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Distribution of rhenium in molybdenite from porphyry Cu–Mo and Mo–Cu deposits of Russia (Siberia) and Mongolia

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Abstract

Rhenium was determined in representative molybdenite samples (concentrates) from the Aksug, Erdenetuin-Obo, Zhireken, Shakhtama and Sora porphyry Cu–Mo and Mo–Cu deposits of Russia (Siberia) and Mongolia. The Re contents in the majority of the concentrates are low, ranging from 6 to 460 ppm. The maximum Re contents were determined in molybdenite concentrates from the Aksug (460 ppm Re) and Erdenetuin-Obo (199 ppm Re) Co–Mo porphyry deposits and are significantly higher than those from the Zhireken, Shakhtama and Sora Mo–Cu porphyry deposits. The Re content of molybdenite concentrates from the studied Mo–Cu porphyry deposits (6 to 57 ppm) are, however, comparable to those from comparable deposits worldwide. The Aksug and Erdenetuin-Obo deposits, with relatively elevated Re content, differ from the Zhireken, Shakhtama and Sora deposits with lower Re contents in terms of (1) higher Cu/Mo ratio; (2) lower $\delta^{34}S$ and $^{87}Sr/^{86}Sr$ values; (3) silica and alkali contents of the host rocks; (4) the alteration type of the associated rocks; (5) the elevated Cl activity in the fluid; (6) the lower temperature of the molybdenite formation; and (7) the higher oxidized conditions. The Re contents of molybdenite from porphyry Cu–Mo deposits may therefore be related to the composition of parent magmas themselves and/or fractionation, sources of the material, and variations of physical and chemical conditions of crystallization (fO_2, Cl activity, P, T).

1. Introduction

In this study, the contents of Re have been investigated in molybdenites from 5 porphyry Cu–Mo and Mo–Cu deposits in Russia (Siberia) and Mongolia. The Siberian and Mongolian fragments of

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the Central Asian Fold belt contain numerous porphyry Cu–Mo deposits that vary in age and Cu/Mo ratio. Deposits of economic scale have been formed over three age intervals: (1) mid-Paleozoic (Mo deposits, e.g., Sora; Mo±Cu deposits, e.g., Aksug), (2) Late Paleozoic–Early Mesozoic (e.g., Erdenetuin-Obo Cu–Mo deposit), and (3) Mesozoic (e.g., Zhireken and Shakhtama Mo deposits). Sotnikov et al. (2001a) have recently discussed PGE and Au contents, as well as other geochemical characteristics, of the Sora, Aksug, Erdenetuin-Obo and Zhireken deposits.

Rhenium is one of the most highly dispersed elements in Earth crust. Data on Re-bearing minerals are relatively scarce (Poplavko et al., 1962; Ekström and Halenius, 1982; Tarkian et al., 1991; Barkov and Lednev, 1993; Korzhinsky et al., 1994 and others). Rhenium is commonly concentrated in Cu–Mo sulfides and tends to be much more abundant in molybdenite than co-existing sulfides. Molybdenite has been shown to be the major host phase for Re in many hydrothermal ore deposits (McCandless et al., 1993). It incorporates Re into its structure at concentrations ranging from some ppb to a few thousand ppm.

Rhenium is widely used in the petroleum refining and the electronics industries. It is also applied in modern super-strong high-temperature resistant alloys; micro-admixtures of Re improve the rheological properties of metals such as Mo, W and Ta. Such alloys have application in the construction of spaceships, aircraft and other products designed to be subjected to high temperatures (Ivanov and Yushko-Zakharova, 1989). Rhenium is generally produced commercially as a by-product of molybdenum from porphyry Cu–Mo deposits, since the Re content of molybdenite in such deposits may be as high as several weight percent (e.g., Melfos et al., 2001).

The Re–Os radiogenic system can be used as a high-precision geochronometer (e.g., Stein et al., 1997) and as geochemical tracer to resolve a range of geological problems (e.g., Todorov and Staikov, 1985; Ishihara, 1988; Xiong and Wood, 2001). In the present study, 24 samples of concentrated molybdenite from the Sora, Aksug, Erdenetuin-Obo, Zhireken and Shakhtama porphyry Cu±Mo deposits were analyzed for Re. The results are presented and their genetic significance is discussed.

2. General characteristics of porphyry Cu–Mo and Mo–Cu deposits of Siberia and Mongolia

A variety of porphyry Cu–Mo deposits are found in Siberia (Russia) and Mongolia (Fig. 1). Mineralization in the Sora (the Kuznetsk Alatau, Russia), Aksug (Tuva, Russia), Zhireken and Shakhtama (Eastern Transbaikalia, Russia), Erdenetuin-Obo (Mongolia) is associated, in both time and space, with porphyry stocks and dikes formed during periods of waning magmatic activity (Sotnikov et al., 1977; Sotnikov and Berzina, 1986, 2000; Berzina and Sotnikov, 1999).

A time gap of 20 to 30 Ma (Ar^{40}/Ar^{39} dating) is established between the porphyries and older granite plutons (Sotnikov and Berzina, 2000). Hydrothermal alteration, similar in style but different in intensity, accompanies each porphyry phase. Pervasive potassic alteration is typical of Mo deposits, while intense quartz–sericite alteration dominates in the Cu deposits. Ore deposition proceeded within a wide temperature range, from 700 to 500 °C (early potassic alteration) to 400 to 200 °C and even less (high-grade mineralization, sericitization and argillization). Ore-bearing alteration and porphyries were derived from transitional magma chambers. Mantle material dominated in the ore–magmatic systems at the Sora, Aksug and Erdenetuin-Obo, whereas crustal contribution was of considerable importance at the Zhireken and Shakhtama deposits (Sotnikov

Fig. 1. Sketch map of central Siberia and Mongolia showing the locations of the studied deposits.

Table 1
Characteristics of Siberian and Mongolian porphyry Cu–Mo and Mo–Cu deposits and mineralization

Characteristic	Erdenetuin-Obo	Aksug	Zhireken	Shakhtama	Sora	Key references
Range and average (in brackets) of Re content (ppm) in molybdenite	104–199 (164)	460	12–57 (29)	9–24 (17)	6–18 (14)	Present study
Deposit status, size (contained metal) and grade	Active open pit; 200 Kt Mo @ 0.012%; 10 Mt Cu @ (0.3–0.6%)	Mine on standby; 52 Kt Mo @ 0.015%; 2.3 Mt Cu @ 0.67%	Active open pit; 100 Kt Mo @ 0.03–0.15%, (average 0.099%); 100 Kt Cu @ 0.04–0.20%, (average 0.1%)	Active underground mine; ~50–60 Kt Mo @ 0.1–0.5%; 50 Kt Cu @ 0.1–0.2%	Active open pit; 200 Kt Mo: 0.04–0.10% in stockwork, 0.1–0.5% in breccia, average 0.058%); 500–600 Kt Cu: 0.02–0.20% in stockwork, 0.02–0.3% in breccia	Lebedev and Kuzhuget (1998), Sotnikov et al. (1998), Yurgenson et al. (1999), Sotnikov and Berzina (2000)
Average Cu/Mo in ores	30–50	40–70	1	<1	2–4	Sotnikov and Berzina (2000)
Age (Ma), $^{40}Ar/^{39}Ar$	240–220	404–401	160–155	155–150	405–388	Sotnikov et al. (2001c), Sotnikov et al. (2002), Sotnikov et al. (2003b)
Mineralization (main minerals)	Pyrite, chalcopyrite, molybdenite, bornite, tennantite, galena, sphalerite	Chalcopyrite, pyrite, chalcocite, bornite, molybdenite, magnetite, tennantite,	Molybdenite, pyrite, chalcopyrite, sphalerite, galena	Molybdenite, sphalerite, galena, tennantite, chalcopyrite, bismuthinite, bournonite, jamesonite, pyrargirite	Pyrite, molybdenite, chalcopyrite, sphalerite, galena	Sotnikov and Berzina (2000)
Dominant rock type	Granodiorite porphyry	Quartz diorite porphyry, granodiorite porphyry	Granite porphyry	Granite porphyry, granodiorite porphyry	Sub-alkaline granite porphyries	Sotnikov and Berzina (2000)
Dominant type of alteration	Quartz–sericite	Quartz–sericite, propylite	Potassic, argillic	Potassic, argillic	Potassic, albitic	Sotnikov and Berzina (2000)
Initial $^{87}Sr/^{86}Sr$ (range)	0.70406–0.70424	0.70454–0.70496	0.70495–0.70642	0.70741–0.70782	0.70460	Sotnikov et al. (2000b)
$\delta^{34}S$ (‰) in molybdenite (range)	(−0.9)–0.4	2.5–3.2	3.7–4.1	5.5–5.7	8.3–10.2	Sotnikov et al. (2004)
T (°C) of molybdenite formation (range)	360–280	360–300	420–330	430–340	470–390	Sotnikov et al. (1979), Sotnikov and Berzina (2000)

and Berzina, 2000). The principal characteristics of the studied deposits are given in Table 1.

