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Tin deposits of the Sikhote–Alin and adjacent areas (Russian Far East) and their magmatic association

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The Sikhote–Alin accretionary belt along the northwestern Pacific Plate hosts the most important tin province of Russia. Here, more than 500 ore deposits were formed between 105 and 55 Ma at transform and active subduction margins. Petrological models suggest an active role of the mantle in the mineralisation processes. The deposits can be divided into three groups according to their mineral content and associated magmatism. The first group, a cassiterite–quartz group is defined by tin-bearing greisens as well as quartz–cassiterite and quartz–cassiterite–feldspar veins and stockworks. The mineralisation shows distinct genetic relationships with S- and A-type granites. The deposits are located mainly in Jurassic accretionary prisms adjacent to the Bureya–Khanka Paleozoic continental terrane margin. The second group is represented by the economically important cassiterite–silicate–sulfide deposits, which produce about 80% of Russian tin. Mineralisation in this group is represented by metasomatic zones or veins related to I-type granitoids. The orebodies consist of cassiterite–tourmaline–quartz or cassiterite–chlorite–quartz associations and contain variable amounts of sulfides. The third group comprises tin deposits containing cassiterite and sulfides with the most complicated ore composition with abundant sulfides and sulfostannates accounting for 60–80% of the total ore mass. In some deposits, zinc, lead and silver dominate, whereas tin is sub-economic. The deposits of this group are generally associated with magmatic rocks of the Sikhote–Alin volcano-plutonic belt. The different associations are found together in the same districts and, locally, also in individual deposits. These are characterised by polychronous and polygenetic mineral systems, formed during long periods of time and in different tectonic settings. This testifies to changes in the many physico-chemical parameters of ore formation and, probably, of ore sources. We suggest that the complex mineral and element compositions of some of the ores were caused by the long-lasting composite tectono-magmatic processes.

KEY WORDS: granitoids, ilmenite series, Russian Far East, tin deposits, Sikhote–Alin.

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INTRODUCTION

The Sikhote–Alin folded accretionary belt, situated in the extreme southeastern part of Russia, is the country's most important tin province. In this area, tin mineralisation occurs in over 500 deposits of different size and includes both major and unique deposits. The real tin potential of this region, however, has not yet been determined. The main tin deposits of the Sikhote–Alin yield $\sim$70% of Russia's tin, and are located in the Komsomolsk, Badzhal (Khabarovsk Territory) and Kavalerovo (Primorye) ore districts (Figure 1). Most of the tin deposits were formed between 105 and 55 Ma, but frequency distributions of available isotopic geochronological data show that three peaks (pulses) of intensive tin-ore formation occurred at 96, 63 and 55 Ma (Figure 2) (Ognyanov 1986; Rodionov 2000, 2005; Korostelev *et al.* 2004; Nokleberg 2010).

These pulses of tin-ore formation are present in various combinations not only in the ore districts, but also in some individual deposits. They are not always identified in terms of isotopic systematics, but are revealed by paragenetic features. Such deposits are characterised by a polychronous, multiphase ore genesis, which occurred during long periods of time and in different tectonic settings (Figure 3). This testifies to changes in the physico-chemical parameters of ore formation and, probably, of ore sources. We propose that this long-lasting and varied geological history may have been the primary cause for the complex mineral and element compositions of the ores.

In contrast to the tin deposits of China, Malaysia and Brazil, where tin occurs in quartz veins, greisens and pegmatite, and which are the main tin contributors to the world market, most of the Sikhote–Alin tin is mined from deposits whose ores are rich in sulfide minerals,

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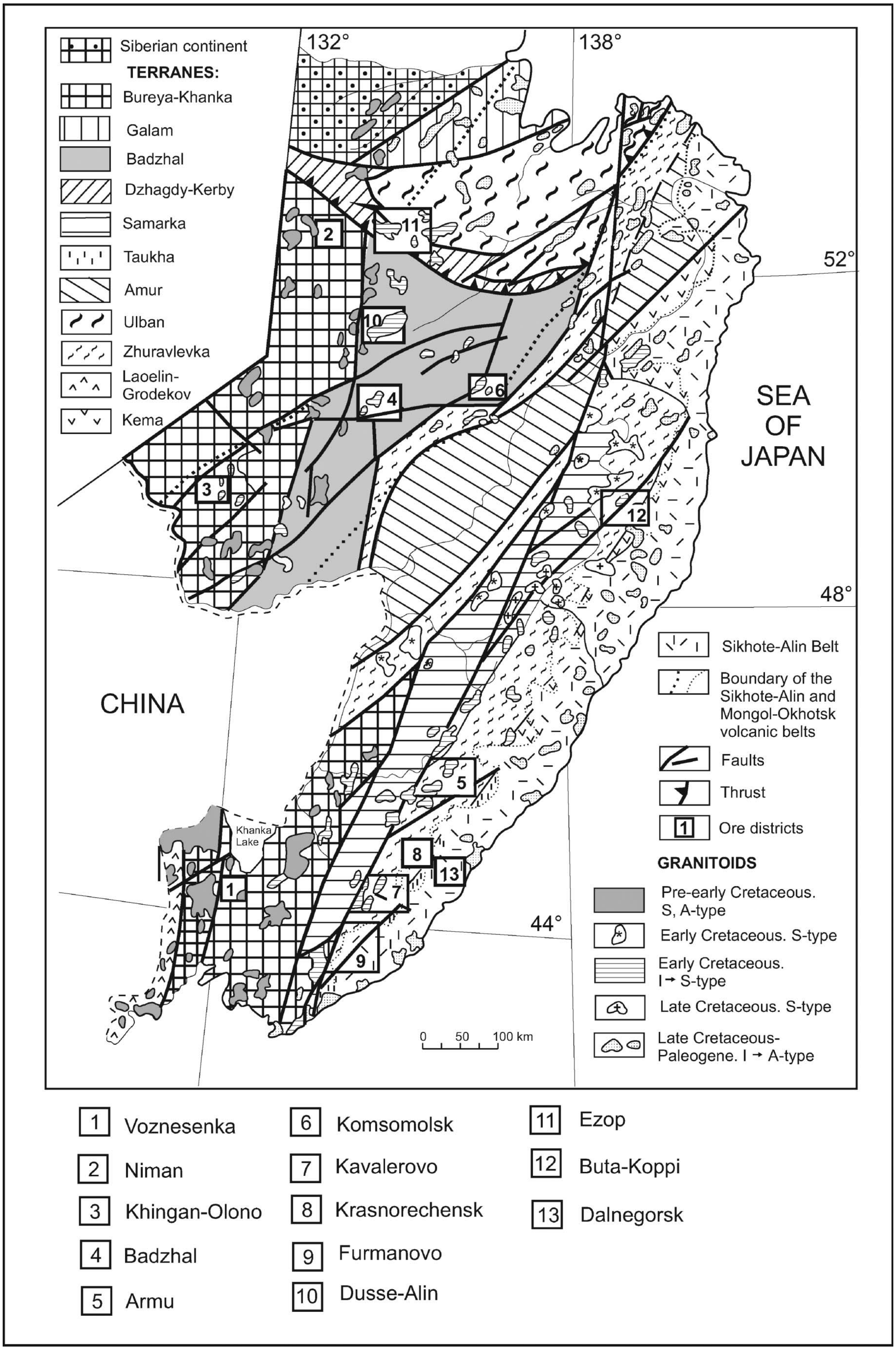

Figure 1 Tin districts in the tectonostratigraphic terranes of the Russian Far East (adapted from Gonevchuk *et al.* 1999).

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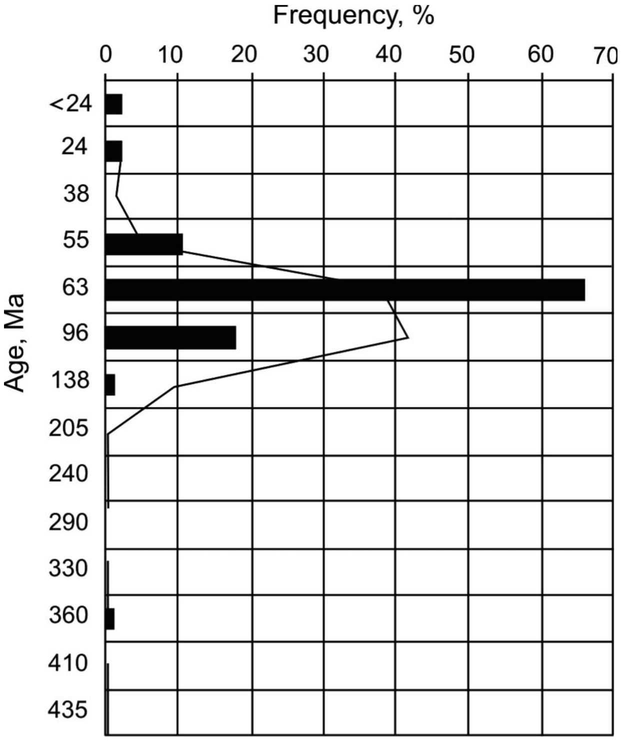

Figure 2 Age of tin deposits and related igneous rocks of the Russian Far East ($n = 96$) (after Rodionov 2000).

including tin sulfides. Cassiterite is present in association with some of the sulfide minerals and with gangue chlorite and tourmaline.

The characteristics of mineralisation and associated magmatism indicate that three groups of tin deposits can be distinguished in the Sikhote–Alin (Radkevich 1968): (i) a cassiterite–quartz group; (ii) a cassiterite–silicate–sulfide group; and (iii) a cassiterite–sulfide group.

CASSITERITE–QUARTZ GROUP

The cassiterite–quartz group includes tin-bearing greisens, quartz–cassiterite and quartz–cassiterite–feldspar veins and stockworks. Mineralisation in this group shows clear relations with S- and A-type granites. These deposits have very simple mineral compositions in comparison with deposits in other groups. Cassiterite is the main ore mineral in this group, commonly associated with wolframite. Sulfide minerals are, for the most part, found in deposits with large vertical extent of the orebodies. These include molybdenite, sulfostannates, chalcopyrite, bornite, sphalerite and bismuthinite. Ore deposits of this group often have high Nb, Ta, Y, Se, Be, In and rare-earth elements contents.

These deposits occur mainly in Jurassic accretionary terranes, adjacent to the margin of the Paleozoic Bureya–Khanka continental terrane (Khanchuk 2000). Sometimes they occur in near-continental basin terranes. The Badzhal ore district is the best example of this group (Semenyak *et al.* 1988, 2006; Gavrilenko & Panova 2001; Gonevchuk 2002).

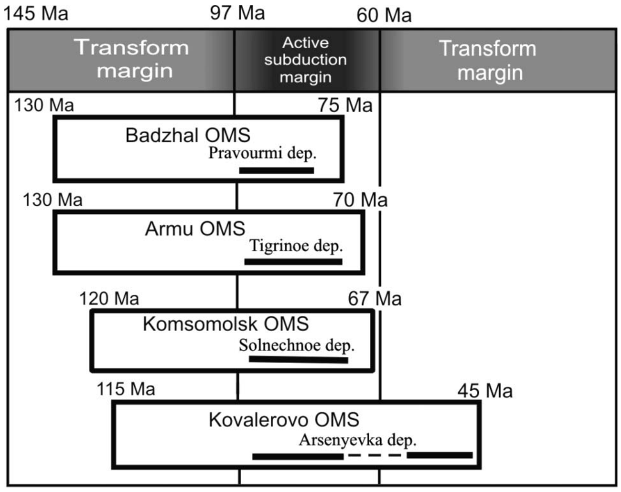

Figure 3 Temporal position of the major tin-bearing ore-magmatic systems (OMS) in the geodynamic evolution of the Sikhote–Alin.

Pravourmi tin greisen deposit

The Pravourmi deposit (50°26′08″N, 134°14′58″E) is located in the Badzhal ore district, and forms one of the largest tin deposits in Russia, containing more than 150 000 t of tin, 160 000 t of copper, plus tungsten and indium (Onikhimovsky & Belomestnykh 1996). But in spite of its polymetallic nature, the Pravourni deposit is known in Russia as a major tin deposit. The deposit is situated in the northeast Solnechnyi administrative district of the Khabarovsk Territory in the western part of the Badzhal ore district (Figure 4).

Basement rocks in the district are Jurassic accretionary prism strata (Badzhal terrane: Khanchuk 2000). They comprise allochthonous blocks from the Bureya–Khanka terrane, including metamorphic rocks, olistoliths of marine carbonates and cherts, and shelf terrigenous rocks, arkosic sandstones, conglomerates, and siltstones. The accretionary prism is overlapped by Early–Late Cretaceous volcanics, which are cut by felsic intrusive bodies of diverse composition. Magmatic formations of the district are divided into four volcanic–plutonic complexes: (i) the Early Cretaceous (≥125 Ma) Dayansky picrites–alkaline-basaltic complex with intrusive bodies of alkaline gabbro–pyroxenites, monzonites and syenites; (ii) the Early Cretaceous (~115 Ma) Laksky andesite complex with small bodies of quartz diorites and granodiorites; (iii) the Early–Late Cretaceous (105–90 Ma) Badzhal rhyolite–granite complex; and (iv) the Late Cretaceous (~95 Ma) Silinka andesite–gabbro–diorite–granodiorite complex (Lugov 1986; Gonevchuk 2002). The Badzhal volcanic–plutonic complex is the most important geological unit of the ore district, in terms of its metallogeny.

According to geophysical data (Lishnevsky & Gershanik 1992), the Upper-Urmi granite body of this complex is a large (>5000 km^2) cupola, which emanates from the batholith underlying the whole ore district. The age of the granites is 97.0–92.5 Ma (K–Ar and Rb–Sr data: Lebedev *et al.* 1999) which were formed in three (Gonevchuk 2002) or four (Brusnitsin *et al.* 1993) phases (Table 1).

