styles further complements geological–genetic models. This is especially true for orogenic Au and epithermal Au, Au–Ag and Ag deposits, SEDEX, VHMS, skarn and porphyry deposits, granite-related Sn, W and Mo deposits, peraluminous and peralkaline granite-related rare-metal (Ta, Nb, Li, Cs, REE) deposits, carbonatite-related deposits, magmatic Cu–Ni–PGE, PGE–chromite and Fe–Ti deposits, and diamondiferous kimberlites. Siberian examples of these deposits should be taken into consideration in the worldwide database of mineral deposit models. In addition, recent developments in Russian geoscience have provided significant advances in understanding and modelling of formation conditions of large and superlarge deposits (Rundqvist *et al.* 2004), and these advances are effectively based on Siberian examples.

The Siberian terranes also host a number of unknown or poorly studied mineral systems and styles. These include, for example, Sn–Au and Au–Mo deposits in the Okhotsk–Chukotka and Mongol–Okhotsk belts (e.g. Bugdaya Au–Mo deposit, Maiskoe Au and related Au–Sn deposits) that are similar to other intrusive-related deposits, recognised as a distinct deposit class (Thompson *et al.* 1999). In this regard, distinct relationships and transitions of intrusive-related Sn–W, Sn–sulfide and Ag–sulfide deposits can further expand this deposit class. Also, the U and U–Au deposits related to alkaline igneous suites such as those on the Aldan Shield, together with alkaline Cu–Au, Cu–Mo and Au deposits may belong to the class of shoshonite-associated mineral systems (Müller & Groves 1997; Chamberlain *et al.* 2007; Cooke *et al.* 2007). It is possible that the epithermal U–fluorite deposits of the Eastern Transbaikalia can also be related to volcanic suites of trachybasalts–trachyandesites–shoshonites–latites. The Angara–Ilim deposits hosted in diatremes, with predominantly Fe oxide mineralisation and its prograde and retrograde skarns and hydrosilicate alteration assemblages, indicate signatures from both hydrothermal and magmatic origin and may belong to the IOCG family (Soloviev in press a).

On the other hand, despite the fact that there are numerous mineral deposits in Siberia, representing a large number of ore system, some other important systems appear to be missing, although they are present in other regions with similar geological and tectonic settings. This creates new opportunities for mineral exploration in Siberia. For example, not much is known in Siberia about the role and importance of well-studied deposit on other cratons and Precambrian shields, as for example Au and Au–U deposits of Witwatersrand type, komatiite-related Au, PGE and other Cu–Ni deposits. Also, despite of the presence of IOCG systems in Siberia, an Olympic Dam analogue is not known yet. This is of special importance due to a possible direct connection of Australian and Siberian cratons in the Proterozoic (Rodinia and Pangea reconstructions: Rogers & Santosh 2002; Santosh *et al.* 2009 and references therein).

Other mineral systems may also have greater abundance and economic importance in Siberia. In particular, the significance of epithermal Au and Au–Ag deposits in some Siberian terranes was just recently recognised: these include the large Kubaka low-sulfidation epithermal Au–Ag deposit often referred to as the last Soviet era discovery; the large Kupol low-sulfidation epithermal Au–Ag deposit was discovered in 1995 and explored in the early 2000s. The recent discovery of these large deposits raises concern as to the real potential of Siberian terranes in hosting large epithermal deposits, especially taking into account the virtual lack of state-funded regional-scale exploration since the Soviet Union breakup in 1991. The fact that great discovery opportunities still exist is supported by the recent discovery of the large Svetloe high-sulfidation epithermal deposit in the Khabarovsk region (East Siberia). Notably, general geological and genetic links of porphyry and epithermal systems in Siberia and possible transitional porphyry–epithermal were only recently recognised (Sidorov & Tomson 1987; Volkov 2005; Prokofiev *et al.* 2006).

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SUPPLEMENTARY PAPER

APPENDIX 1: DATA REPOSITORY OF LARGE MINERAL DEPOSITS IN SIBERIA

[NB (i) –skoe is a suffix commonly used in Russia; (ii) bold letters refer to deposits discussed in the text.]