2.1. Sora deposit, Kuznetsk Alatau, Russia

The Sora deposit (Fig. 2) is located in the north-eastern Uibat Pluton (Amshinskii and Sotnikov, 1976). The latter is composed of three magmatic series: Kogtakh (490 to 480 Ma), Martaiga (466 to 452 Ma) and Tygertysh (433 to 422 Ma) series of monzodiorite–granosyenite–leucogranite association (Sotnikov and Berzina, 2000; Sotnikov et al., 2001b,c). The Uibat pluton hosts ore-bearing sub-volcanic stocks and dikes of the Sora Porphyry Series. Porphyry rocks consists of monzodiorite, diorite, granosyenite and sub-alkaline granite porphyries. $^{40}Ar/^{39}Ar$ dating by Sotnikov et al. (2001c) has shown the age of the porphyries to be 405 to 388 Ma. Granite porphyries are dominant among the porphyry rocks. Initial $^{87}Sr/^{86}Sr$ values of apatites from sub-alkaline granite porphyries show 0.70460 ± 17 (Sotnikov et al., 2000b).

Several ore-forming stages can be recognized in the stock-like porphyry rocks. An early stage of mineralization, characterized by chalcopyrite and molybdenite disseminations, is related to quartz–biotite–K-feldspar altered rocks and intensely altered zones dominated by K-feldspar. The most economically valuable, and dominant mineralization consists of disseminations, stockwork and breccia ores. Stockwork ores contain 0.04 to 0.10% Mo and 0.02 to 0.20% Cu. The breccia ore consists of intensely K-feldspathized and albitized angular fragments of host rocks, cemented by a quartz–fluorite matrix, containing molybdenite, pyrite and chalcopyrite. The breccia ore contains from 0.1 to 0.5% Mo and 0.02 to 0.3% Cu. Quartz–fluorite–galena–sphalerite veinlets, hosted within sericitized and pyritized rocks, are the final products of the ore-bearing process.

2.2. Aksug deposit, North-eastern Tuva, Russia

The Aksug deposit (Fig. 3) is localized within the Kandat Fault Zone, which cuts the granitoids of
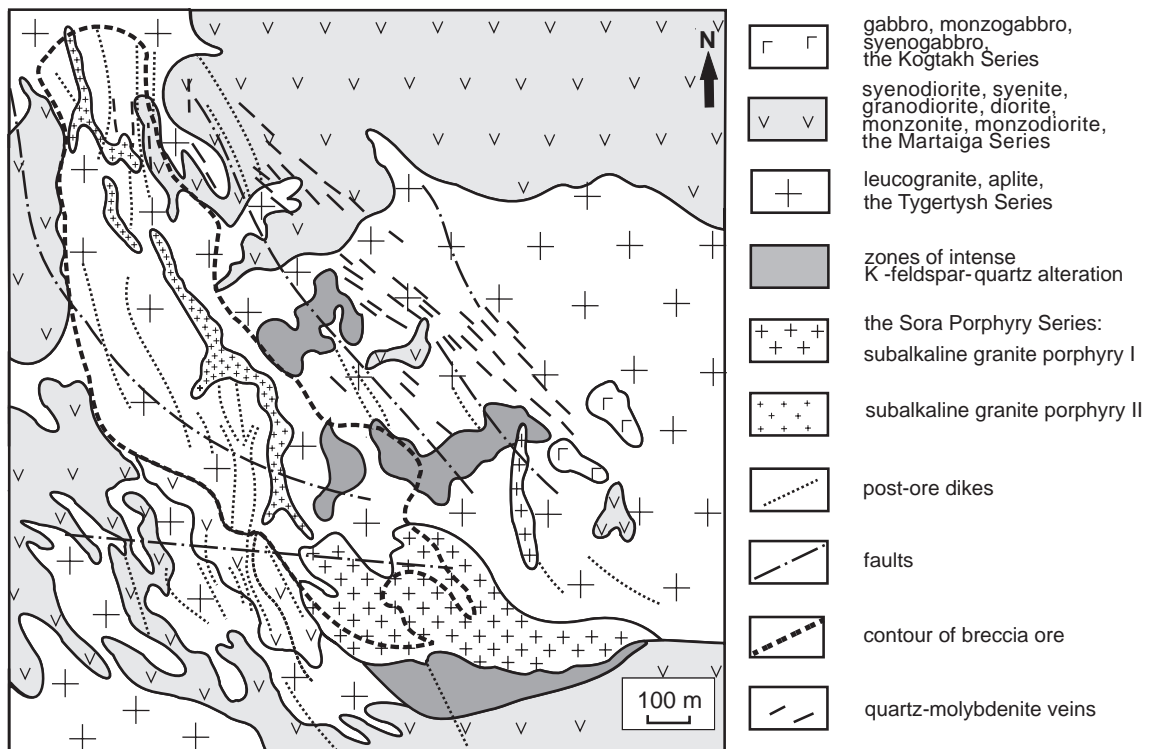

Fig. 2. Geologic map of the Sora deposit (modified after Sotnikov and Berzina, 2000).
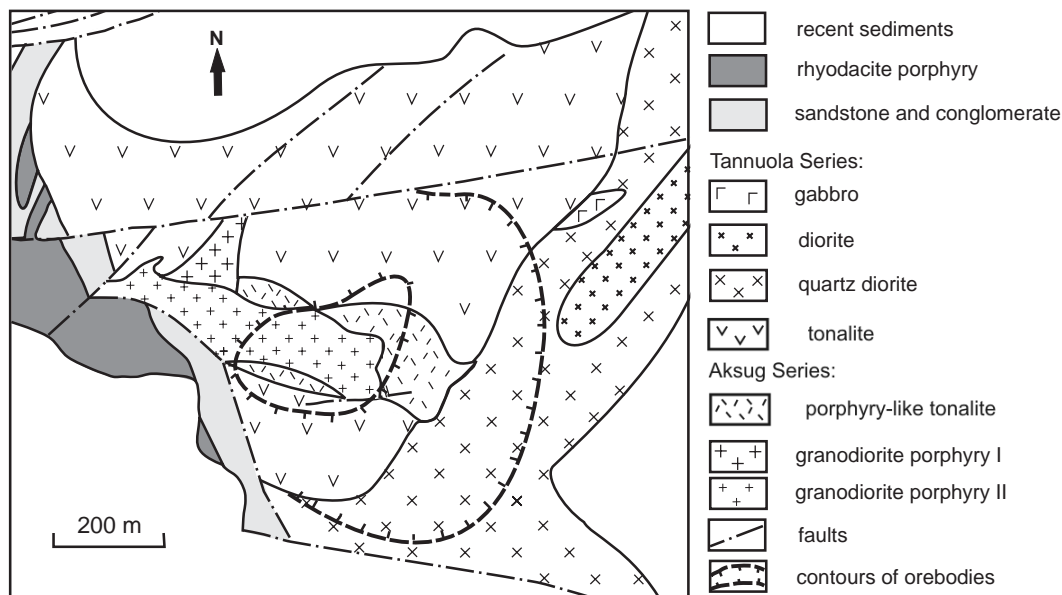
Fig. 3. Geologic map of the Aksug deposit (modified after Sotnikov and Berzina, 2000).

Aksug Pluton (Popov et al., 1988; Dobryanskii et al., 1992). The pluton consists of quartz–diorite, with subordinate diorite, tonalite and gabbro; $^{40}Ar/^{39}Ar$ dating yielded an age of 497 to 462 Ma (Sotnikov et al., 2003b). Stocks and dikes of the ore-bearing porphyry intrude these rocks within the ore field. The porphyries consist of quartz–diorite and granodiorite. Initial $^{87}Sr/^{86}Sr$ ratios obtained for porphyries are 0.70454 to 0.70496 (Sotnikov et al., 2000b). $^{40}Ar/^{39}Ar$ dating showed an age of the porphyries to be in the range 404 to 401 Ma (Sotnikov et al., 2003b).