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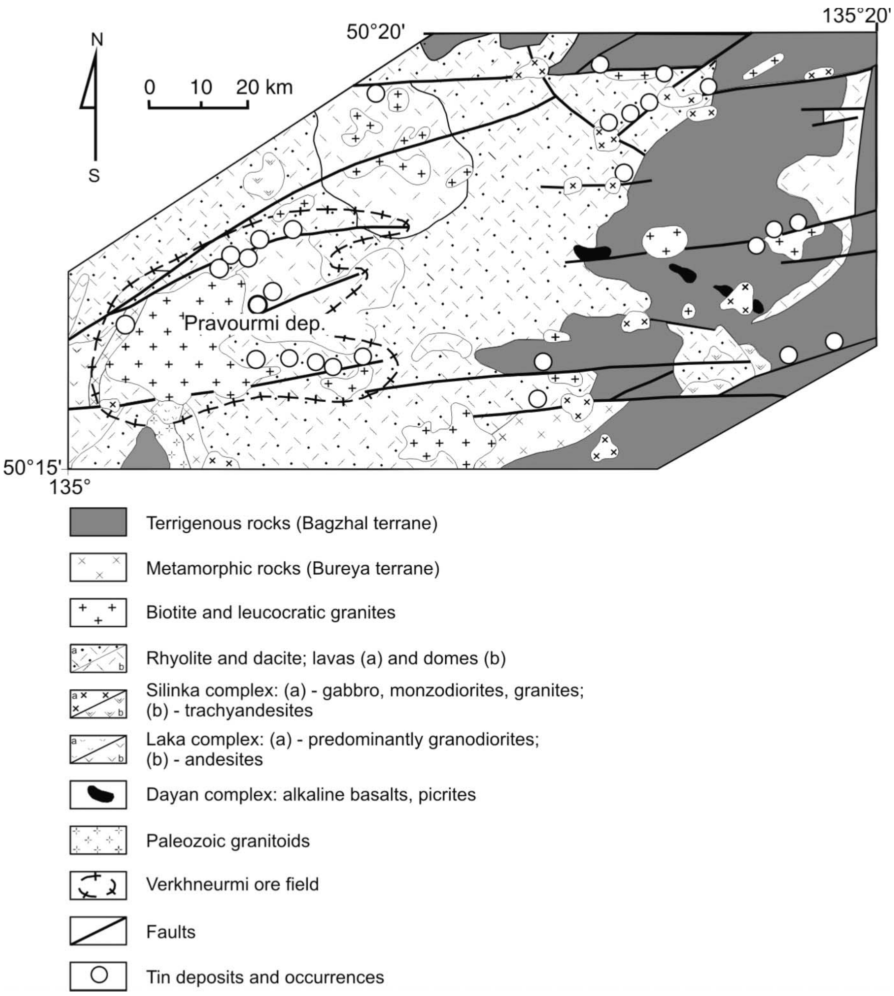

Figure 4 Geological map of the Badzhal ore district (after Gonevchuk 2002).

The first phase includes biotite-granite porphyries and porphyritic granites, in places containing hornblende and pyroxene in the marginal parts of the intrusive body and in dykes. Biotite granites of the second phase are fine- and medium-grained weakly porphyritic rocks. They form the larger part of the intrusive body, and are cut by dykes and small stocks of fine-grained leucocratic granites of the third phase which contain biotite and rarely, protolithionite. Geochemically, the granites evolved from I-type (Phase I) to S-type (Phase II) and then to A-type (Phase III) of ilmenite or intermediate series (Gonevchuk 2002).

The Pravourmi deposit is 4 km east of the Verkhneurmi granite body contact. The orebody is 3–300 m thick, and is confined to the contact of a large dyke of granite porphyry in the central part of the laccolith, composed of porphyritic rhyolites (Figure 5).

A zone of hydrothermally altered rocks, gently dipping eastward, can be traced from the surface for about 9 km and has been explored at 2500 m intervals. The orebodies extend downdip for $\sim$300 m with a core of linear stockwork, surrounded by metasomatitic rocks, which consist of an outer epidote–chlorite and inner siderophyllite facies. In the upper horizons of the deposit, metasomatites of tourmaline–sericite–quartz and quartz–tourmaline subfacies are included in the siderophyllite facies. Analogous zoning is known to occur at depth (Figure 6). Many Russian researchers (Semenyak 1987, Krymsky *et al.* 1997) consider the Pravourmi deposit as an excellent example of a polychronous and polygenetic type of ore deposit (Figure 6).

The first post-magmatic (pegmatoidal) stage of mineralisation is represented by small siderophyllite–quartz–feldspar veins with apatite, loellingite, molybdenite, bismuthinite, scheelite and wolframite that dominate in deep horizons of the deposit.

The second stage is characterised by the formation of the stockwork ore, which is represented by a combination of veins and veinlets of quartz–muscovite, siderophyllite–quartz, quartz–siderophyllite–topaz, quartz–topaz and topaz with pockets of ore minerals. The bulk of cassiterite and wolframite—the main ore minerals of the deposit—as well as loellingite and arsenopyrite, is concentrated in these veins and veinlets. Quartz–tourmaline veins with sulfides are located in the upper part of the stockwork and cut topaz-bearing veins. The age of tin mineralisation is 91.8 $\pm$ 2.3 Ma (Ishihara *et al.* 1997) or 92–88 Ma (Lebedev *et al.* 1999) (Figure 6).

The isotopic age of the quartz–tourmaline–sulfide association is 83–78 Ma (K–Ar data: Lebedev *et al.* 1999) (Figure 6). Metasomatites of epidote–chlorite facies with fine epidote–chlorite–quartz streaks and isolated xenomorphic grains of cassiterite prevail in the uppermost part of the stockwork. The second stage of ore formation

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Table 1 Chemical composition of granites from the Verkhneurmi intrusive body (50°30′36″N, 134°52′48″E).

	Phase I		Phase II	Phase III	
wt%					
SiO_2	73.22	73.44	75.66	77.46	76.91
TiO_2	0.21	0.19	0.11	0.07	0.07
Al_2O_3	14.40	13.85	12.75	11.54	11.56
Fe_2O_3	1.13	0.28	0.70	0.94	0.74
FeO	1.06	1.66	0.99	0.59	0.43
MnO	0.03	0.01	0.01	0.02	0.03
MgO	0.42	0.90	0.49	0.04	0.12
CaO	1.70	1.42	1.35	0.95	0.98
Na_2O	3.17	3.45	3.25	3.23	3.49
K_2O	3.94	4.01	4.52	4.51	4.80
F	0.04	0.17	0.10	0.01	0.08
H_2O	0.52	0.25	0.35	0.73	0.44
Total	99.84	99.63	100.28	100.09	99.65
ppm					
Rb	247	182	245	303	305
Sr	99.7	100.0	45.3	21.5	20.4
Y	41.5	30.5	45.9	19.3	40.9
Zr	99.9	111	89.9	121	117
Cs	15.6	10.8	11.0	10.9	8.25
Ba	601	478	308	125	137
Nb	29	13	18	18	11
Sn	5	5	7	3	2
Pb	27	51	47	56	33
Zn	55	58	62	39	5
B	9	$\leq$5	$\leq$5	$\leq$5	$\leq$5
La	30.1	30.2	26.2	18.7	18.2
Ce	66.2	65.2	62.2	46.3	47.5
Pr	7.88	7.68	7.49	5.72	5.73
Nd	28.2	27.1	27.0	20.2	21.1
Sm	6.21	5.51	6.32	4.66	5.59
Eu	0.653	0.654	0.272	0.134	0.144
Gd	6.44	5.43	6.67	3.99	5.95
Tb	1.11	0.899	1.16	0.694	1.05
Dy	7.05	5.49	7.72	4.24	7.17
Ho	1.48	1.14	1.67	0.867	1.56
Er	4.37	3.28	5.12	2.57	4.89
Tm	0.683	0.510	0.805	0.410	0.786
Yb	4.33	3.28	5.32	2.68	5.10
Lu	0.659	0.497	0.793	0.409	0.760
Hf	3.69	3.78	4.57	5.95	6.09
Pb	25.6	22.9	24.1	32.3	31.3
Th	14.4	14.5	15.2	21.0	21.6
U	2.24	2.51	2.34	3.53	3.21

Analyses were carried out at the Analytical Centre of the Far East Geological Institute, Far East Branch Russian Academy of Sciences, Russia, and REE were determined at the Geoscientific Research Centre, GeoForschungsZentrum, Potsdam, Germany.

is characterised by carbonate veins, veinlets and streaks, with minor muscovite, epidote and chlorite (carbonate stage). Formations of this second stage are divided by tectonic zones into blocks, with horizontal displacements of about 150 m. Locally, these zones contain minor stibnite mineralisation. This is allocated to the third stage of ore formation.

Tigrinoe rare-metal–tungsten–tin deposit

The Tigrinoe deposit (Gonevchuk *et al.* 2005a; Rodionov 2005) is in the north of Primorye in the Armu ore district and is located in the Zhuravlevka turbidite terrane (Figure 7). It is genetically less complex compared with the polygenetic Pravourmi deposit.

The Tigrinoe deposit (46°15′00″N, 135°59′00″E) was discovered in 1954, and with reserves $>$10 Mt it is a large deposit suitable for opencast mining, with ores containing $\geq$0.115% Sn and $\geq$0.034% WO_3. High concentrations of Zn, Bi, In, Cd, Ag, Ta, Nb and Sc make the ores much more valuable. The REE contents may also be of potential economic importance.

Features of magmatism and mineralisation in the Tigrinoe deposit characterise it as a tin–fluoride-type mineral system, which is represented elsewhere in Russia by the Odinokoe and Kesterskoe deposits in Yakutia (Nekrasov 1984). In Europe, Sn–W deposits and occurrences of similar genesis are common in the areas of Paleozoic folding, e.g. the Bohemian Massif in Germany, Austria and Poland, the Armorican Massif

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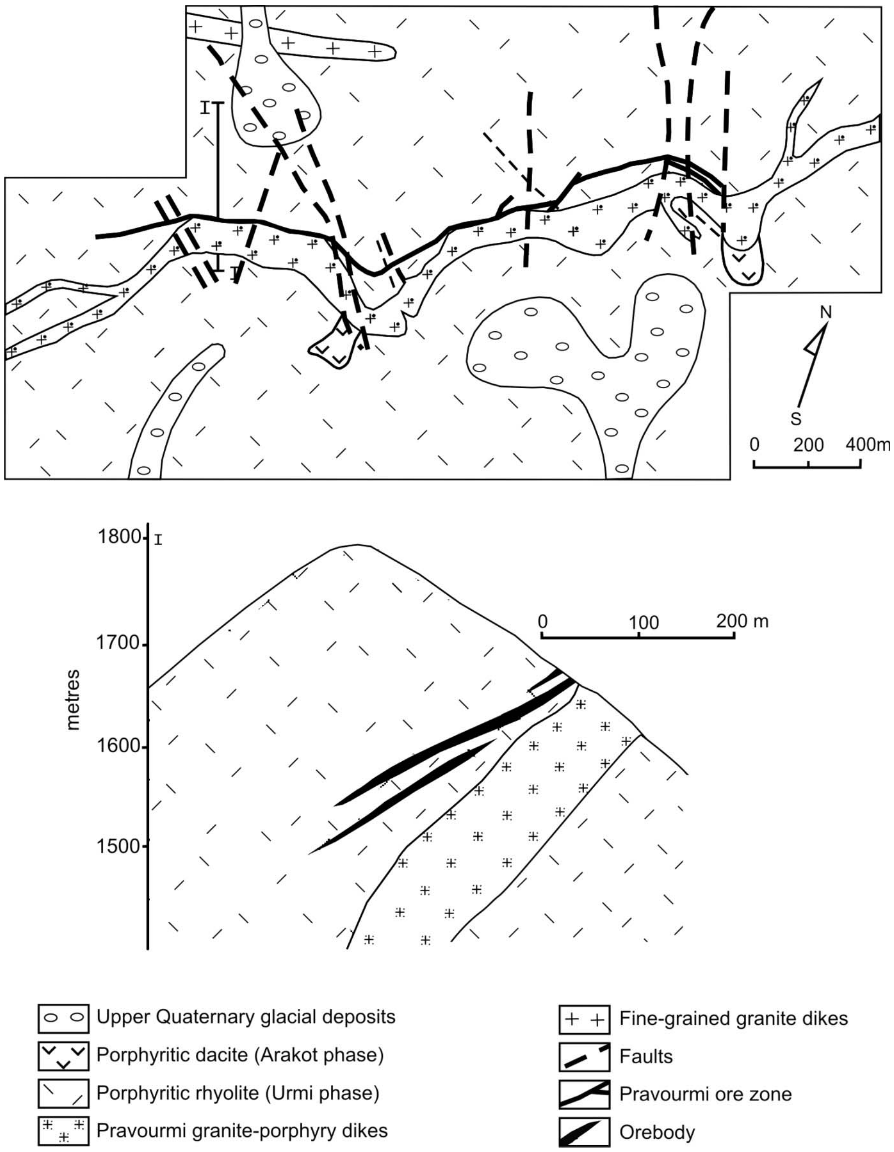

Figure 5 Geological map and cross-section on a line I–I of the Pravourmi deposit (after Semenyak *et al.* 2006).

and the Massif Central in France, and the Hesperic Massif in the Iberian Peninsula (Lehmann 1990; Makeev & Politov 1991).

The Tigrinoe deposit is located in rocks of the Zhuravlevka turbidite terrane, where the apical part of a granitoid body is found at the intersection of regional tectonic displacements. At the surface, the granitoid body is represented by the Bolshoi stock, in which granite porphyries predominate, and the Malyi stock containing porphyritic protolithionite granites, with zinnwaldite (endocontact zone) and zinnwaldite granites with protolithionite. At a depth of more than 200 m, granites have porphyritic texture and contain light-pink zinnwaldite and isometric (rounded) grains of quartz. Zones of pegmatoids and strongly silicified rocks and quartzites are restricted to the contact of these granite varieties (Figure 8a, b).

The pipe-like body of the Malyi stock (maximum size 350 m $\times$ 102 m) is complicated by apophyses. On the southern flank, the stock is contoured by marginal pegmatites that are $\sim$6 m thick. The granite body is surrounded by dykes of pre-granite ongonitic rhyolites and a stock of monzonitic porphyry located 4 km south-west of the deposit, and post-ore olivine basalts. The country rocks intruded by the Bolshoi and Malyi stocks, are thermally metamorphosed to hornfels.

Relationships between the three varieties of these Phase I granites show that they were emplaced in the sequence: granite porphyries (porphyry rhyolites) of the Bolshoi stock → protolithionite–zinnwaldite granites of the Malyi stock → zinnwaldite granites of the Malyi stock. These granitoids have chemical compositions of peraluminous subalkaline leucogranites of the lithium–fluorine geochemical type of the ilmenite series (Table 2).