Stockwork mineralization is confined to the porphyry stock and is related to quartz–sericite altered rocks. The low-grade (0.1 to 0.2% Cu; ~0.003% Mo) molybdenite–pyrite–chalcopyrite mineralization relates to first-generation granodiorite porphyries (I). Subsequent emplacement of a second generation of granodiorite porphyries (II) transformed this disseminated mineralization and produced superimposed chalcopyrite–bornite–molybdenite ore (0.3 to 1.0% Cu; 0.01 to 0.02% Mo). The average Cu and Mo grade is 0.67% and 0.015% respectively (Lebedev and Kuzhuget, 1998). The general sequence of mineral assemblages at the Aksug deposit has been distinguished by Sotnikov and Berzina (2000) as: (1)

quartz–pyrite with hematite, (2) quartz–molybdenite with pyrite and chalcopyrite, (3) quartz–chalcopyrite with bornite, pyrite and molybdenite, (4) fahlore, enargite, galena and sphalerite, (5) quartz–calcite. At lower levels, the rocks are rich in anhydrite, and, to a lesser extent, also barite and celestine.

2.3. Erdenetuin-Obo deposit, Northern Mongolia

The Erdenetuin-Obo deposit is located in the Erdenet Pluton (Khasin et al., 1977; Zhamsran et al., 1986; Sotnikov et al., 1995). The pluton is composed of granodiorites, granosyenites with minor granites and gabbro (Fig. 4). $^{40}Ar/^{39}Ar$ dating of these rocks (Selenga Series) yielded an age of 270 to 260 Ma (Sotnikov et al., 2002). Ore-bearing porphyries (Erdenet Porphyry Series) consist predominantly of granodiorite, with rare diorite, granite. $^{40}Ar/^{39}Ar$ ages of porphyries are 240 to 220 Ma (Sotnikov et al., 2002), initial $^{87}Sr/^{86}Sr$ ratios are 0.70406 to 0.70424 (Sotnikov et al., 2000b).

Mineralization is represented by disseminations and veinlets in a NW-trending zone of sericitized and silicified rocks. The ore zone is 2.8 km long and 0.3 to 1.3 km wide, largely confined to the porphyry stock, but also extending up to 500 m into the
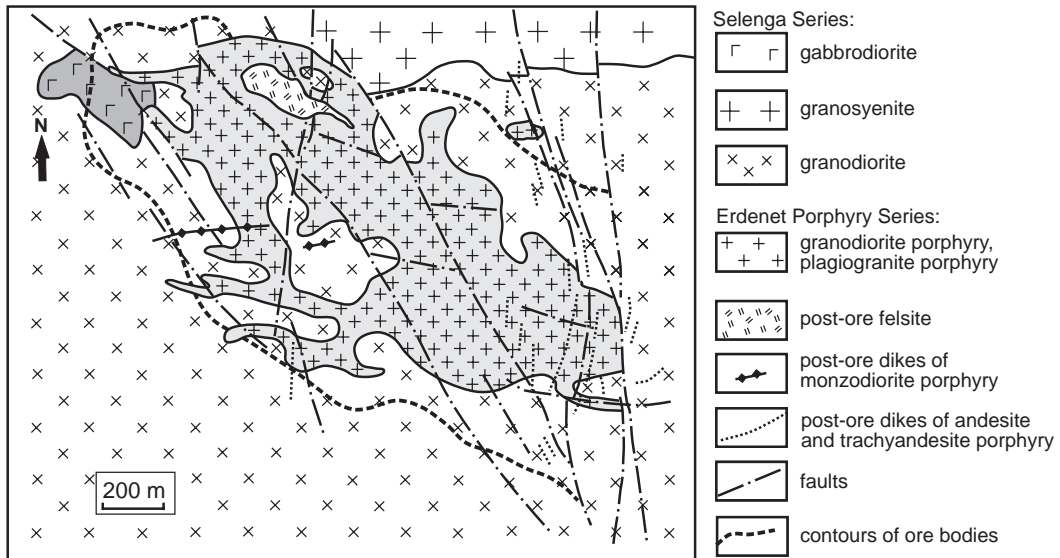
Fig. 4. Geologic map of the Erdenetuin-Obo deposit (modified after Sotnikov and Berzina, 2000).

neighboring granite. The mineralization pinches out at a depth of 900 to 1000 m. The deposition sequence of the mineral assemblages is as follows: (1) quartz–pyrite, (2) quartz–pyrite–molybdenite with chalcopyrite, (3) quartz–pyrite–chalcopyrite with bornite, (4) quartz–pyrite–galena–sphalerite with fahlore, (5) chalcedony–carbonate. Deeper levels of the deposit are enriched in anhydrite. The Cu content in primary ores is 0.3 to 0.6%; the average Mo content is 0.012%.

2.4. Zhireken deposit, Eastern Transbaikalia, Russia

The Zhireken deposit (Sotnikov et al., 1985; Pokalov, 1992) is located within the Bushulei Pluton. The pluton is composed mainly of granites with minor granodiorites and granosyenites (Amanan Series). The age of Amanan series of rocks is 188 to 168 Ma. Ore-bearing porphyries (Zhireken Porphyry Series) are represented predominantly by sub-alkaline granite porphyry with minor diorite, granosyenite porphyry (Fig. 5). $^{40}Ar/^{39}Ar$ ages of porphyries are 160 to 155 Ma and initial $^{87}Sr/^{86}Sr$ ratios range from 0.70495 to 0.70642 (Sotnikov et al., 2000b, 2002).

Vein-disseminated Mo–Cu mineralization (0.03 to 0.15% Mo; 0.04 to 0.20% Cu) is confined to the zones of hydrothermal alteration in the rocks of pluton

and porphyry rocks. More than 60% of explored Mo and Cu reserves are associated with the K-feldspar metasomatites (Sotnikov et al., 1977). Mo–Cu mineralization is composed of quartz veinlets with molybdenite–pyrite; chalcopyrite–Mo-bearing scheelite, as well as disseminated molybdenite. Frequently, molybdenite disseminations display no relations to veinlets. The last ore stage is represented by quartz–pyrite–sphalerite–galena veinlets in sericitized zones.

2.5. Shakhtama deposit, Eastern Transbaikalia, Russia

The Shakhtama deposit (Sidorenko, 1961; Sotnikov and Berzina, 2000) is located within the Shakhtama pluton (Fig. 6). This pluton is composed mainly of granodiorites and granosyenites ($^{40}Ar/^{39}Ar$ ages are 193 to 167 Ma; Sotnikov et al., 2002). The pluton and the country rocks embody the sub-lateral belt of dikes and stocks of ore-bearing porphyry. Porphyry rocks are dominated by granite porphyries and granodiorite porphyries with $^{40}Ar/^{39}Ar$ ages ranging from 155 to 150 Ma (Sotnikov et al., 2002). Initial $^{87}Sr/^{86}Sr$ ratios are 0.70741 to 0.70782 (Sotnikov et al., 2000b).

The ores occur within the porphyry belt. The Mo-bearing stage of mineralization is represented by steep sub-lateral trending quartz–molybdenite veins, carrying pyrite and scarce chalcopyrite. The veins
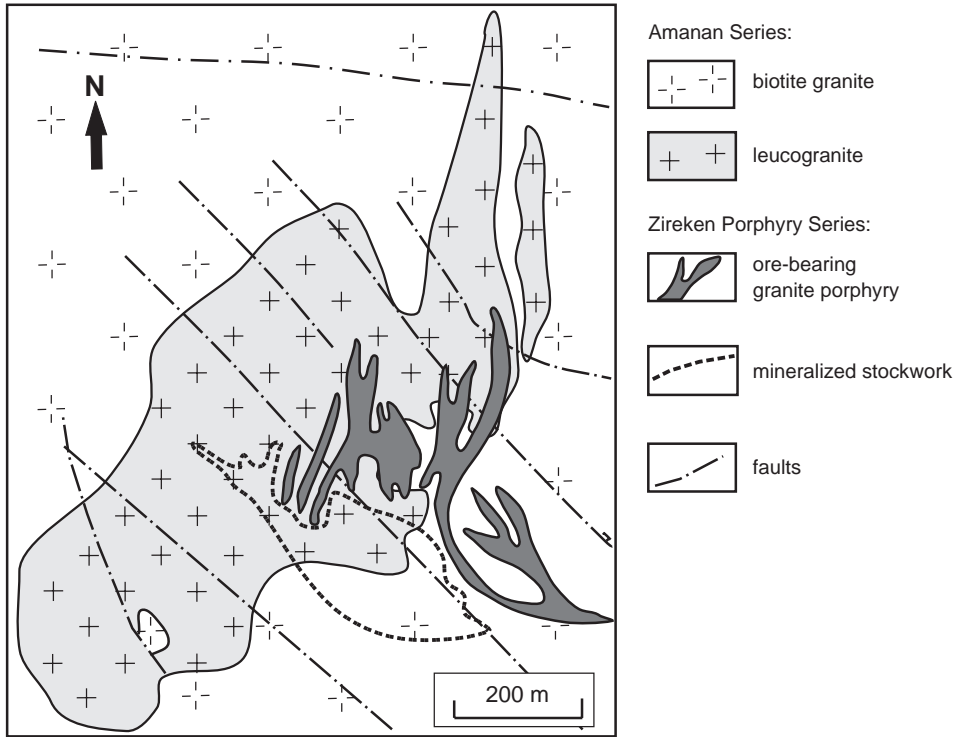
Fig. 5. Geologic map of the Zhireken deposit (modified after Sotnikov and Berzina, 2000).

contain 0.1 to 0.5% Mo and 0.1 to 0.2% Cu. The Mo content in altered rocks is 0.03 to 0.15%. Younger Pb–Zn mineralization consists of quartz–carbonate veins with galena, sphalerite, tennantite, pyrite and, less frequently, chalcopyrite, bournonite, jamesonite, bismuthinite and pyrargyrite. Carbonates, chalcedony and rare stibnite represent the final stage of ore formation.