Isotopic age data for the Bolshoi stock rocks are not available, but we consider a reasonable age for the Malyi stock Phase II protolithionite–zinnwaldite granites to be $\sim$90 Ma, and for the Phase III (subphase) zinnwaldite granites $\sim$85 Ma. In addition to K–Ar dating on micas (Gerasimov *et al.* 1990; Gonevchuk *et al.* 1987; Rub *et al.* 1986; Tomson *et al.* 1996; Ishihara *et al.* 1997), this age is supported by Sm–Nd dating (Belyatsky *et al.* 1998). K–Ar whole-rock geochronology yielded an age of 89 ± 4 Ma, which is the same as that of the earliest

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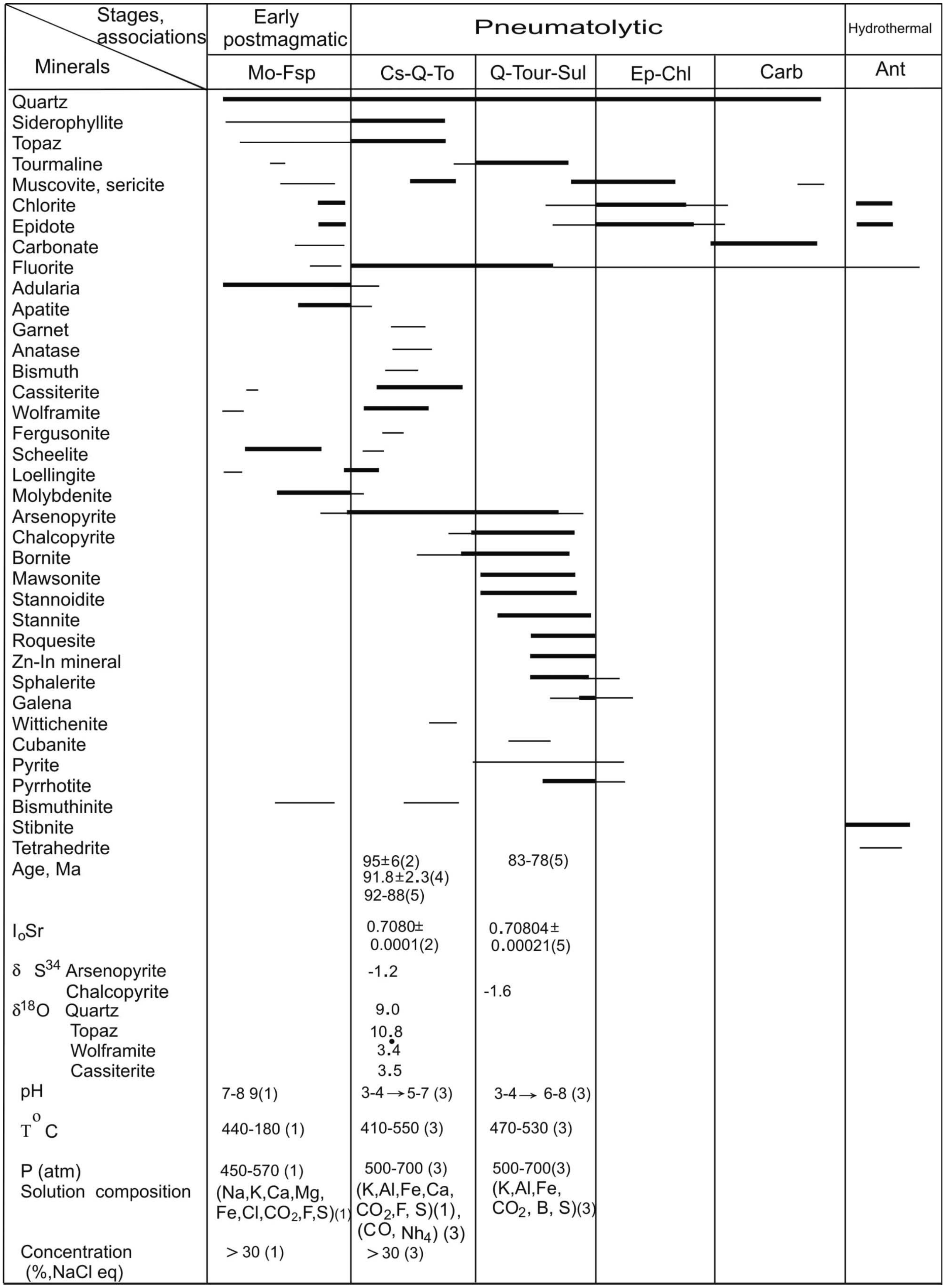

Figure 6 Paragenetic sequence and parameters of ore deposition at the Pravourmi deposit (after: 1, Semenyak *et al.* 1997; 2, Krymsky *et al.* 1997; 3, Semenyak *et al.* 2006; 4, Ishihara *et al.* 1997; 5, Lebedev *et al.* 1999). Mo, molybdenite; Fsp, feldspar; Cs, cassiterite; Q, quartz; To, topaz, Tour, tourmaline; Sulf, sulfides; Ep, epidote; Chl, chlorite; Carb, carbonate; Ant, stibnite.

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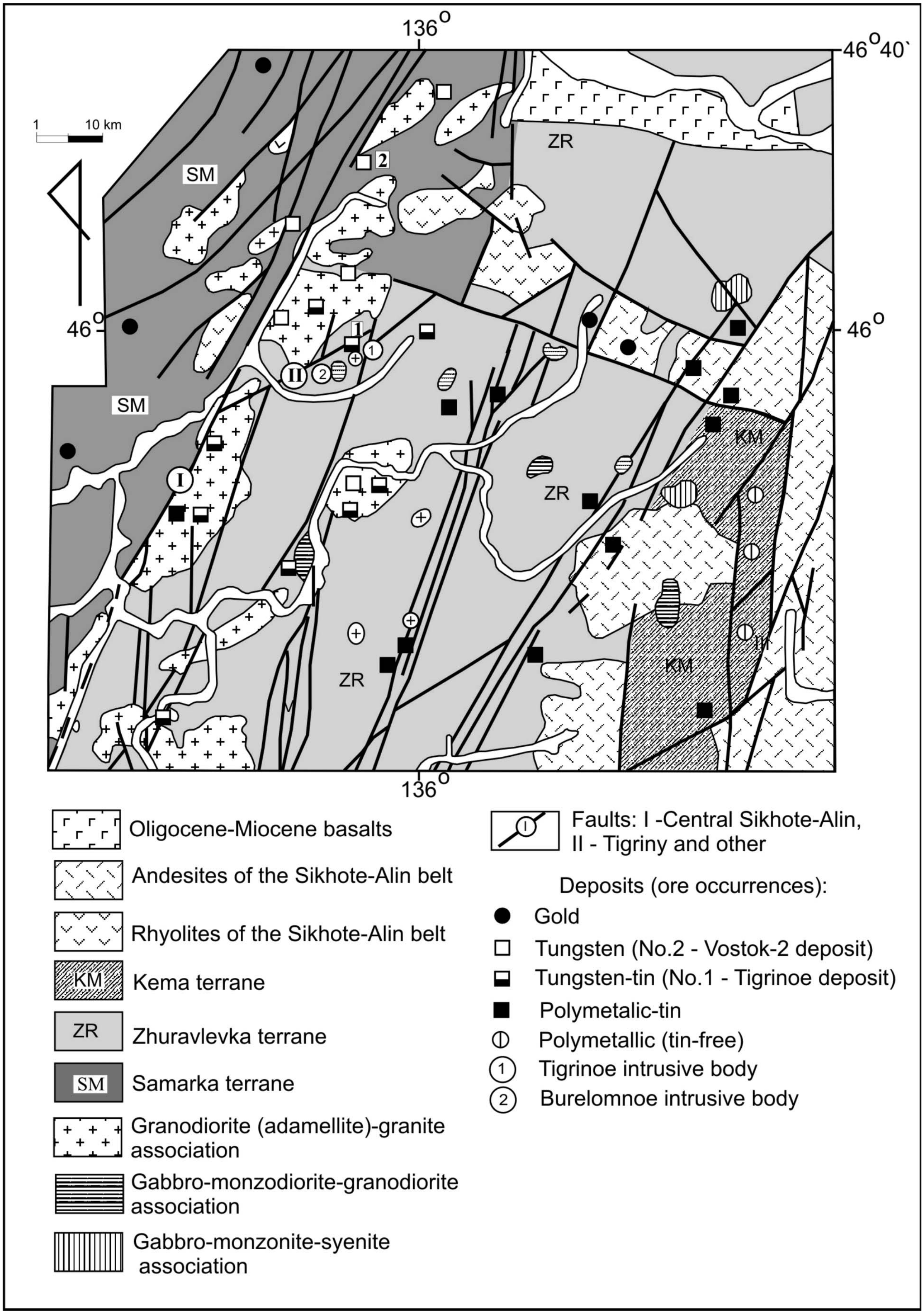

Figure 7 Geological and metallogenic setting of the Armu ore district.

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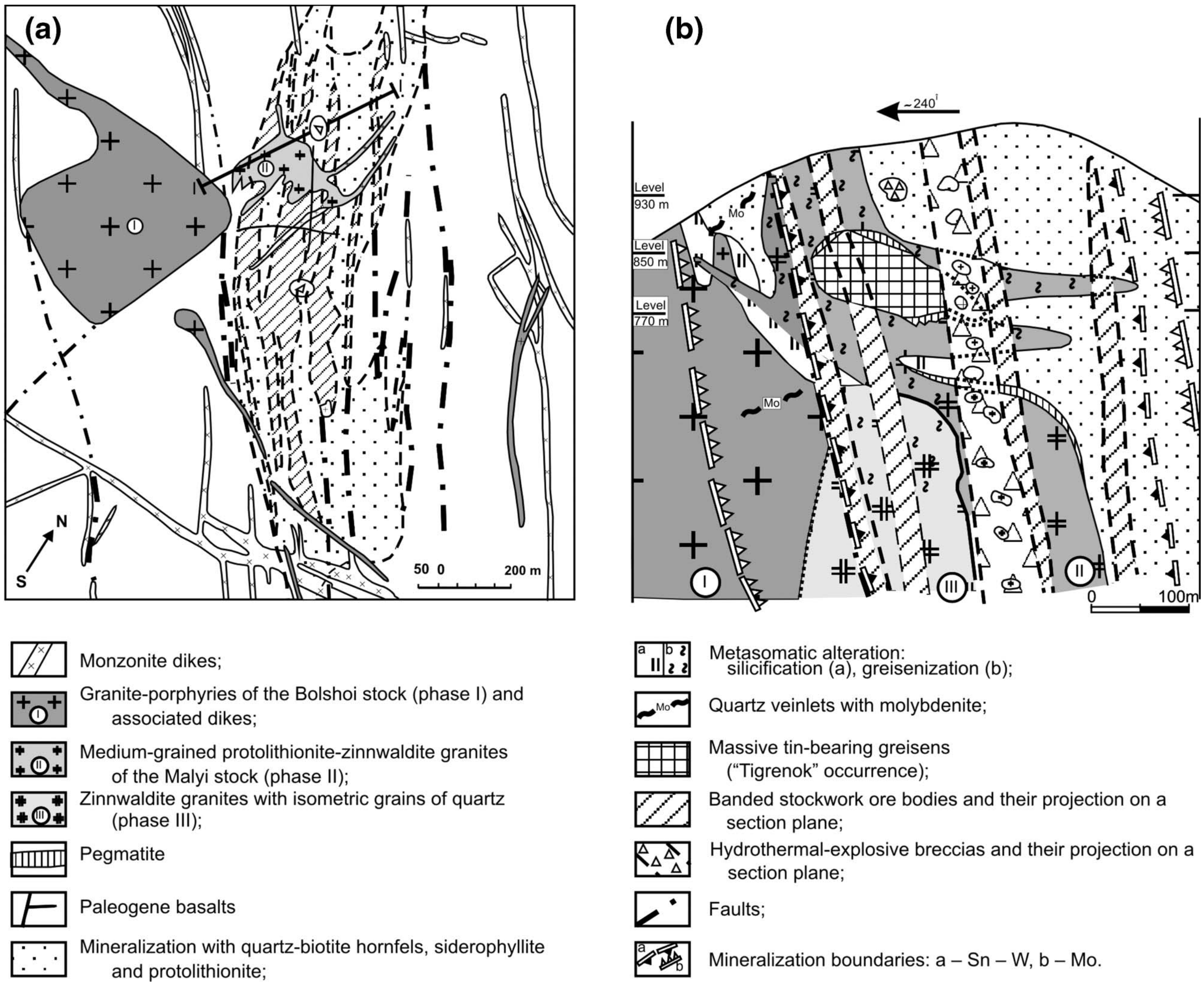

Figure 8 (a) Geological map and section of the Tigrinoe deposit (after Popov & Popova 1992, with additions from the authors). (b) Cross-section on line I–I through the Tigrinoe deposit.

granite phase (Tomson *et al.* 1996). The isotopic age of the olivine basalts is 27 ± 3 Ma (K–Ar method: Rub *et al.* 1986).

The Tigrinoe mineralisation is represented by molybdenum- and tungsten-rich types located in two stockworks. The molybdenum mineralisation is earlier, and is restricted to a system of fractures in the granite porphyries of the Bolshoi stock and the surrounding sedimentary rocks. The size of the stock is unknown. The results of drilling show that molybdenum mineralisation increases to the west and northwest of the stock.

The main tungsten–tin orebody is an elongated stockwork zone composed of veinlets with different compositions to those in the Malyi stock granites and surrounding rocks. The stockwork extends for $\sim$2000 m along strike, with a maximum thickness of 500 m, and mineralisation can be traced downdip for at least 1000 m. The voluminous greisen body 'Tigrenok' was formed where the stockwork intersects the Malyi stock granites. This greisen body contains about 10% of the tin and tungsten reserves of the deposit. From north to south, greisenisation becomes more and more intensive, with the most intensive greisen confined to the Malyi stock southern contact and is accompanied by a breccia zone. Here quartz–topaz–micaceous greisens contain rounded (diameter up to 2 m) zinnwaldite and fluorite accumulations.

On the basis of geological observations it is probable that the ore is Late Cretaceous in age. The development of the ore occurred in three stages, each ending with the formation of magmatic rocks and breccias (Figure 9). Isotopic dating (K–Ar data on mica: Rub *et al.* 1986; Gonevchuk *et al.* 1987; Ishihara *et al.* 1997) reveals ages of the early voluminous (late magmatic) greisenisation similar to that of the protolithionite–zinnwaldite granites of Phase II ($\sim$86 Ma). The age of the veined greisen formation is between 81 ± 4 and 78 ± 2 Ma, becoming younger with depth.

About 150 minerals are present in the orebodies of the Tigrinoe deposit, but only 60 have been reliably identified (Figure 9). Among the ore minerals, cassiterite, wolframite, stannite, sphalerite, arsenopyrite and molybdenite dominate. Vein minerals are mainly represented by quartz, topaz, mica (zinnwaldite predominant) and, more rarely, by feldspar, triplite and carbonates.

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Table 2 Chemical composition of granitoids from the Tigrinoe deposit (46°15′00″N, 135°59′00″E).