3. Samples and analytical methods

Samples were taken from open pits (Zhireken, Sora and Erdenetuin-Obo) and mine benches (Shakhtama). These 22 samples are monomineralic molybdenite, coarse (3 to 7 mm)- or medium-grained (1 to 2 mm), representing the main phase of mineralization, and occurring within quartz–molybdenite veinlets, breccia
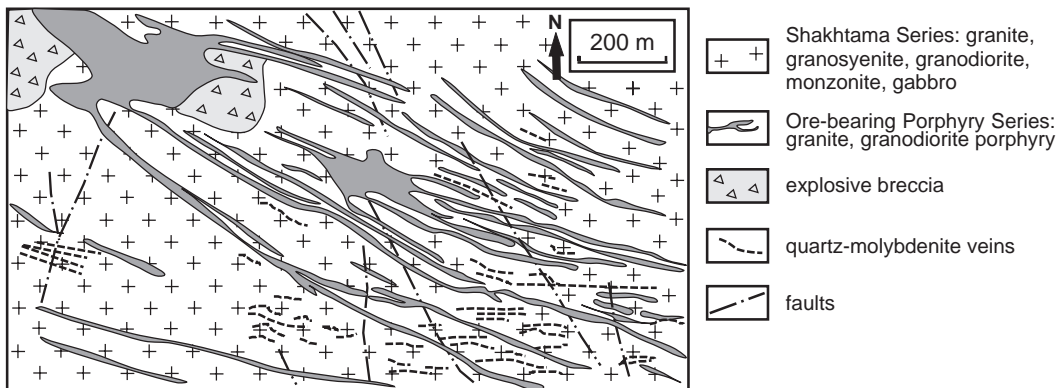

Fig. 6. Geologic map of the Shakhtama deposit (modified after Sotnikov and Berzina, 2000).

ores and as aggregates of molybdenite flakes, rosettes or plates in alteration zones. Molybdenite was hand picked to produce a flaky powder. Two additional samples (4T and CM-2) are milled flotation concentrates supplied by the mining companies at Aksug and Erdenetuin-Obo. Re contents in the two concentrates were recalculated to 100% MoS_2.

The Re content of molybdenite samples was determined using inductively coupled plasma mass spectrometry (ICP-MS) at Actlabs Laboratories (Ontario, Canada), following acid digestion. Detection limits for Re are 0.1 ppm. Analyses were run on a suite of 24 molybdenite samples and concentrates; ca. 100 mg of powdered sample was used for each run.

4. Characteristics of molybdenite-bearing mineralization

In the porphyry Mo–Cu deposits of Shakhtama, Zhireken and Sora, molybdenite occurs in: (1) quartz veins and veinlets in association with pyrite and chalcopyrite; (2) in breccia ores, where molybdenite along with other sulfides (mainly pyrite, chalcopyrite, with minor sphalerite, fahlore and galena) occurs as a cement mass among the fragments of hydrothermally altered host rocks; (3) in the zones of intense K-feldspar–quartz replacement as monomineralic aggregates of flakes and coarse plates up to 1 to 2 cm in size; and (4) in thin (1 to 2 mm) monomineralic molybdenite veinlets hosted by relatively unaltered granites. In the Cu–Mo porphyry deposits (Aksug, Erdenetuin-Obo), molybdenite occurs mainly in quartz veinlets in association with pyrite, chalcopyrite, with subordinate bornite and chalcocite. Fine-grained molybdenite is predominant at these two deposits. The bulk of molybdenite occurs at the earlier stage of ore formation at all studied deposits.

5. Re contents in molybdenites from porphyry deposits of Siberia and Mongolia

Re was determined in representative molybdenite samples from the Aksug, Erdenetuin-Obo, Zhireken, Shakhtama and Sora Cu–Mo and Mo–Cu deposits of Siberia (Russia) and Mongolia. Among 24 analyzed molybdenite samples from 5 deposits, 4 samples are

from Cu–Mo porphyry deposits (Aksug and Erdenetuin-Obo) and 20 are from Mo–Cu porphyry deposits (Sora, Zhireken and Shakhtama). Re concentrations and descriptions of the analyzed samples are summarized in Table 2. Concentrations are of the order of a few tens of ppm Re in the majority of samples. The maximum Re content is in molybdenite concentrate 4T from the Aksug deposit, Russia (460 ppm Re). Although we have only a single sample of molybdenite concentrate from the Aksug deposit, the sample was taken from a sizeable volume of molybdenite concentrate produced by Aksug mining company from high-grade mineralization zones of the deposit and can thus be considered as representative for molybdenite from across the deposit.

The studied deposits can be divided into two groups according to the Re content of molybdenite: (1) deposits with relatively elevated Re concentrations: Aksug (460 ppm), Erdenetuin-Obo (104 to 199 ppm), and (2) deposits with low Re concentrations: Zhireken (12 to 57 ppm), Shakhtama (9 to 24 ppm), and Sora (6 to 18 ppm).

Deposits of the first group (Aksug and Erdenetuin-Obo) are characterized by decreased alkalinity and more mafic composition of the host porphyry rocks. Quartz–diorite porphyries prevail among the rocks at Aksug; granodiorite porphyries are abundant at Erdenetuin-Obo. The predominant wall rock alteration types in both deposits are quartz–sericitic and propylitic. The Cu concentration is considerably higher than that of molybdenum; Cu/Mo ratios range from 30 to 70 (Table 1).

Elevated silica contents and alkalinity are characteristic for the porphyry rocks of the deposits of the second group (Zhireken, Shakhtama and Sora). Granite porphyries with increased content of K dominate the ore-bearing porphyry rocks at these deposits. The predominant alteration type is quartz–biotite–potassic. Ore mineralization is essentially molybdenum, with lowered Cu/Mo ratios (from <1 up to 4; Table 1).

6. Comparison with other provinces worldwide

The Re contents of molybdenite from Cu–Mo and Mo–Cu porphyry deposits of the world vary widely, ranging across several orders of magnitude from ppm

Table 2
Re content in molybdenites from porphyry Cu–Mo and Mo–Cu deposits of Russia and Mongolia

Deposit	Sample	Description	Re (ppm)
Erdenetuin-Obo, Northern Mongolia	CM-2	Molybdenite from flotation concentrate	199[a]
	S-280A	Molybdenite from quartz–molybdenite veinlets	188
	E-1	Molybdenite from breccia	104
Aksug, North-Eastern Tuva, Russia	4T	Molybdenite from flotation concentrate	460[a]
Shakhtama, Eastern Transbaikalia, Russia	P-259	Monomineral molybdenite veinlet in altered granite	16
	P-260	Molybdenite from quatrz–molybdenite vein	18
	P-279	Molybdenite from quatrz–molybdenite vein	9
	P-354	Molybdenite from quartz–molybdenite vein	24
Sora, Kuznetsk Alatau, Russia	S-2031	Molybdenite from breccia	11
	S-2033	Molybdenite from quartz–molybdenite vein	13
	S-2035	Molybdenite from quartz–molybdenite vein	18
	S-2036	Molybdenite from quartz–molybdenite vein	17
	S-2038	Molybdenite from breccia	9
	S-2039	Molybdenite from breccia	16
	S-2042	Molybdenite from quartz–molybdenite vein	6
	S-2046	Molybdenite from breccia	17
	S-2053	Molybdenite from quartz–molybdenite vein	15
Zhireken, Eastern Transbaikalia, Russia	S-0517	Aggregates of molybdenite flakes in potassically altered granites	17
	S-0518	Molybdenite breccia ore	39
	S-0518D	Monomineral molybdenite veinlets in fine-grained granite	57
	S-456A	Quartz–molybdenite veinlet in granite	35
	S-768	Disseminated coarse-grained molybdenite in potassically altered granites	20
	S-794G	Quartz–K-feldspar metasomatite with disseminated molybdenite	12
	S-794V	Aggregates of molybdenite flakes in quartz–K-feldspar metasomatites	21

[a] Re content recalculated to 100% MoS_2.

to percentages. The highest reported concentrations of Re in molybdenite from a porphyry Cu–Mo deposit is that of the Kirki deposit, Thrace, Greece (4.21%; Melfos et al., 2001).

The distribution of Re content in molybdenite from 75 porphyry Cu–Mo and Mo (Cu) deposits of the world are shown in Table 3 and Fig. 7. On the basis of the Cu and Mo contents, the porphyry deposits can be divided into two groups: Cu±Mo deposits, containing major or co-product Cu with variable Mo content (average Mo grade ≤0.05%; Cu/Mo>4 up to 160) and the Mo±Cu deposits, that are Mo-dominant and Cu-poor, containing either only co-product or by-product Cu (average Mo grade >0.05%; Cu/Mo<4). This is the simplified classification used in the following discussion.

In a comparison between numerous porphyry Cu and Cu–Mo deposits of other relevant provinces of the world (Table 3, Fig. 7), the Re concentrations in molybdenites from the studied Cu–Mo porphyry

deposits of Siberia and Mongolia are generally low. Even the Re concentrations in molybdenite from Aksug (460 ppm) and Erdenetuin-Obo (104 to 199 ppm) deposits are markedly lower than those from comparable provinces around the world. The global average of Re in molybdenite, calculated on the basis of available data from 56 porphyry Cu–Mo deposits in Europe, Asia, North and South America (Table 3) is 1830 ppm. Porphyry Cu (Mo) deposits of Central Asia (Uzbekistan, Kazakhstan) are usually characterized by elevated Re contents in molybdenites, ranging from 50 to 4050 ppm (mean 1360 ppm). The highest Re content among the deposits of this province is the molybdenite from the Kounrad deposit in Kazakhstan (Table 3). Molybdenite from porphyry Cu–(Mo) deposits of Armenia (Transcaucasian province) show a wide range in Re content from 33 to 18800 ppm (Table 3, Fig. 7). Magakian et al. (1984) showed that the highest Re contents in molybdenite among these

Table 3
Rhenium content in molybdenites for Cu±Mo and Mo±Cu porphyry deposits of the world

Deposit	Country	n[a]	Re (ppm)			References	Cu grade	Mo grade	Cu/Mo	References
			Average	Min	Max					
Porphyry Cu and Cu–Mo deposits										
Aksug	RUSSIA	1	460			Present study	0.67	0.015	45	Lebedev and Kuzhuget (1998)
Erdenetuin-Obo	MONGOLIA	3	164	104	199	Present study	0.45	0.012	38	Sotnikov and Berzina (2000)
Dubaoshan	CHINA	3	470	303	567	Zhao et al. (1997)	0.47			
Tongshan		2	660	498	822	Chen and Li (1998)				Singer et al. (2002)
Tongkuangyu		3	900	172	1280		0.69	0.032	22	
Aktogay	KAZAKHSTAN	30	850	50	2700	Yudin (1969), Mukhlya et al. (1989)	0.39	0.008	49	Singer et al. (2002)
Borly		19	3160	250	5500		0.34	0.011	31	
Boshchekul		23	825	230	1500		0.66	0.01	66	
Kounrad		20	1540	620	4050		0.4	0.01	40	
Dal'neye	UZBEKISTAN	1	650			Badalov et al. (1971)	0.4			
Kal'makyr		20	1500	700	2000		0.4	0.005	80	Singer et al. (2002)
Sary-Cheku		12	600	320	960					
Yangakly		3	1800	1600	2000					
Agarak	ARMENIA	106	820	57	6310		0.56			Singer et al. (2002)
Ankavan		11	220	150	340					
Dastakert		8	220	130	300					
Dzhindara		6	980	472	1650	Magakian et al. (1984)				
Elpin		1	4500							
Kadzharan		237	245	33	2620		0.65	0.05	13	Singer et al. (2002)
Vardenis		3	16600	12200	18800					
Kirki	GREECE	53	19800	4500	42100	Arikas (1979), Todorov and,				
Maronia		58	7260	900	28800	Staikov (1985), Filippidis,				
Melitena		51	7850	2100	17400	et al. (1986), Economou-				
Skouries		4	900	800	1000	Eliopoulos and Eliopoulos (1996), Melfos et al. (2001)	0.35			Singer et al. (2002)
Elatsite	BULGARIA	19	1250	273	2740	Todorov and Staikov (1985),	0.32			Singer et al. (2002)
Medet		22	905			Zimmerman et al. (2003)	0.37	0.01	37	
Bor	SERBIA	3	1520			Todorov and Staikov (1985)	0.6			Singer et al. (2002)
Majdanpek		3	2770	2320	3550		0.6	0.006	100	
Cananea	MEXICO		700			Sutulov (1974);	0.42	0.008	53	Singer et al. (2002)
Maria		4	300	100	500	McCandless et al. (1993)				
Chuquicamata	CHILE	3	220	194	245	Giles and Shilling (1972);	0.65	0.04	16	Singer et al. (2002)
Collahuasi		2	410	368	448	Mathur et al. (2001)	0.86	0.04	22	
El Salvador			570				1.41	0.01	141	
El Teniente		6	390	182	1154		0.92	0.019	48	
Escondida		1	1355				0.97	0.006	156	
Los Pelambres		3	600	450	820		0.63	0.016	39	
Cerro Verde	PERU	2	3280	3060	3497	Giles and Shilling (1972);	0.67	0.01	67	Singer et al. (2002)
Cuajone		1	60			Mathur et al. (2001)	0.69	0.0214	32	
Tintaya		1	550							
Toquepala		3	790	387	1496		0.55	0.04	14	
Bettlehem	CANADA		430			Giles and Shilling (1972);	0.45	0.016	28	Singer et al. (2002)
Brenda			80			Sutulov (1974)	0.16	0.039	4	

|		a								
Bagdad	USA	7	460	330	642	Giles and Shilling (1972);	0.4	0.01	40	Carten et al. (1993);
Bingham		6	360	130	2000	Sutulov (1974);	0.812	0.044	18	Singer et al. (2002)
Butte			240			McCandless et al. (1993);	0.673	0.028	24	
Castle Dome			1550	1200	1750	Barra et al. (2003)	0.33	0.0055	60	
Copper Creek		3	2300	1200	4200		0.75	0.0046	163	
Ely			2020	1250	2840		0.613	0.01	61	
Esperanza			610	90	1800		0.26	0.0276	9	
Miamy			600				0.63	0.01	63	
Mineral Park			270	250	290		0.458	0.032	14	
Morenci		5	1180	100	4100		0.524	0.095	6	
Ray			820	440	1500		0.49	0.01	49	
San Manuel		5	950	700	1200					
Santa Rita		5	750	200	1100		0.468	0.008	59	
Silver Bell		18	470	340	620		0.52	0.013	40	
Twin Buttes			600				0.502	0.023	22	
Porphyry Mo–Cu and Mo deposits										
Amanan-Makit	RUSSIA	5	43	10	70	Present study; Ivanov and,				
Amudzhikan		6	82	40	170	Poplavko (1982), Mao		0.31		Borisov (1985)
Bugdaya		70	8	0.5	51	et al. (2003)		0.071		Unpublished data
Davenda		13	73	47	105			0.5		Borisov (1985)
Shakhtama		4	17	9	24		0.3	0.15	2	Sotnikov and Berzina (2000)
Sora		9	14	6	18		0.17	0.058	3	Sotnikov and Berzina (2000)
Zhireken		7	29	12	57		0.1	0.099	1	Sotnikov and Berzina (2000)
Shameika		11	12	2	37			0.08		Seltmann et al. (2000)
Shalgiya	KAZAKHSTAN	4	32	22	39	Ivanov and Poplavko (1982)				
Unkurtash	KYRGYZSTAN	3	30	26	32	Ivanov and Poplavko (1982)				
Jinduncheng	CHINA	5	17	13	20	Stein et al. (1997), Mao et al. (1999)	0.03	0.1	0.3	Carten et al. (1993)
Copaquirre	CHILE	2	84	81	86	Mathur et al. (2001)	0.3	0.07	4	Carten et al. (1993)
Boss Mountain	CANADA		62			Giles and Shilling (1972)		0.074		Carten et al. (1993)
Endako			32	22	43			0.087		
Lime Creek			69	36	129					
Climax	USA		35	11	80	Giles and Shilling (1972)		0.24		Carten et al. (1993)
Questa			68	42	113			0.144		
Urad Henderson			14	7	18			0.209		