	Granite-porphyries from the Bolshoi stock (phase I)	Medium-grained granites from the Malyi stock (phase II)	Porphyraceous granites from the Malyi stock (phase III)	Monzodiorites from the Burelomnyi stock
wt%				
SiO_2,	75.74	75.73	71.72	56.45
TiO_2	0.06	0.03	0.01	0.75
Al_2O_3	13.34	13.18	16.18	16.37
Fe_2O_3	0.20	0.17	0.23	1.21
FeO	0.55	0.60	0.55	6.03
MnO	0.01	0.03	0.09	0.15
MgO	0.13	0.10	0.12	5.63
CaO	0.48	0.45	0.36	6.13
Na_2O	4.00	4.13	5.87	2.87
K_2O	4.98	4.52	3.56	2.99
Li_2O	0.01	0.08	0.11	0.002
Rb_2O	0.05	0.13	0.12	0.01
P_2O_5	0.02	0.03	0.05	0.40
F	0.53	0.55	0.80	0.04
ppm				
Ni	7	4	3	190
Co	3	0.2	<0.1	23
Cr	7	2	10	230
V	9	9	3	265
Cu	45	22	26	170
Sn	21	28	38	4
Pb	79	75	56	21
Zn	102	162	244	76
B	29	15	18	10
W	32	53	302	3
Mo	12	4	11	4
Be	5.9	6.8	5.0	1.8
Nb	50	55	86	21
Y	125	357	27	19
Sc	87	166	126	15
Sr	22	40	18	155
Na_2O/K_2O	0.80	0.91	1.65	0.96

Analyses were carried out at the Analytical Centre of the Far East Geological Institute, Far East Branch Russian Academy of Sciences, Russia.

The main ore characteristics are: (i) high amounts of sulfides—arsenopyrite, sphalerite and stannite (25% mass of tin)—enriched in indium; (ii) enrichment of veins and ore (cassiterite, wolframite) minerals in rare elements (Nb, Ta, Sc, TR); and (iii) the presence of Mo, Bi minerals and Au, which is typical for tungsten–tin–rare-metal deposits. An approximate estimate of the abundances of the principal ore minerals in this deposit (Table 3) confirms that it can be classified as a large deposit.

CASSITERITE–SILICATE–SULFIDE GROUP

Economically, the cassiterite–silicate–sulfide group of deposits is the most important in the Sikhote–Alin region. About 80% of Russian tin is mined from ores of these deposits, and one in four tin deposits of the Sikhote–Alin region belong to this group. Most deposits are located at a significant distance from the eastern boundary of the Bureya–Khanka terrane, and are mainly found at the junction of turbidite basin terranes and the accretionary prism, east of the Central Sikhote–Alin fault zone (Figure 1). Some researchers consider that tin mineralisation in the area is related to the special compositions of the enclosing terrigenous rocks (Ratkin 1995). The igneous rocks that are associated with this deposit group are predominantly I-type, ilmenite series, subalkaline granitoid (monzonites).

Deposits of the cassiterite–silicate–sulfide group have been studied in detail in the Komsomolsk and Kavalerovo ore districts, and in less detail in the Armu ore district. The mineralisation occurs as metasomatic zones or veins and the orebodies consist of cassiterite–tourmaline–quartz or cassiterite–chlorite–quartz, with different amounts of sulfides: molybdenite, arsenopyrite, chalcopyrite, pyrrhotite, pyrite, sphalerite, galena and others. These mineral contents are commonly of economic significance.

Metasomatic zones with tourmaline dominate in the Komsomolsk ore district (Figure 10), which is sometimes considered as a Mesozoic analogue of the Paleozoic Cornubian tin-bearing province of southwest England (Rundkvist 1980; Shcheglov 1991; Gonevchuk & Gonevchuk 2008). Major deposits in the Khabarovsk region, include Solnechnoe (Sn, Pb, Zn, Mo), Festivalnoe (Sn, Cu, W), Perevalnoe (Sn, Pb, Zn, W) and Sobolinoe

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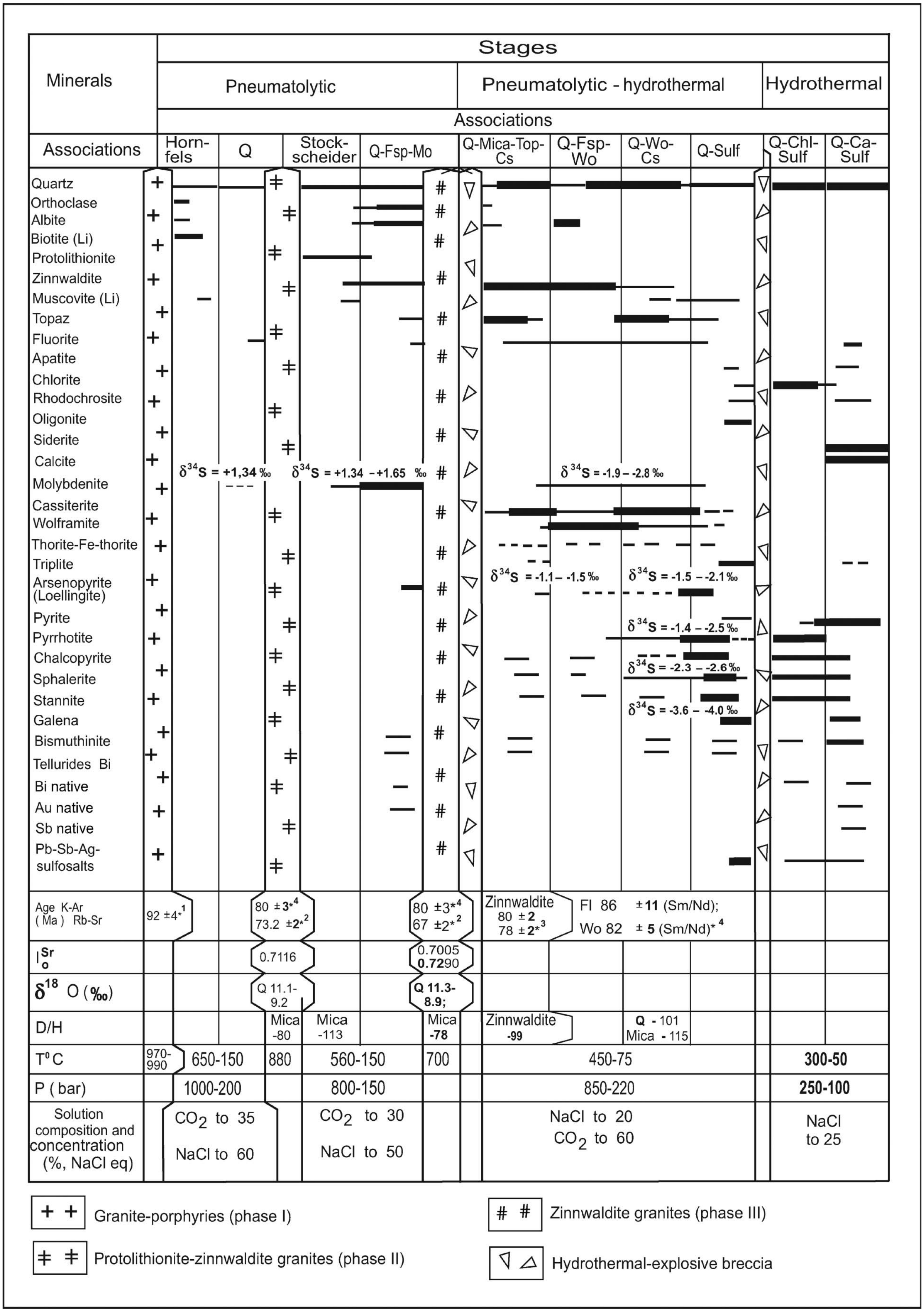

Figure 9 Paragenetic sequence and parameters of ore formation at the Tigrinoe deposit (after Gonevchuk *et al.* 2005b).

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Table 3 Content of the main minerals in ores of the Tigrinoe deposit (Popov & Popova 1992).

	Mineral	Content in orebodies (mass %)	Mineral reserves (kt)
1	Cassiterite	0.23	200
2	Stannite	0.11	90
3	Wolframite	0.10	180
4	Sphalerite	0.29	270
5	Arsenopyrite and loellingite	0.20	160
6	Topaz	1.06	1000
7	Fluorite	0.24	250
8	Zinnwaldite	0.63	625
9	Carbonates (Fe, Mn)	0.11	100

(Sn, Cu) with several small deposits currently being evaluated for possible mining. About 3000 t Sn and 6000 t Cu were mined annually from these deposits before 1994. Other metals, such as Ag, Bi, Au and In are recovered as by-products. Platinum-group elements, concentrated in arsenopyrite and chalcopyrite, have also been detected (Korostelev *et al.* 2001).

The Komsomolsk ore district is situated in the southwestern part of the Badzhal terrane, which forms part of the Jurassic accretionary prism, at the boundary with the Zhuravlevka turbidite terrane. The district boundaries are fault zones, which also define the areal extent of the Miao–Chan volcanic zone (120–70 Ma: K–Ar and Rb–Sr), which is characterised by a complex volcano–plutonic association consisting of rhyolites and rhyolite tuffs of the Kholdama complex (125–90 Ma; $I_{Sr} = 0.7083$–0.7095), granitoids of the Puril complex (~ 113 Ma; $I_{Sr} = 0.7050$), andesites (102 Ma; $I_{Sr} = 0.7045$) and comagmatic granitoids (98–85 Ma; $I_{Sr} = 0.7055$–0.7075) of the Silinka complex, and the Chalba granites (two phases: 84 Ma; $I_{Sr} = 0.7063$; 72 Ma; $I_{Sr} = 0.7080$) (Table 4). The main tin mineralisation of the district is related to diorite, granodiorite and monzonite of the potassic Silinka complex, as shown by high K/Na ratios. The potassium content increases sharply from early gabbro to late leucocratic granites. The granitoids of this complex, which also includes tourmaline granites, have dominantly I-type, ilmenite series features.

Solnechnoe tin–molybdenum vein–stockwork deposit

A typical representative of the tourmaline-type cassiterite–silicate formation is the Solnechnoe deposit (50°47′32″N, 136°16′01″E) (Gonevchuk *et al.* 2006) (Figure 11), which was discovered in 1955 and exploited between 1961 and 2002, when about 50 000 t of tin were mined. The deposit is located at the intersection of the sublatitudinal Silinka and submeridional Solnechny faults. The Silinka Fault controls the outcrop distribution of the Silinka igneous complex, and the Solnechny Fault is a main ore-bearing structure of the district, and can be traced for ~ 16 km along strike.

The main orebodies of the Solnechnoe deposit are located north of the Silinka Fault in Late Jurassic metamorphosed (hornfels) quartz–feldspar sandstones, sandstones and siltstones, and the quartz–diorite porphyries that are intrusive into these rocks. Diorite porphyries, in turn are intruded by granodiorites and granites of the Silinka complex. Bodies of granite (85 ± 2 Ma; K–Ar data) and granodiorite extend in a submeridional direction. The orebody was formed above an elongate cupola of an intrusive body. The highest tin content is located above the flanks of this intrusive body in granitic rocks. The northernmost flank of the deposit is covered by Oligocene basalts. Basaltic dykes of the same composition cross-cut the ore zone.

North of the Silinka Fault, quartz–diorite porphyries and granodiorites dominate the intrusive complex. Small orebodies are present in its endo- and exocontacts.

The 'Glavnaya Zone' orebody in the Solnechnoe deposit contains economic tin mineralisation over ~ 1000 m along strike (Figure 11), with a vertical extent of about 800 m, and is spatially associated with granitoid apophyses. Quartz–tourmaline metasomatites, replacing the fractured sedimentary and intrusive rocks, dominate the gangue. These metasomatites are cut by abundant veins and bands of quartz, which contain cassiterite and later sulfides. Hence, this zone has the appearance of a linear stockwork, locally with a thickness reaching 115 m and thinning out to < 1 m.

A quartz–feldspar–biotite–molybdenum mineralisation occurs in the ore zone in the vicinity of the granites. Geological observations indicate that this is earlier than the tin mineralisation because it occurs in quartz–tourmaline veins and streaks formed earlier. Biotite K–Ar data yield an age of 86 ± 2 Ma for the mineralisation.

The composition of tin and molybdenum mineralisation is different (Figure 12). Tourmaline and quartz are the main gangue minerals for the tin orebody and in addition to cassiterite, ore minerals are arsenopyrite, wolframite, rarely scheelite (as a product of replacement of wolframite), pyrrhotite, chalcopyrite, galena, sphalerite, pyrite, markasite, boulangerite and stannite. Native bismuth, bismuthinite enriched in antimony and lead, silver sulfosalts (pyrargyrite) and native silver, and bismuth jamesonite are rare. In the tin ores, a significant portion of Ag and Bi is concentrated in galena, containing a solid solution of matildite, in which bismuth predominates (Ag:Bi = 1:3).

In the molybdenum mineralisation, vein minerals are feldspars (adularia, microcline and more rarely andesine), biotite, apatite, fluorite, sericite and rarely topaz. The association of ore minerals is represented by molybdenite, scheelite, native bismuth, arsenopyrite, loellingite, rarer pyrite and very rare chalcopyrite. The group includes native bismuth and its sulfotellurides and tellurides, enriched in selenium (joseite A, joseite B, hedleite), with which gold is associated (early association). Late minerals are bismuthinite enriched in lead, and lead sulfosalts of bismuth (cosalite), with an insignificant admixture of selenium and tellurium. In places, galena appears as a result of cosalite disintegration. Carbonates are common in these ores.

Molybdenum and tin ores differ not only in composition, but also in formation conditions (Figure 13). The characteristics of the molybdenum ores indicate that

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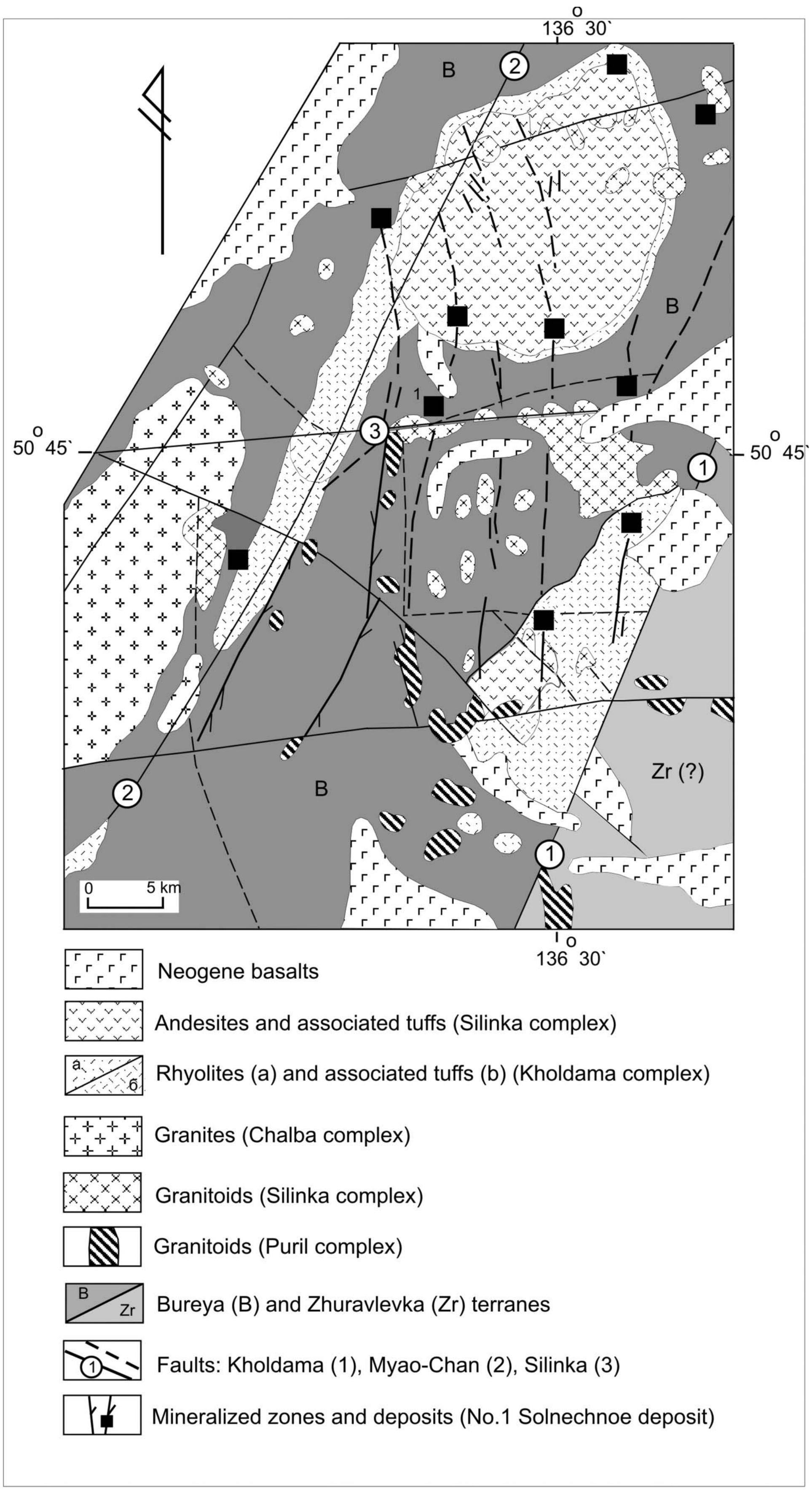

Figure 10 Geological map of the Komsomolsk ore district (adapted from Gonevchuk *et al.* 1999).