[a] Number of samples.
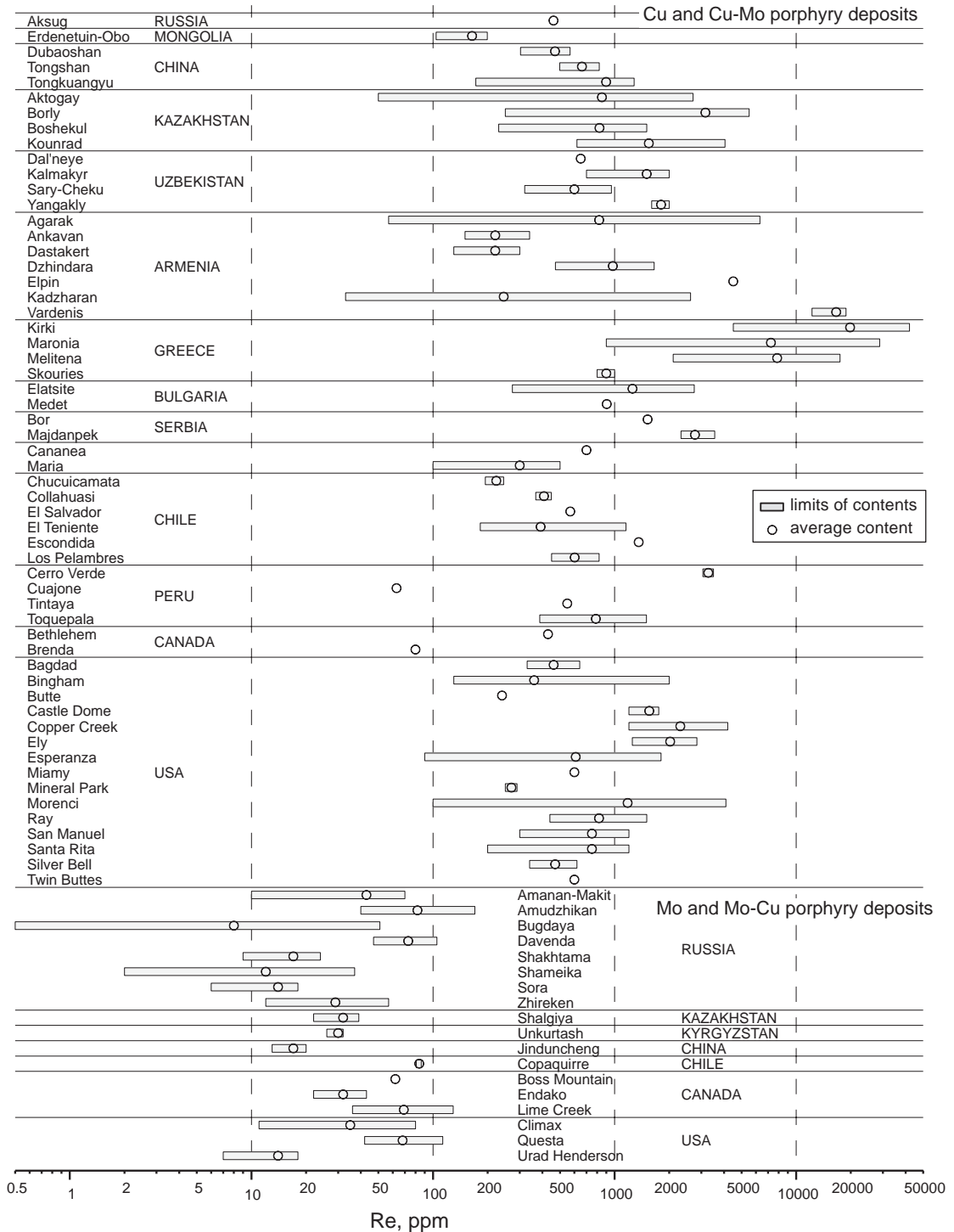
Fig. 7. Distribution of Re content of molybdenite for porphyry Cu–Mo and Mo–Cu deposits in the world, after the data summarized in Table 3.

deposits are from low-temperature shallow-level deposits, confined to regions with abundant complex Pb–Sb mineralization (e.g., Vardenis and Elpin deposits).

Elevated Re contents in molybdenite are typical for porphyry Cu–Mo deposits of the Carpathian–Balkan–Dinaride system. Molybdenite from the Elatsite porphyry Cu deposit in Bulgaria (Srednegorie metallogenic zone) contains up to 2740 ppm Re (Zimmerman et al., 2003), with an average Re content of 1250 ppm (Table 3). High Re contents, ranging from 2320 to 3550 ppm, are reported for molybdenite from for the Majdanpek deposit in Serbia (Table 3).

Rhenium values for the porphyry Cu–Mo deposits of Northern Greece can be considered as exceptionally high (Arikas, 1979; Todorov and Staikov, 1985; Filippidis et al., 1986; Economou-Eliopoulos and Eliopoulos, 1996; Melfos et al., 2001). The average Re content (8950 ppm) in molybdenites from Northern Greece is calculated on the basis of 4 deposits (166 samples, Table 3). More specifically, Re content in molybdenite from deposits of Northern Greece (Melitena, Maronia and Kirki) shows a variation from 2110 to 17400 ppm (average 7900 ppm, 49 samples) in the Melitena dacitic porphyry, from 4500 to 42100 ppm (average 19800 ppm, 51 samples) in the Kirki dacitic andesite porphyry, and from 1200 to 28800 ppm (average 7600 ppm, 55 samples) in the Maronia microgranite porphyry, all in the Thrace district, Greece (Melfos et al., 2001). The average of the Re content obtained for molybdenite from the Skouries porphyry Cu deposit in Northern Greece is 900 ppm (Economou-Eliopoulos and Eliopoulos, 1996).

The distribution of Re concentrations in porphyry Cu–Mo deposits in North and South America are notably different. The Re contents of molybdenite from North American deposits (Canada, USA) show wide variations from 90 to 4200 ppm (Table 3, Fig. 7). The largest range is at Morenci—4000 ppm (McCandless et al., 1993), followed by Bingham (1900 ppm) and Esperansa (1750 ppm) (Giles and Shilling, 1972). The highest Re contents in molybdenite from porphyry Cu–Mo deposits of North America (4200 and 4100 ppm) are reported for Copper Creek and Morenci, respectively (McCandless et al., 1993). Molybdenites from Ely and Castle Dome deposits also contain high Re concentrations, ranging from

1250 to 2840 and 1200 to 1750 ppm respectively (Giles and Shilling, 1972).

The distribution of Re in molybdenites from porphyry Cu–Mo deposits of South America is not so widespread as that for North America, varying from 81 to 1500 ppm (Table 3, Fig. 7). However, the Cerro Verde deposit (Peru) is characterized by considerably high Re contents (3060 to 3500 ppm), on the basis of only two samples (Mathur et al., 2001). It has been further emphasized (Mathur et al., 2001) that there is no obvious relationship between the tectonic position or temporal occurrences within the Andean porphyry copper deposits and the Re contents of molybdenite.

Rhenium contents of molybdenites from porphyry Mo–Cu and Mo deposits are significantly lower than those from porphyry Cu–Mo deposits (Table 3, Fig. 7). The Mo–Cu porphyry deposits of Siberia (Zhireken, Shakhtama and Sora) correlate well enough with Mo–(Cu) porphyry deposits in other relevant provinces in the world with respect to their Re concentrations. The mean Re content, obtained from 19 porphyry Mo–Cu and Mo deposits (Table 3), is 42 ppm. Molybdenite from the Zhireken, Shakhtama and Sora deposits shows a comparable range of Re with those of the Urad Henderson (USA), Endako (Canada), Bugdaya and Shameika (Russia), Shalgiya (Kazakhstan), Unkurtash (Kyrgyzstan) and Jinduncheng (China) deposits. Relatively elevated average Re contents in molybdenites from Mo–(Cu) porphyry deposits are obtained for Brenda (80 ppm), Questa (68 ppm), Boss Mountain (62 ppm) and Lime Creek (69 ppm) deposits from North America (Giles and Shilling, 1972); Amudzhikan (82 ppm) and Davenda (73 ppm) deposits from Russia (Ivanov and Poplavko, 1982).