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Table 4 Chemical composition of granitoids from the Komsomolsk ore district (50°47′32″N, 136°16′01″E).

Complex	Puril		Silinka				Chalba	
Sample no.	VG-89	8421	VG-752/1	VG-735	ChG-332	VG-729	8234	ChG-469
wt%								
SiO_2	68.07	67.28	63.93	64.23	69.34	72.17	68.75	71.69
TiO_2	0.56	0.58	0.47	0.47	0.33	0.26	0.48	0.30
Al_2O_3	15.64	16.48	15.21	15.31	14.21	13.35	14.38	13.67
Fe_2O_3	0.13	0.05	3.53	1.24	2.23	0.80	1.77	1.50
FeO	3.95	3.00	2.56	4.41	1.78	1.46	2.68	2.00
MnO	0.09	0.06	0.09	0.13	0.07	0.01	0.08	0.05
MgO	1.20	1.60	2.98	3.02	1.28	1.10	1.02	0.42
CaO	2.52	3.79	4.40	4.60	2.39	2.32	2.41	1.72
Na_2O	4.18	3.78	2.68	2.56	3.25	2.68	3.19	2.93
K_2O	3.40	2.82	3.37	3.17	4.58	4.71	4.40	4.96
H_2O	0.10	0.40	0.85	0.48	0.40	0.58	0.70	0.45
F	0.02	0.04	0.03	0.04	0.12	0.20	0.12	0.09
Total	99.86	99.88	100.08	99.56	99.98	99.64	99.98	99.78
ppm								
Rb	141	104	185	140	210	206	220	206
Sr	333	454	183	208	186	190	215	141
Y	13.4	13.3	28.4	23.1	22.6	22.2	28.4	22.0
Zr	75.7	80.6	101	89.8	104	121	153	103
Cs	10.9	6.17	19.0	5.68	14.1	9.51	12.6	10.6
Ba	554	535	479	549	518	546	503	419
Nb	17	15	10	11	18	14	17	29
Sn	3	3	9	5	16	3	9	19
Pb	30	55	30	47	73	30	170	66
Zn	45	33	61	81	63	38	120	49
B	20	69	82	68	27	43	46	14
La	24.3	26.4	26.2	26.4	34.0	37.3	37.1	39.1
Ce	49.3	52.0	56.9	56.6	69.4	77.5	76.8	82.9
Pr	5.66	5.88	6.65	6.49	7.64	8.63	8.57	8.34
Nd	19.4	20.0	23.5	22.9	24.5	28.0	28.9	27.3
Sm	3.51	3.38	4.84	4.41	4.38	4.95	5.47	4.86
Eu	0.806	1.02	0.803	0.807	0.591	0.574	0.715	0.487
Gd	2.85	2.91	4.87	4.02	4.01	4.19	4.92	4.10
Tb	0.425	0.411	0.764	0.656	0.625	0.644	0.763	0.660
Dy	2.42	2.40	4.76	3.92	3.85	3.75	4.82	3.94
Ho	0.481	0.448	0.962	0.783	0.806	0.768	1.02	0.794
Er	1.38	1.37	2.86	2.40	2.39	2.30	3.02	2.31
Tm	0.202	0.196	0.426	0.361	0.372	0.348	0.492	0.373
Yb	1.41	1.31	2.78	2.33	2.47	2.31	3.25	2.46
Lu	0.213	0.203	0.428	0.369	0.383	0.372	0.497	0.349
Hf	2.49	2.37	3.26	3.01	4.21	4.53	5.44	4.00
Pb	22.1	22.0	14.5	17.9	25.0	13.8	27.5	23.6
Th	10.5	9.79	14.3	15.6	19.7	22.2	23.7	18.6
U	3.31	1.72	4.42	3.74	2.07	6.76	2.58	2.50

REE were determined at the Geoscientific Research Centre, GeoForschungsZentrum, Potsdam, Germany. The rest of the analyses were carried out at the Analytical Centre of the Far East Geological Institute, Far East Branch Russian Academy of Sciences, Russia. VG-729 sample is granite from the Solnechnoe deposit.

they are similar in composition to the ores of granite-related molybdenum deposits.

A study of the composition, concentrations and homogenisation temperatures of fluid inclusions (Bortnikov *et al.* 2004, 2005) shows that molybdenum mineralisation is related to multicomponent high-temperature solutions, whose concentrations were twice as high as those for tin ores. Pressure differences are even greater: for molybdenum ores, with pressures of 30–40 to 315 MPa having been recorded, whereas for the tin ores, pressures of 4.9–22.1 MPa are observed. These variations indicate several pulses in the development of the fluid-system regime.

Arsenyevka tin–tungsten–base-metal deposit

In large parts of the upper horizons of the orebodies, cassiterite–tourmaline mineralisation was replaced by a cassiterite–chlorite association. Analogous changes take place in ore districts with increasing distance from ore-generating igneous bodies. An example of this is the Arsenyevka deposit, which clearly demonstrates the combination of different types of tin mineralisation.

The Arsenyevka deposit (44°25′26″N; 134°47′14″E) in the Primorye Territory, one of the largest deposits of the Sikhote–Alin area, is located in the western part of the

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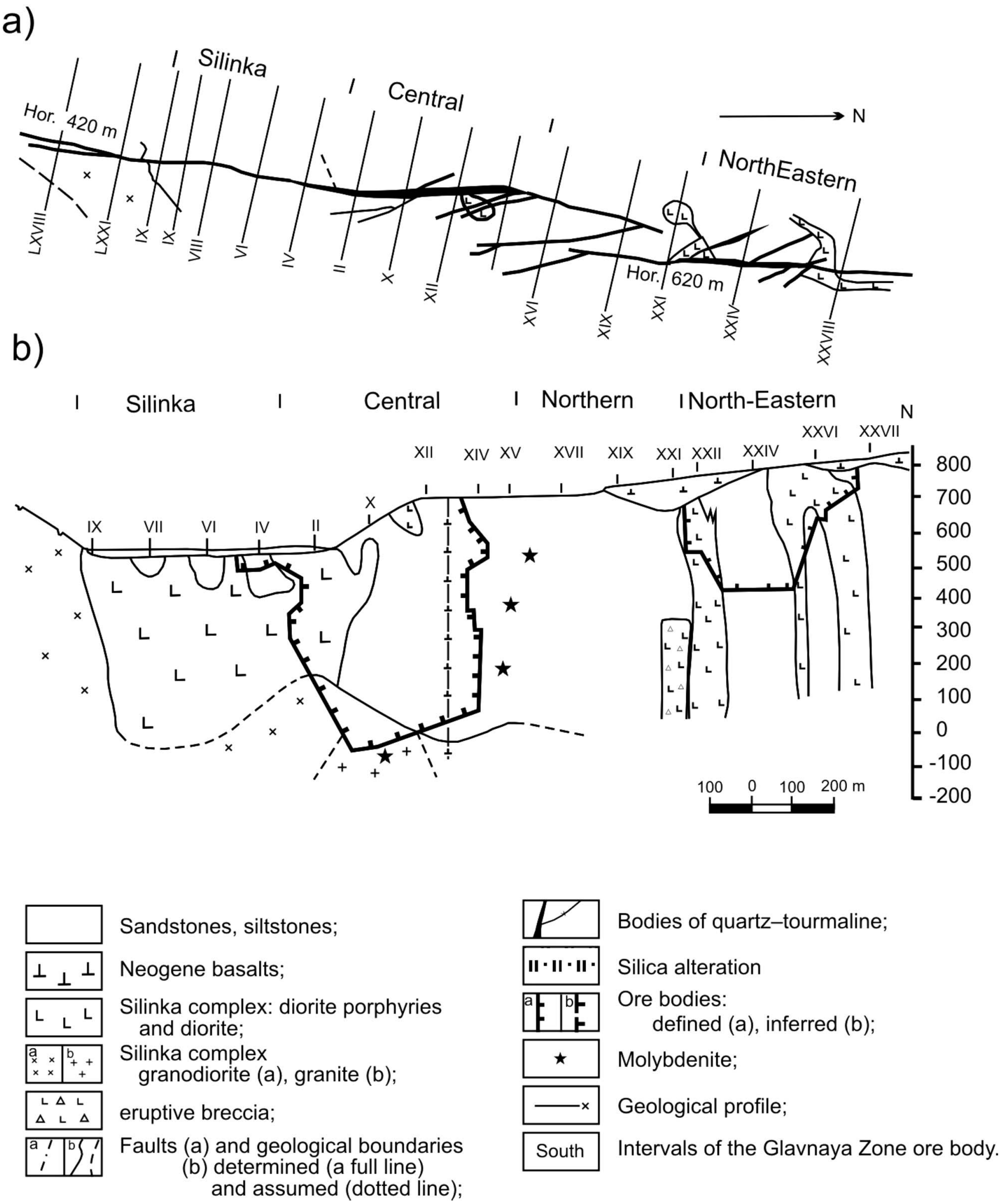

Figure 11 Geological map (a) and projection on vertical plane (b) of the Glavnaya Zone orebody in the Solnechnoe deposit (after Korostelev *et al.* 2006).

Kavalerovo ore district (Seltmann *et al.* 1998; Khanchuk *et al.* 2004), east of the Central Sikhote–Alin fault zone, which forms the boundary between the Zhuravlevka and Samarka terranes. The eastern part of the ore district reaches deeply into the Taukha terrane (Figure 14).

The Kavalerovo ore district is a good example of a long-lived ore-forming system, subjected to different geodynamic regimes. According to geological and isotopic–geochronological data, ore–magmatic associations in this district occurred between 120 and 45 Ma, with peaks of igneous activity recorded between

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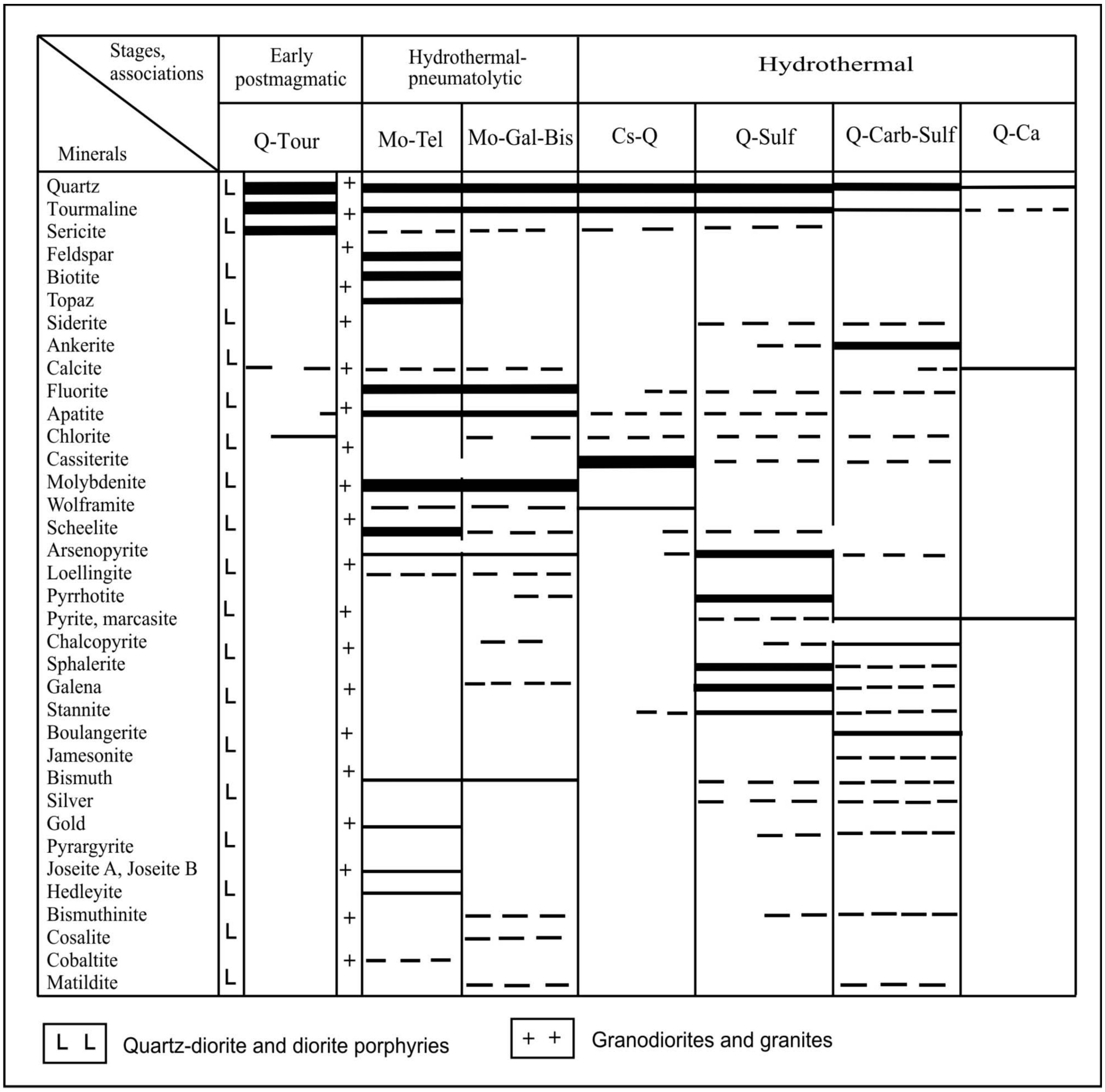

Figure 12 Paragenetic sequence of the Solnechnoe deposit (after Korostelev *et al.* 2006). Q, quartz; Tour, tourmaline; Mo, molybdenite; Tel, telluride; Gal, lead sulfides and sulfosalt; Bis, bismuth sulfides and sulfosalt; Cs, cassiterite; Sulf, sulfides (Fe and/or Cu); Carb, carbonates (Fe and Mg); Ca, calcite.