It has been accepted that molybdenites associated with porphyry Cu±Mo deposits exhibit higher Re contents compared to those associated with porphyry Mo±Cu deposits (Giles and Shilling, 1972; Newberry, 1979; Stein et al., 1997 and others). Although there is a significant positive correlation ($r=0.58$) between the average ($n=58$) Cu/Mo ratio in ores and the Re content in associated molybdenite (Table 3; Fig. 8a), these two types of deposits show some similarities and differences. The majority of Mo and Mo–Cu porphyry deposits are found in association with quartz monzonite and granite intrusions of calc–alkaline and high K calc–alkaline magma series in
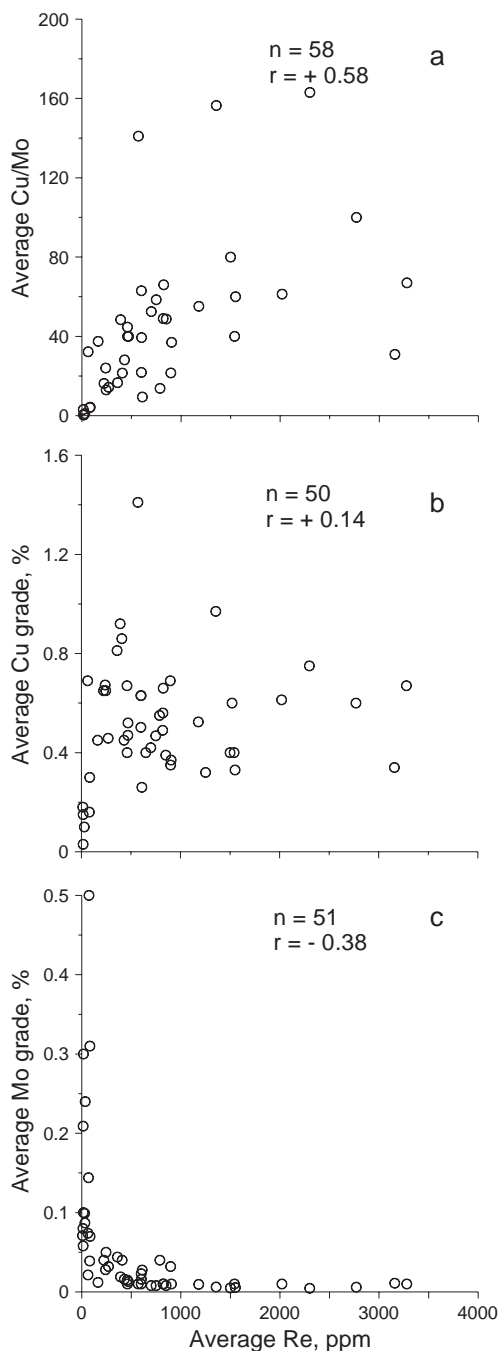
Fig. 8. Plots of (a) Cu/Mo ratio, (b) Cu grade and (c) Cu grade vs. Re content in molybdenite from several Cu±Mo and Mo±Cu deposits of the world. Data are taken from Table 3. *r*—correlation coefficient, *n*—number of deposits.

zones of continental intraplate rifting or continental environments, associated with continental arcs. Porphyry Cu–(Mo) deposits were formed in association with more mafic rocks of calcic to alkali–calcic magma series in island-arc or continental arc settings at or near destructive plate margins (Titley and Beane, 1981; Carten et al., 1993). However, higher Re contents in Cu-rich porphyry systems are not always well established. Molybdenites from deposits of similar geological setting and ore composition may exhibit highly variable Re contents. This is well exemplified by a comparison of porphyry Cu–Mo deposits of Siberia and Mongolia (Aksug and Erde-netuin-Obo) with deposits of Carpatho–Balkan metal-logenic system. The porphyry Cu–Mo deposits in Bulgaria, Serbia and Northern Greece have been formed in an extensional post-collisional environ-ment, comparable to that of the Siberian and Mongolian deposits, have similar rock compositions and high good grades (Berzina et al., 1999; Econo-mou-Eliopoulos and Eliopoulos, 2000). In spite of this, molybdenites from the porphyry Cu–Mo deposits of Carpatho–Balkan metallogenic system differ fun-damentally in their Re content compared to that of molybdenites from the Siberian and Mongolian deposits (Table 3, Fig. 7).

The lack of any correlation between Cu and Re contents in molybdenites ($r=0.14$, $n=50$, Fig. 8b) negative correlation between Mo grade and Re content ($n=51$, $r=-0.38$, Fig. 8c) and the significant correlation between Cu/Mo ratio and Re content confirm the significant role of the amount of molybdenite in the porphyry system on Re concen-tration in molybdenite (Stein et al., 1997).

7. Discussion

The debate over the factors controlling Re contents of molybdenite continues unabated. Studies of molyb-denite from Cu–Mo porphyry deposits show that a wide variation of the Re content of molybdenites may be related to the composition of parent magmas themselves and/or fractionation, reactions between crustal rocks and magmas (assimilation), the depth of the subvolcanic stocks, variations in the physical and chemical conditions at which crystallization takes place (e.g., fO_2, P, T), as well as the different

polytypes of molybdenite (2H1 and 3R) (Giles and Shilling, 1972; Newberry, 1979; Todorov and Staikov, 1985; Ishihara, 1988; Economou-Eliopoulos and Eliopoulos, 1996; Melfos et al., 2001; Xiong and Wood, 2001, 2002).

Some workers consider that the concentration of Re in molybdenite to be an inverse function of the Mo concentration in the mineralizing system (Giles and Shilling, 1972; Newberry, 1979). Indeed, it is well known, and has already been discussed above, that molybdenite from Cu–Mo porphyry systems generally tend to contain more Re than molybdenite from porphyry Mo systems. Stein et al. (2001) proposed a that wide variation in the Re concentration of molybdenite in the porphyry–magmatic environment, and large differences in the Re concentrations observed in porphyry Cu–Mo deposits vs. porphyry Mo deposits, may be attributed to mass balance phenomena. They considered that since almost all Re in Cu–Mo porphyry magmatic system is taken up by molybdenite, the limited presence of molybdenite in any given porphyry Cu–Mo system results in high Re concentrations relative to those in Mo porphyries (climax-type systems) in which Re concentrations are volume-diluted within enormous quantities of molybdenite.

Mao et al. (1999) suggested that the metal source of the deposits may affect the Re content in molybdenites, resulting in decreasing of Re content in molybdenites from mantle to I-type and then to S-type granite-related deposits. Stein et al. (2001) also proposed that deposits that involve mantle under-plating or metasomatism, or melting of mafic and ultramafic rocks have significantly higher Re contents in associated molybdenites than those deposits that are crustally derived. Further detailed studies are required to contribute to the delineation of processes critical to the Re distributions. The compilation of present and published data on Re content and associated trace element content in porphyry–Cu intrusions may provide evidence of genetic importance.

In general, among the five studied deposits of Siberia and Mongolia, relatively increased Re contents in molybdenite are typical for the deposits with increased Cu/Mo values in ores (e.g., Erdenetuin-Obo and Aksug). The Re content in molybdenites of these deposits correlates positively with Cu/Mo ratio in ores and with average Cu grade: Aksug: 460 ppm Re, Cu/Mo=40–70, 0.67% Cu; Erdenetuin-Obo: 104–199

ppm Re, Cu/Mo=30–50, 0.3–0.6% Cu (Table 1, Fig. 9a, b). The deposits with essential Mo mineralization (Sora, Zhireken, Shakhtama), with Cu/Mo values in ores ranging from <1 to 4 are characterized by relatively low Re content and a correlation between Re and Cu is not obvious (Table 1, Fig. 9b).

There is no obvious relationship between Mo reserves, Mo grade and Re content (Table 1, Fig 9c, d). Although both the Sora and Erdenetuin-Obo deposits are large (reserves of contained Mo metal are about 200 kt Mo; Sotnikov et al., 1998), the Re content of molybdenite ranges from 6 to 18 ppm in the former, and from 104 to 199 ppm in the latter. Furthermore, the Shakhtama and Aksug deposits have medium reserves (50 to 60 kt and 52 kt contained Mo respectively; Yurgenson et al., 1999; Lebedev and Kuzhuget, 1998). The Aksug molybdenites, however, contain higher Re concentrations relative to those from Shakhtama. The Re contents in the studied Mo–Cu porphyry deposits (all in ppm), ranging from 6 to 18 in Sora, 9 to 24 in Shakhtama and 12 to 57 in Zhireken are not consistent with any correlation between Re content in molybdenites and Mo reserves. Considering all deposits of Siberia and Mongolia, there is no obvious interrelationship between Re content in molybdenites and Cu reserves (Table 1, Fig. 9e). The total contained Cu at the Aksug deposit, where molybdenite is the most enriched in Re, is in the order of 2.3 Mt. The Re content in molybdenite is significantly lower in the Erdenetuin-Obo deposit, which has the highest Cu reserves (10 Mt) among the deposits considered. The low Re content in molybdenites is typical for Mo–Cu deposits with total Cu content of 100 Kt (Zhireken), 50 Kt (Shakhtama) and 500 to 600 Kt (Sora). Thus, the available data from Siberian and Mongolian porphyry Cu–Mo deposits do not support any correlation between the Mo grade and total amount of molybdenite in porphyry Cu–Mo mineralizing system and the Re distribution in molybdenites.