110–105, 95–80, 75–70 and 65–50 Ma (Matyunin 1989; Gonevchuk 2002).

The trachyandesite–monzonite Berezovka–Ararat complex is the oldest magmatic association (120–90 Ma; K–Ar and Rb–Sr data). This intrusive complex evolved from subalkaline gabbroic to granosyenitic rocks (Table 5), showing I-type, ilmenite series geochemical features. Pyrite mineralisation, with insignificant tin content and accompanied by tourmaline metasomatites, is related to this complex.

Next in the time sequence of igneous activity is the Novogorka–Uglovsky complex (100–80 Ma), which includes andesite, andesite–dacite and related intrusives, diorites and granodiorites, and more rarely granites (I- and S-types, ilmenite series). They form small intrusive bodies at the surface, but according to geophysical data they may merge into a large body at a depth of >3 km. Most researchers relate the main tin mineralisation of the district—cassiterite–chlorite type of the cassiterite–silicate group—to this complex. The Paleogene magmatism is manifested by andesite, dacite and rhyolite dykes with high K/Na ratios and high alumina content. Occasionally, these contain primary magmatic sulfide segregations (syngenetic sulfide concentrations as described by Nekrasov & Popov 1990). Their intrusive analogs are leucocratic granites (S- and A-types: 60–55 Ma; K–Ar data) rich in fluorine and ore elements including tin, which have been

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Stages, associations / Minerals	Early postmagmatic: Q-Tour			Hydrothermal-pneumatolytic: Mo-Tel	Mo-Gal-Bis	Hydrothermal: Cs-Q	Q-Sulf	Q-Carb-Sulf	Q-Ca
Age, Ma									
Diorite	97-92								
Granite			85						
Sericite		95-86							
Feldspar				86 ± 1.8					
Biotite				86					
$\delta^{18}O$									
Hornblende			8.0						
Biotite			4.7-5.0	5.0					
Tourmaline		6.1-8.7				8.7			
Quartz		6.1-11.6		10.2-12.0		8.7-11.8			12.3-15.6
Feldspar				5.7					
Cassiterite						1.9-2.6			
δD									
Tourmaline		-102				-107.9			
$\delta^{34}S$									
Molybdenite				-4.24 to -0.39					
Arsenopyrite				-3.56 to +0.98			+0.5 to -1.3		+16
Pyrrhotite							-0.5 to +0.5		
Chalcopyrite							-0.5 to +1.0		
Sphalerite							+0.2 to +2.5		
Galena							-2.5 to -1.5		
Pyrite							-4.0 to +1.5		+12.5
T°C				543-165		410-390	340-200	240-70	125-40
P, bar				3150-300		221-49			
Solution composition		Na, Cl		Mg,Ca,Na,K,Cl H_2O, CO_2, N_2		Mg, Na, Cl H_2O	Na, Cl, CO_2		
Solution concentration, (%, NaCl eq)				65.0-20.0		34.9-0.7			

L L Quartz-diorite and diorite porphyries

\+ \+ Granodiorites and granites

Figure 13 Parameters of ore deposition of the Solnechnoe deposit (after Korostelev *et al.* 2006). See Figure 12 for abbreviations.

recognised up to 1 km, beneath some deposits. Similar intrusions are also present in the western part of the ore district in the Central Sikhote–Alin fault zone (Orekhov *et al.* 2006). Leucocratic granites are considered to be a late phase of the Shumny granite complex. The above-mentioned igneous complexes host cassiterite–silicate mineralisation and small greisen bodies.

The Arsenyevka deposit was discovered in 1958, its economic viability established by 1965, was exploited for about 30 years and with tin reserves of >100 000 t it can be considered as a large deposit. It has no analogs in Russia due to its metal association of tin, tungsten, polymetallic and silver ores in uniform bodies. Metal reserves in the ores exceed 1 Mt with an average total content of ~5% (combined Pb+Zn+Cu). The ores also contain 2000 t of silver at average grade of 120 ppm (Kokorin *et al.* 2008). Early in the 1990s, the deposit was recognised as unprofitable due to the low concentration of tin and at present it is not being exploited. The host complex has a thickness of about 2000 m and consists of Lower Cretaceous (Aptian–Albian) rocks of the Zhuravlevka turbidite terrane (Figure 15).

The igneous rocks in the district, which formed in the Albian–Turonian, Cenomanian–Maastrichtian and Paleogene, occur as dyke suites and stocks of various intrusive complexes formed during different geodynamic regimes.

The first of these regimes is an Albian–Turonian transform continental margin (Khanchuk 2000) which is associated with monzodiorite stocks and rare trachyandesite–basalt dykes. The mineralisation is associated with the early stages of this magmatism. It has been suggested that the stocks may represent an intrusive facies of the Berezovka–Ararat complex (Gladkov 1982; Popovichenko 1989; Gonevchuk 2002). The ore minerals are sulfides and sulfosalts hosted in tourmaline metasomatites located in two sublatitudinal breccia zones, which form a strip about 400 m wide and more than 1000 m long (Tourmaline, Shirotnaya, Starushka, and Dorozhnaya zones). In the upper horizons of the deposit (to about 150 m below the surface), mineralisation of this stage occurs together with mineralisation of the second stage. At >150 m depth, mineralised tourmaline metasomatites of the first stage dominate. Zone thickness here is

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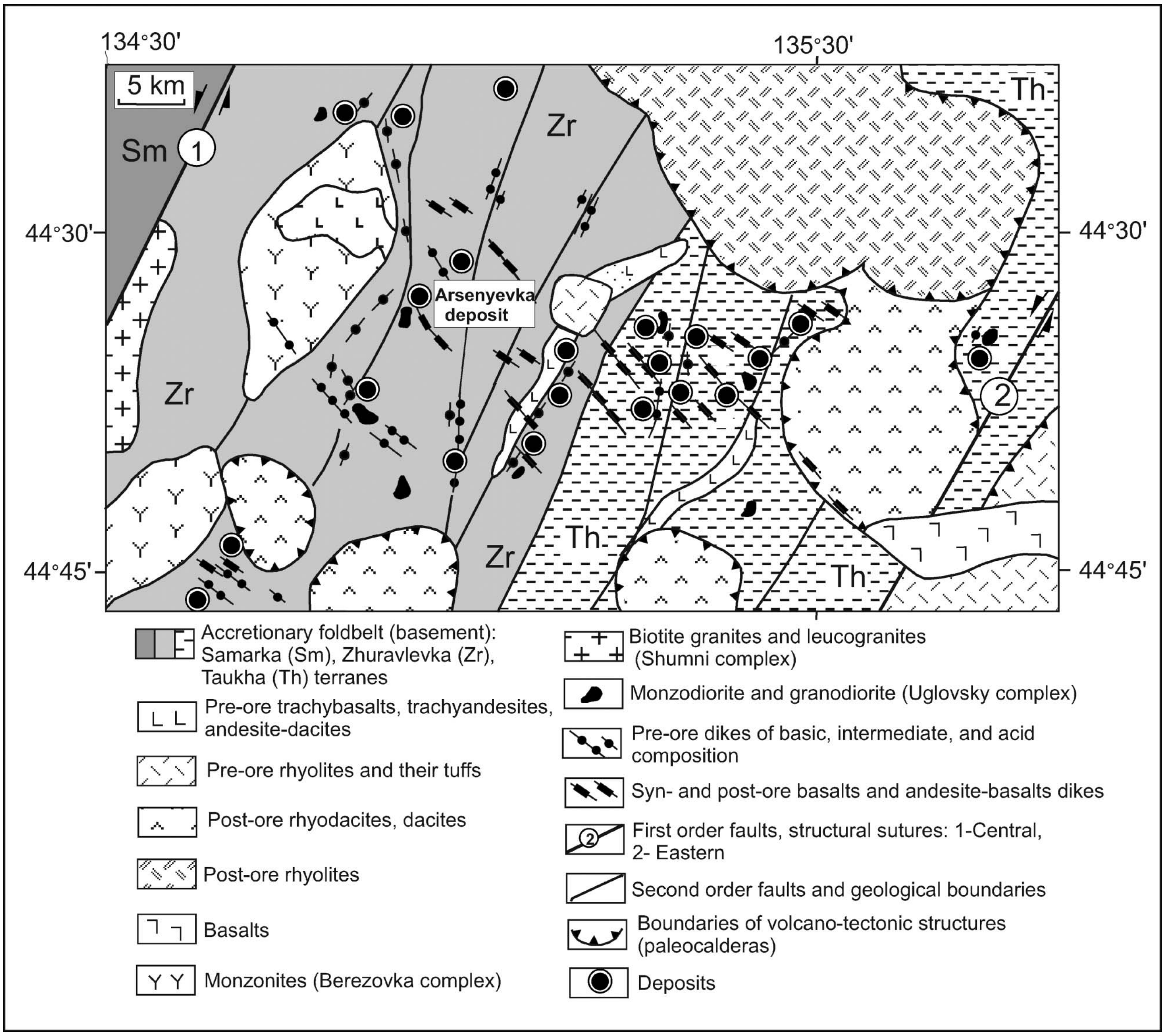

Figure 14 Geological map of the Kavalerovo ore district (after Gonevchuk 2002).

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0.5–12 m (average 2.5 m). Ore textures are streaky (in the selvages of the orebodies) to brecciated, to massive in places. The orebodies in tourmaline metasomatites are associated with abundant veinlets of arsenopyrite, chalcopyrite and pyrrhotite. In massive ores, sphalerite and galena content increases with variable amounts of other sulfides. The shape of tourmalinite clasts in the brecciated and streaky ores and sulfide laminae, testify to ore deformation in the first stage. Quartz–tourmaline, sulfide and sulfosalt mineral associations were formed during the first ore-magmatic stage.

A Cenomanian–Maastrichtian subduction stage is characterised by the emplacement of granodiorite porphyries and very rare granite and rhyolite dykes (80–76 Ma: Tomson *et al.* 1996; Gonevchuk 2002). Granodiorite and granite are also present as clasts in explosive breccias of Paleogene age. A cassiterite–chlorite-type of tin mineralisation (Radkevich 1953, 1968) corresponds to this stage, and is represented in submeridionally oriented vein-type orebodies (Yuzhnoe, Induktsionnoe, Pervoe and others). The orebodies are cassiterite-bearing quartz veins with the cassiterite concentrated in the vein selvages, whereas away from the selvages, sulfides (arsenopyrite, pyrrhotite, chalcopyrite, sphalerite, galena and pyrite) and sulfosalts are present. The central part of the veins is usually occupied by a late, often dominating, quartz–carbonate and fluorite association. The intensity of quartz–chlorite hydrothermal alteration of wall-rocks increases towards the ore veins and at the vein–wall-rock contact a monomineralic chlorite zone with cassiterite can be observed.

Magmatism of the Paleogene transform continental margin (65–45 Ma) is represented by peraluminous andesite and porphyritic andesite–basalt dykes dominating the central part of the orefield, as well as dykes and subvolcanic bodies of ultra-potassic dacite and

Table 5 Chemical composition of tin-bearing granitoids from the Kavalerovo ore district (44°25′26″N, 134°47′14″E).

Complex	Berezovka–Ararat			Novogorka–Uglovsky			Shumny		
Sample no.	GV-24	GV-65	GV-35	KG-45	KG-44	F-899/4	GV-412	GV-252	GV-67
wt%									
SiO_2	54.60	58.60	76.10	58.50	64.55	73.70	72.80	75.95	76.00
TiO_2	1.13	0.75	0.21	0.74	0.57	0.25	0.28	0.04	0.05
Al_2O_3	15.91	16.92	12.34	16.44	15.65	13.32	13.94	13.19	12.60
Fe_2O_3	2.32	2.65	1.13	0.91	0.35	1.20	0.93	1.16	1.03
FeO	6.54	2.94	0.73	5.74	4.31	1.33	1.82	0.37	0.62
MnO	0.45	0.41	0.01	0.14	0.08	0.20	0.04	0.05	0.02
MgO	5.56	4.55	0.21	4.61	2.87	1.18	0.22	0.01	0.75
CaO	6.38	5.16	1.11	5.37	4.37	1.28	1.69	0.17	0.79
Na_2O	2.91	3.14	2.50	2.97	2.54	2.46	3.42	4.03	3.61
K_2O	2.30	3.26	4.35	2.65	3.22	4.13	4.22	4.39	4.33
F	0.08	0.25	0.020	0.047	0.034	0.030	0.127	0.010	0.015
H_2O	1.29	0.60	1.20	1.73	1.09	1.30	0.60	0.69	0.40
Total	99.47	99.23	99.94	99.82	99.63	100.37	100.09	100.04	100.21
ppm									
Rb	115	210	148	102	156	224	291	757	281
Sr	583	687	177	429	292	139	137	5.59	9.78
Y	29.4	22.3	16.4	23.8	22.3	24.1	42.5	32.8	31.7
Zr	60.3	35.9	167	92.0	121	116	125	110	96.8
Cs	8.22	12.3	12.7	7.88	19.2	8.61	17.4	39.0	4.78
Ba	193	678	365	592	450	460	354	13.3	23.7
Nb	13	8	6	8	7	10	14	69	34
Sn	5	17	8	8	7	3	5	24	3
Pb	17	45	54	56	32	44	16	74	36
Zn	140	170	33	89	71	16	39	61	24
B	70	71	$\geq$100	33	17	5	11	20	4
La	36.1	28.5	35.5	29.0	30.2	19.9	37.5	16.7	7.69
Ce	78.6	60.6	70.0	60.7	62.3	41.2	80.6	43.3	52.8
Pr	9.66	7.31	7.27	7.18	7.16	4.78	9.53	5.38	2.49
Nd	36.0	27.1	23.2	26.2	24.8	16.7	33.8	19.2	8.63
Sm	7.15	5.16	3.81	5.27	4.95	3.62	7.23	5.95	2.51
Eu	1.14	1.20	0.483	1.13	0.981	0.481	0.679	0.032	0.048
Gd	6.54	4.75	2.99	4.98	4.43	3.54	7.07	6.08	2.82
Tb	0.928	0.692	0.462	0.742	0.676	0.597	1.16	1.17	0.653
Dy	5.43	4.02	2.77	4.42	3.97	3.68	7.08	7.41	4.84
Ho	1.09	0.817	0.578	0.874	0.805	0.785	1.47	1.48	1.08
Er	3.09	2.26	1.73	2.48	2.34	2.43	4.40	4.51	3.55
Tm	0.454	0.343	0.297	0.367	0.357	0.409	0.689	0.710	0.596
Yb	2.97	2.17	2.06	2.34	2.29	2.86	4.67	4.72	4.25
Lu	0.448	0.345	0.324	0.368	0.353	0.453	0.706	0.682	0.635
Hf	2.04	1.36	6.34	3.09	3.87	4.06	4.22	6.72	5.26
Pb	16.0	17.8	27.8	31.6	9.00	19.6	16.3	21.8	26.5
Th	15.6	14.5	34.7	15.4	19.3	26.8	36.2	57.2	44.2
U	3.52	3.28	4.08	3.37	4.95	6.24	10.5	19.9	12.6

REE were determined at the Geoscientific Research Centre, GeoForschungsZentrum, Potsdam, Germany. The rest of the analyses were carried out at the Analytical Centre of the Far East Geological Institute, Far East Branch Russian Academy of Sciences, Russia.

rhyolite, which locally have primary magmatic (syngenetic) tin and sulfide mineralisation.

Mineralisation of this stage (50–44 Ma; K–Ar) occurs in independent orebodies (e.g. Felsitovaya zone). However, it is usually combined with mineralisation of the first and second stages, but in contrast to these, dominant streak minerals are fluorite and muscovite second in prevalence to quartz. As for previous stages, multiphase sulfide associations are common, some of which are likely to be a result of the redistribution of sulfides from earlier stages. A distinguishing factor of this stage is that bismuth minerals are more abundant (Figure 16). Mineralisation of this stage, as a whole, shows many of the typical features of mineralisation of the cassiterite–quartz group.

CASSITERITE–SULFIDE GROUP

The cassiterite–sulfide group (Radkevich 1953; Lugov 1986) comprises tin deposits with the most complex and varied ore compositions and with abundant chalcophile minerals. In this group, the sulfides and sulfostannates account for 60–80% of the ore mass, whereas in the cassiterite–silicate–sulfide groups they only account for about 25%. Tin sulfide makes up ~50% of the total tin

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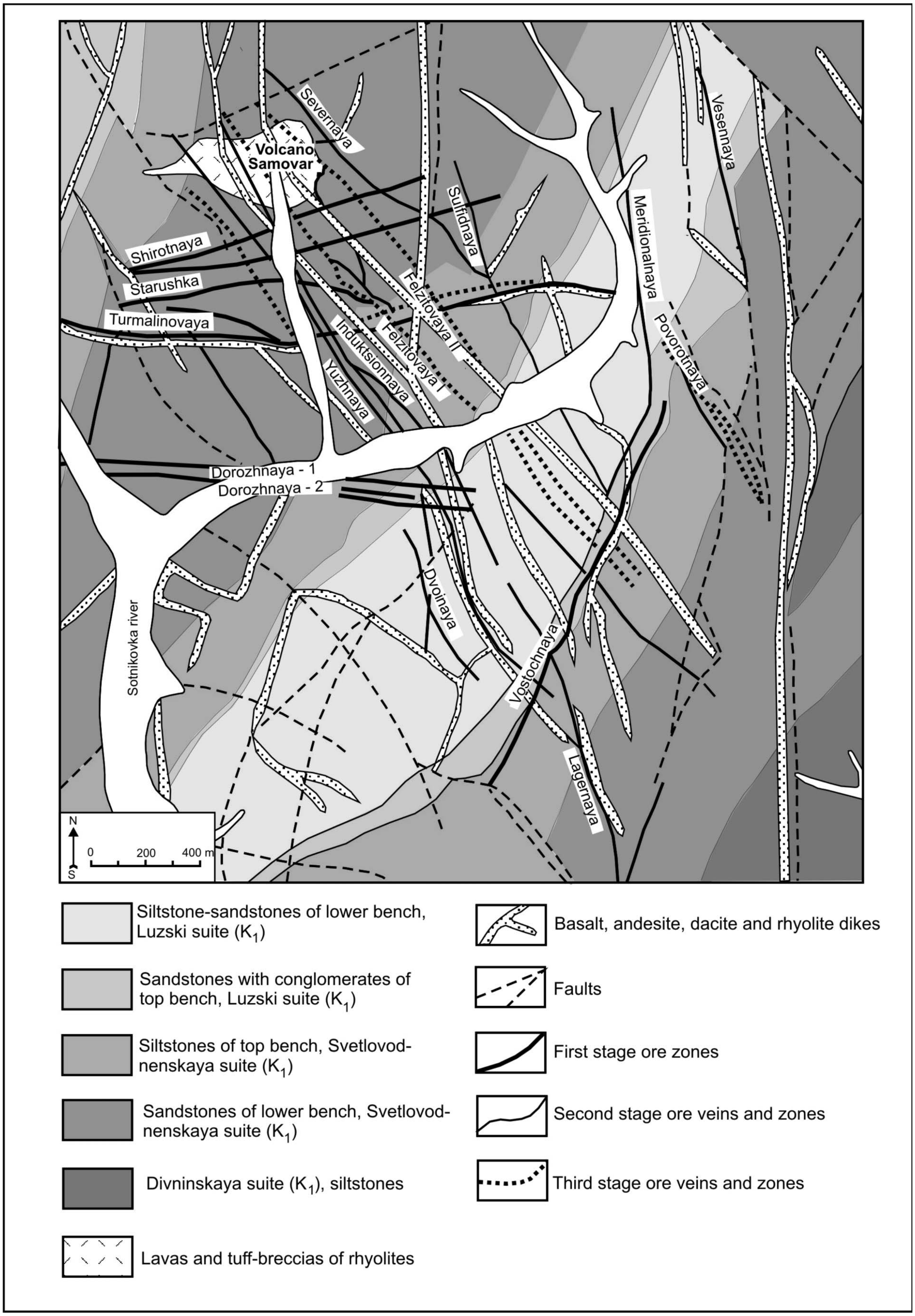

Figure 15 Schematic geological map of the Arsenyevka deposit (adapted from Kokorin *et al.* 2008).

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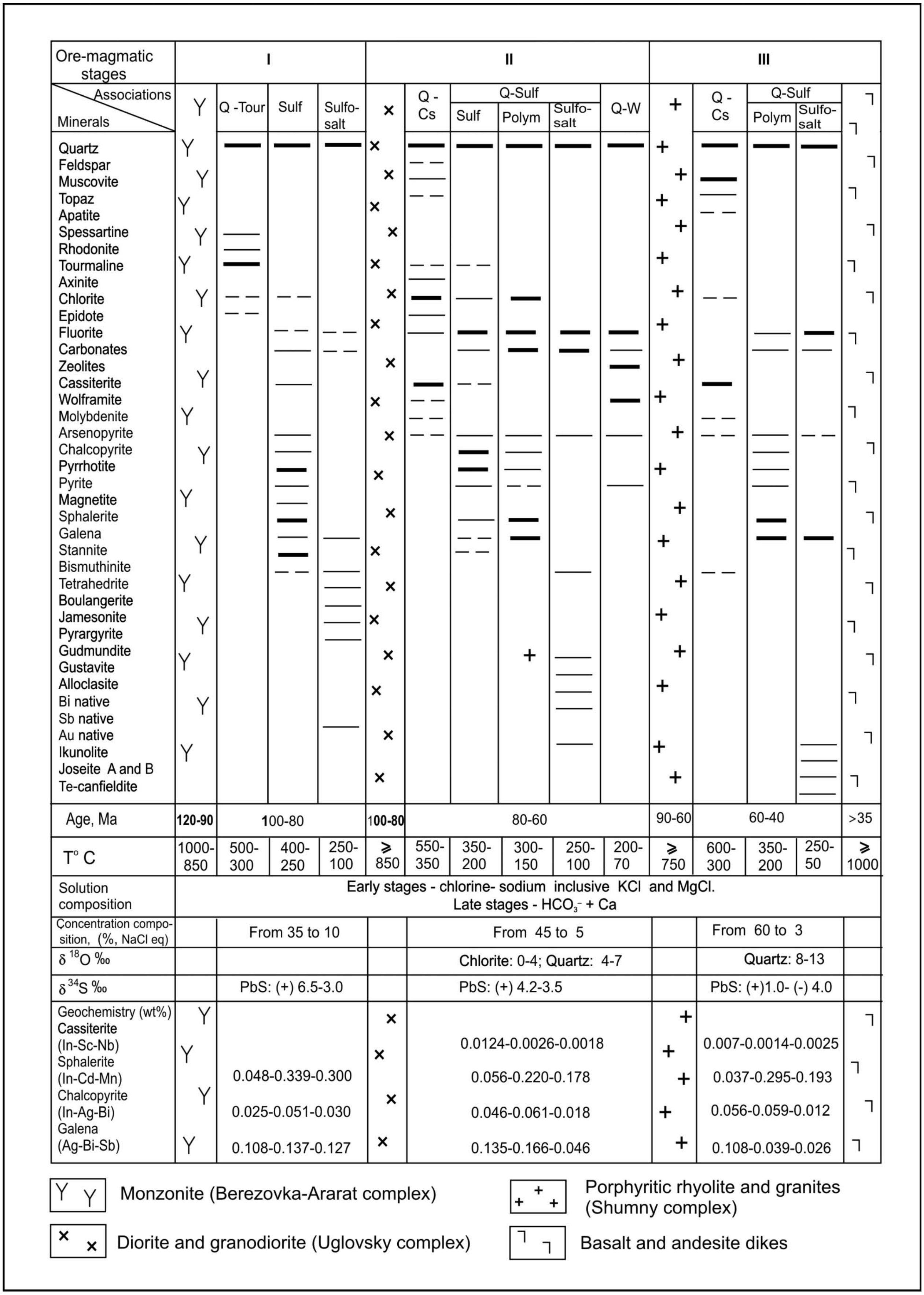

Figure 16 Paragenetic sequence and parameters of ore deposition of the Arsenyevka deposit (after Kokorin *et al.* 2006). Q, quartz; Tour, tourmaline; Sul, sulfide; Cs, cassiterite; Polym, polymetallic; W, wolframite.

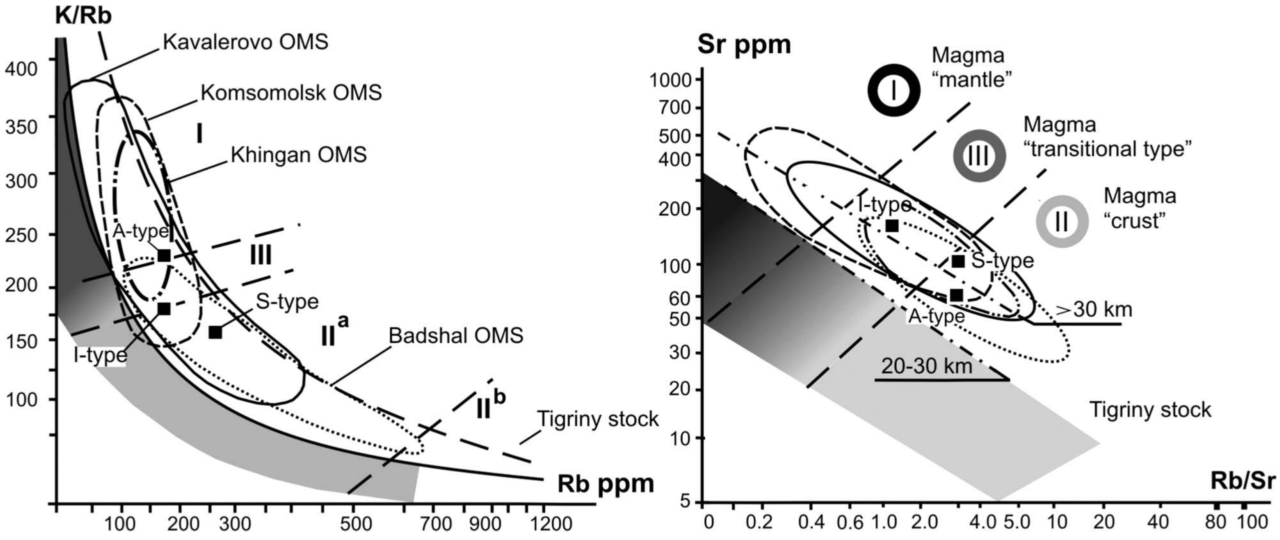

Figure 17 Sources of melts of magmatic associations of the main tin-bearing ore magmatic system of the Sikhote–Alin, interpreted from content and ratio of alkali components.

content in the ores of these deposits. Tin associated with Zn, Fe, Cu and Pb, enters the composition of different sulfide minerals, among which pyrrhotite, pyrite, chalcopyrite, sphalerite, galena and stannite predominate. Such tin deposits occur mainly in the Late Mesozoic and Paleogene–Miocene volcanic belts of the Pacific margins. They have been well studied in Japan, where they have been the main focus of mineral exploration for tin. In the Sikhote–Alin, deposits of the cassiterite–sulfide group are for the most part related to magmatic rocks of the Sikhote–Alin volcano–plutonic belt, in which they are generally hosted in volcanic rocks. Deposits in this part of the volcanic belt contain ores rich in iron and copper sulfides (pyrrhotite, less often pyrite and chalcopyrite), whereas deposits located within the belt comprise ores dominated by galena, sphalerite and sulfosalts. Deposits of the cassiterite–sulfide group occur in the Kavalerovo, Krasnorechensk, Armu and Ezop ore districts (Figure 1). Tin occurrences in the Dalnegorsk ore district also belong to this group (Khanchuk *et al.* 2004). Some deposits in this group are targets for polymetallic (Zn, Pb, Ag) ore extraction.

DISCUSSION AND CONCLUSIONS

Specific features of the main tin deposits of the Sikhote–Alin are governed by their relationships to magmatism at transform zones and active subduction margins (Khanchuk *et al.* 2003). Petrological models of the magmatism presuppose an active role by the mantle. Tin-bearing systems are located in accretionary prism terranes and turbidite complexes, and as such are developed in areas of lithospheric plate interaction. This predetermines a probable active role of mantle material in the genesis of these systems. This includes formation of ore zones by fluid and melt infiltration along crustal-scale faults such as the Central

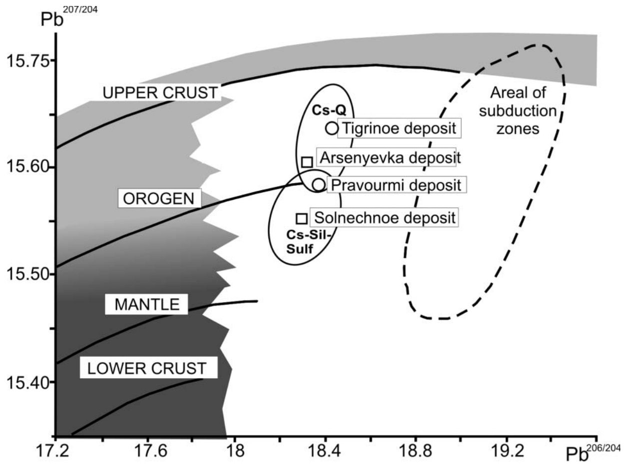

Figure 18 Lead isotope composition of galena from the ore deposits of the Russian Far East based on plumbotectonics model. Pb isotope curves from Zartman & Haines (1988).

Sikhote–Alin Fault and other similar faults: Urmi in the Badzhal ore district, Elga–Gorikan and Kholdama in the Komsomolsk ore district (Gonevchuk 2002).

The mantle–crust interaction that presumably led to the tin-bearing magmatic associations of the Sikhote–Alin is suggested by the presence of subalkaline and alkaline mafic rocks and also by their geochemical features, e.g. Rb–Sr–K ratios (Figure 17).

Initial strontium isotopes fall within the 0.7085–0.7065 interval (Rodionov 2000, 2005; Gonevchuk 2002) in most of the tin-bearing granitoids found in the Sikhote–Alin. This, in our opinion, also indicates a mantle–crust source. Nd and Pb isotope compositions support this conclusion in some of the tin-bearing systems. For example, the probable source of minerals for the Badzhal ore–magmatic system is characterised by the following isotopic markers: $I_0Sr = 0.70730–0.70850$; $\epsilon_{Nd(t)} = -1.8$ to -2.6; $^{206}Pb/^{204}Pb = 18.450$; $^{207}Pb/^{204}$

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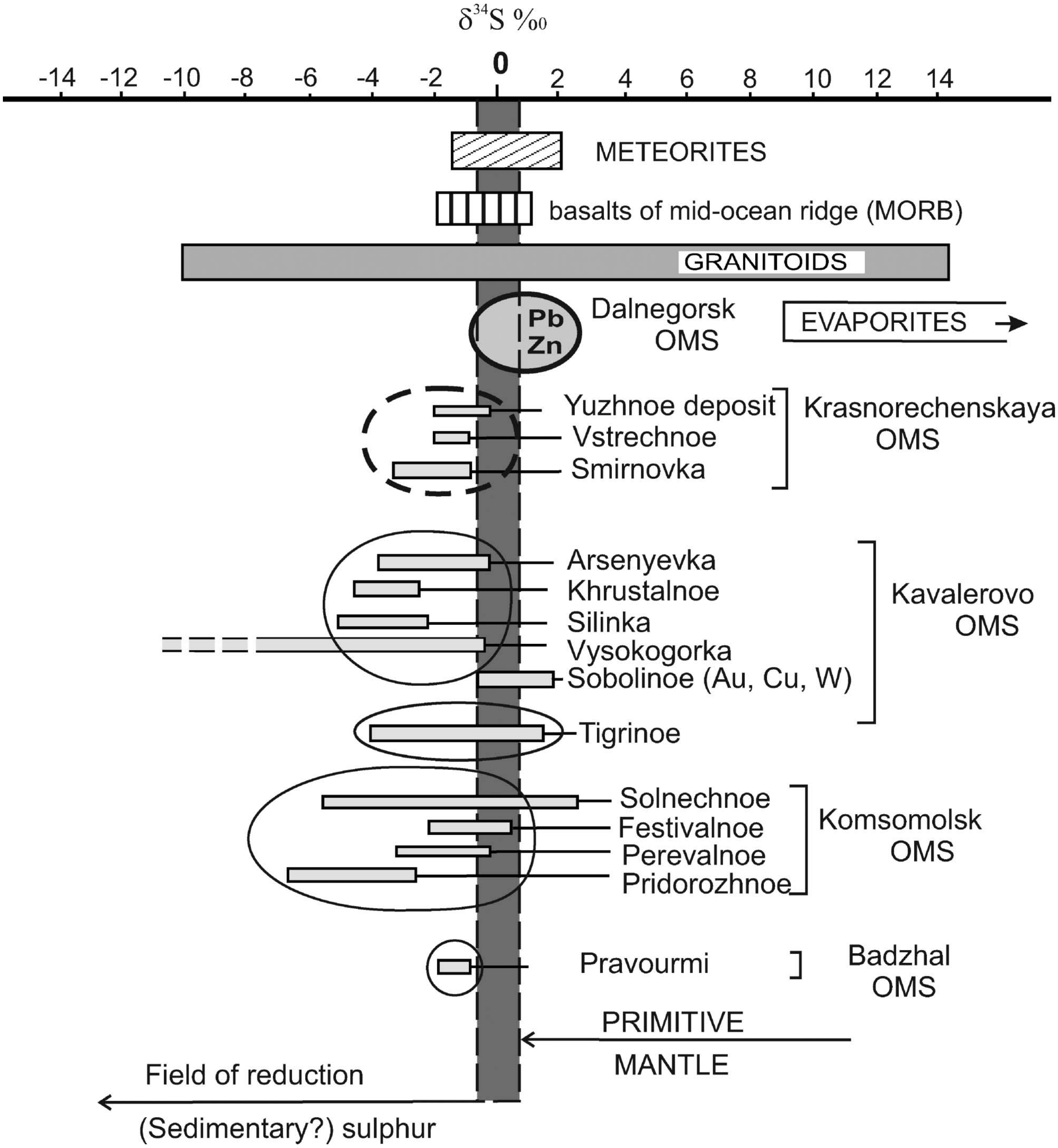

Figure 19 Sulfur isotope composition of ore minerals of the Sikhote–Alin tin-bearing systems.

Pb = 15.600; ^{208}Pb/^{204}Pb = 38.450. This is interpreted as evidence of the participation of continental and oceanic crust in the formation of tin-bearing magmas, or the mixing of mantle fluid with continental crust matter (Lebedev *et al.* 1999; Gavrilenko & Panova 2001). A mantle component is still more distinct in the Komsomolsk district with I_0Sr = 0.70630–0.70750, ^{206}Pb/^{204}Pb = 18.362, ^{207}Pb/^{204}Pb = 15.556 and ^{208}Pb/^{204}Pb = 38.376; whereas the Kavalerovo district is characterised by I_0Sr = 0.70470–0.710, ^{206}Pb/^{204}Pb = 18.452–18.395, ^{207}Pb/^{204}Pb = 15.652–15.603 and ^{208}Pb/^{204}Pb = 38.806–38.580.

Generally, when the lead isotope composition of galena is examined, according to the plumbotectonic model (Zartman & Doe 1981; Zartman & Haines 1988), crustal material is indicated as a source for minerals of deposits of the cassiterite–quartz group of deposits, and mixing of crust and mantle material is indicated for the cassiterite–silicate and cassiterite–sulfide group of deposits (Figure 18).

Sulfur isotope compositions of sulfide minerals from the tin-bearing systems overlap with the field of mantle sulfur (Figure 19). Oxygen isotope compositions (δ^{18}O) of cassiterite from most of the studied deposits is between

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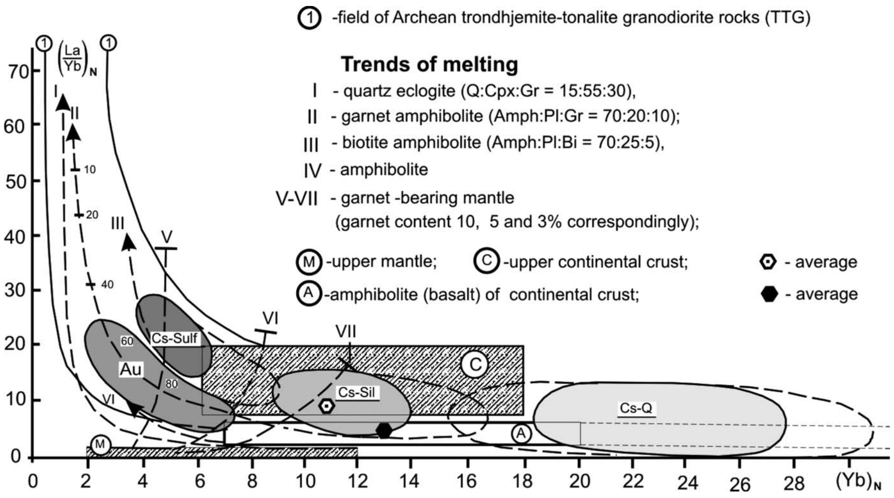

Figure 20 Variation diagram of $(La/Yb)_N$ *vs* $(Yb)_N$ in magmatic rocks from ore magmatic systems in the Sikhote–Alin with differing ore content (adapted from Gonevchuk 2002). (Cs-Q), with cassiterite–quartz (rare-metal tin) mineralisation; (Cs-Sil), with cassiterite–silicate (silicate–sulfide) mineralisation; (Cs-Sulf), with cassiterite–sulfide (tin–polymetallic) mineralisation; (Au), with gold mineralisation.

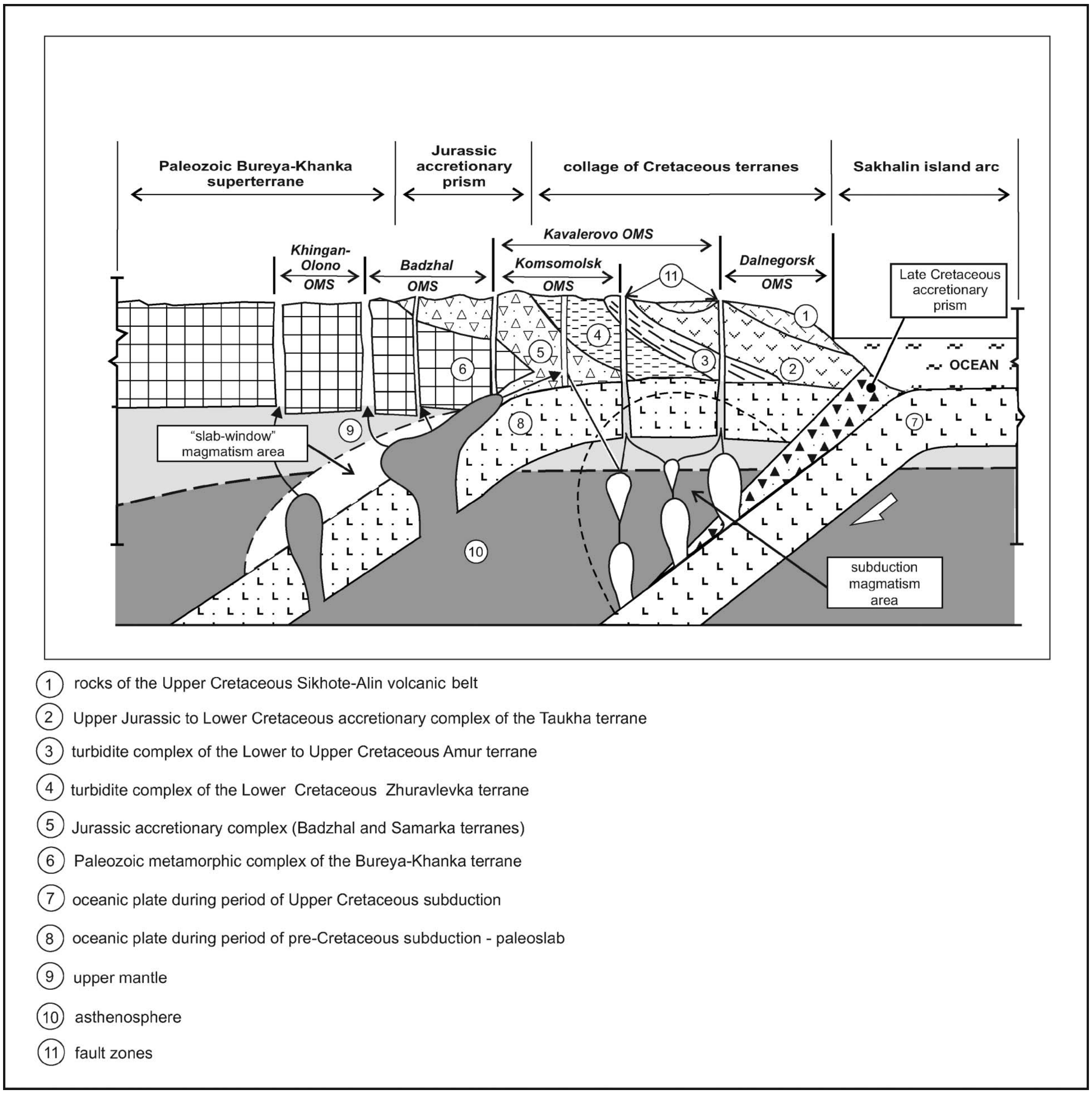

Figure 21 Model of the tectonic setting of subduction-related magmatism of the Sikhote–Alin belt and its associated mineral systems (after Khanchuk *et al.* 2003).

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–3 and +6‰, indicating mixing of magmatic and meteoric water in the mineralising hydrothermal systems.

The distribution of some rare-earth elements in magmatic rocks also testifies to a mixed mantle–crust origin for tin-bearing mineralisation. The participation of mantle material increases from deposits of the cassiterite–quartz group to those of the cassiterite–silicate group, and further to the cassiterite–sulfide group (Figure 20).

From this research, we present a genetic model for the main tin-bearing mineral systems of the Sikhote–Alin (Khanchuk *et al.* 2003) (Figure 21) in which we take into account changes in the geodynamic regime and interaction of the earth's crust and mantle.

Between 130 and 95 Ma, a transform margin dominated the region. Mantle–crust interactions were likely achieved through a slab window. This stage is recognised in tin-bearing systems by the presence of 125–110 Ma alkaline and subalkaline basalts sourced from the mantle, followed by andesite and rhyolite magmas formed as a result of melting of the continental Bureya–Khanka terrane and accretionary prisms. The tin mineralisation is mainly of the cassiterite–quartz and cassiterite–silicate–sulfide types.

From 95 to 60 Ma, a subduction regime prevailed. The formation of magma diapirs in the upper mantle and their ascent with subsequent melting of turbidite basin and accretionary prism terrane rocks became the main mechanism of mantle–crust interaction. Associated mineralisation is cassiterite–silicate–sulfide and polymetallic with tin.

In the Eocene, a regime of transform tectonics was resumed, associated with slab-window magmatism. In the Kavalerovo district, where this stage is important in the formation of tin ores, the transform regime is manifested by the formation of ultra-potassic rhyolite–dacite and mafic porphyritic dikes, associated with cassiterite–silicate and cassiterite–quartz mineralisation.

We conclude that the tin districts of the Sikhote–Alin evolved in the course of different geodynamic regimes (Figure 3) and comprise polygenetic and polychronous magmatic associations and unusual types of mineral systems. Probably, the most intensive mineralisation took place during changes in the geodynamic regime.

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