The recorded difference in the Re abundance in Cu–Mo and Mo–Cu porphyry deposits is possibly related to its concentration in ore-forming fluids (Popov, 1977; Stein et al., 2001). Ore-bearing porphyry rocks at Cu–Mo porphyry deposits are composed mainly of quartz diorite porphyries and granodiorite porphyries. These rocks show low initial $^{87}Sr/^{86}Sr$ values, corresponding to those of
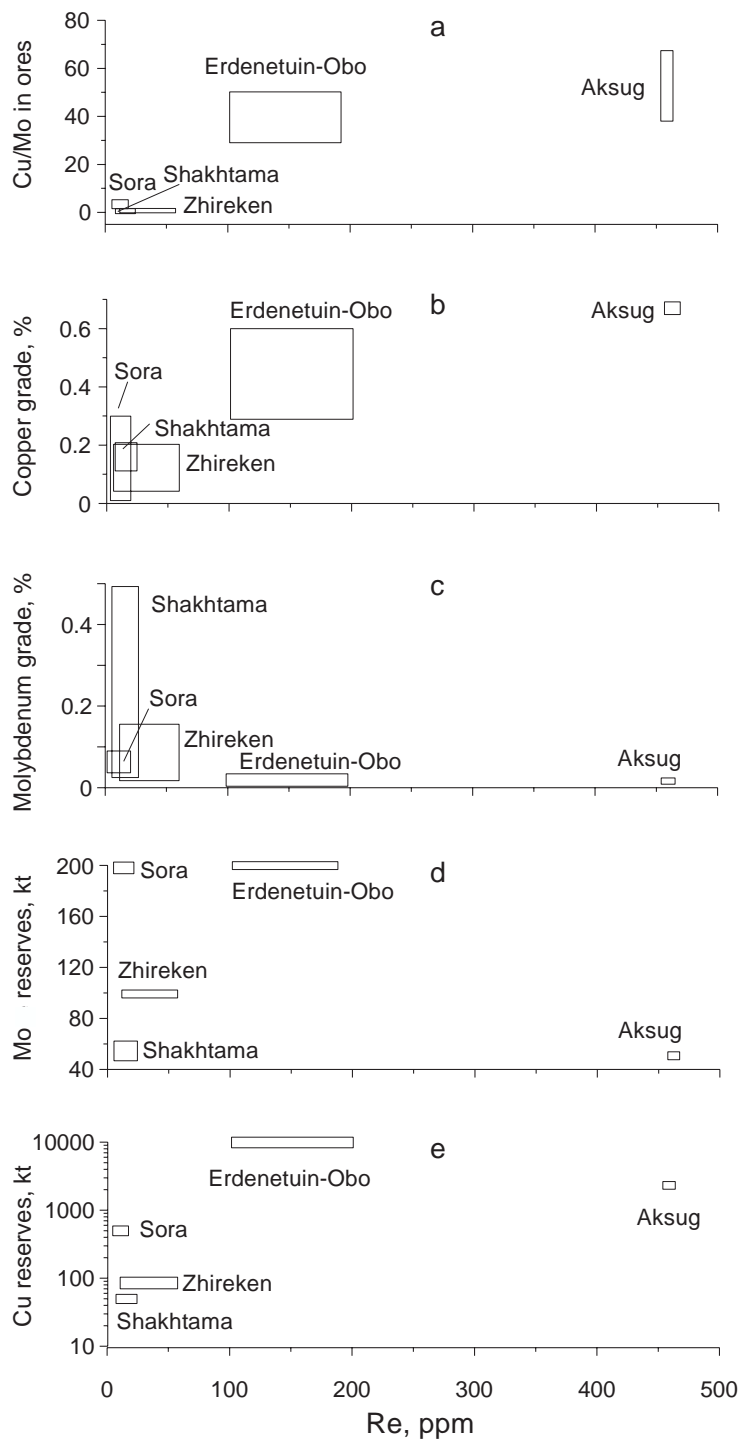
Fig. 9. Plots of (a) Cu/Mo ratio, (b) Cu grade, (c) Mo grade, (d) Mo reserves and (e) Cu reserves vs. Re content of molybdenite for porphyry Cu–Mo and Mo–Cu deposits of Russia and Mongolia.

mantle, ranging from 0.70406 to 0.70424 at the Erdenetuin-Obo deposit, and from 0.70454 to 0.70496 at the Aksug deposit (Table 1, Fig. 10a). Granite porphyries of increased alkalinity are dominated in ore-bearing porphyry associations at Mo–Cu porphyry deposits, with higher initial $^{87}Sr/^{86}Sr$ ratios in the Zhireken deposit (0.70495 to 0.70642) and, particularly, at Shakhtama (0.70741 to 0.70782). These isotope data may suggest that the Shakhtama and Zhireken porphyry rocks have been affected by crustal material to a larger extent compared to Aksug and Erdenetuin-Obo. However, the Sora Mo–Cu porphyry deposit hosting molybdenite with low Re content, as in the Zhireken and Shakhtama deposits, shows low initial $^{87}Sr/^{86}Sr$ (0.70460) ratios, which may reflect a complex interplay of many factors.

A salient feature is the similarity of the relationships between the Re content in Siberian and Mongolian molybdenites and their S- and Sr-isotope data (Table 1, Fig 10b, Sotnikov et al., 2004). The $\delta^{34}S$ composition of molybdenite with relatively elevated Re contents from Cu–Mo porphyry deposits varies from −0.9 to +0.4‰ at the Erdenetuin-Obo deposit and from +2.5 to +3.2‰ at the Aksug deposit. The $\delta^{34}S$ data for low-Re molybdenites from Mo–Cu porphyry deposits are higher, ranging from +3.7 to +4.1‰ at the Zhireken

deposit, from +5.5 to +5.7‰ at the Shakhtama deposit and from +8.3 to +10.2‰ at the Sora deposit.

Experimental data on the solubility of Re phases under geologically reasonable conditions provide a framework for understanding the possible enrichment and depositions mechanisms in various hydrothermal environments (Xiong and Wood, 1999, 2001, 2002). Their results demonstrate that ReS_2 (or a ReS_2 component in molybdenite) is the solubility-controlling phase in sulfur-bearing, reducing environments. Reducing fluids containing sulfur have much less capacity to transport Re and environments dominated by reducing fluids are not favorable to Re deposition. Xiong and Wood (2002) concluded that mixing processes involving an oxidized Re-containing solution and a solution with reduced sulfur should be effective depositional mechanisms for rhenium. The Cu–Mo Aksug and Erdenetuin-Obo deposits which have probably formed under relatively oxidized conditions, as indicated by the presence of abundant anhydrite and low values of the $(CO/CH_4)/CO_2$ ratio (Table 3, Fig. 11a), indicate that the oxidizing fluids were favorable for the transport of Re and subsequent deposition and incorporation in the structure of molybdenite.

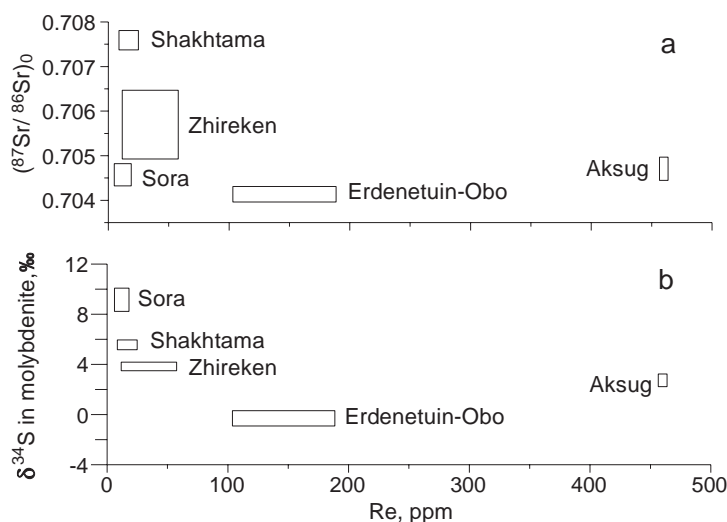The studied Cu–Mo porphyry deposits display hydrothermal features indicative of elevated chlorine

Fig. 10. Plots of (a) initial $^{87}Sr/^{86}Sr$ and (b) $\delta^{34}S$ in molybdenite vs. Re content of molybdenites for porphyry Cu–Mo and Mo–Cu deposits of Russia and Mongolia.
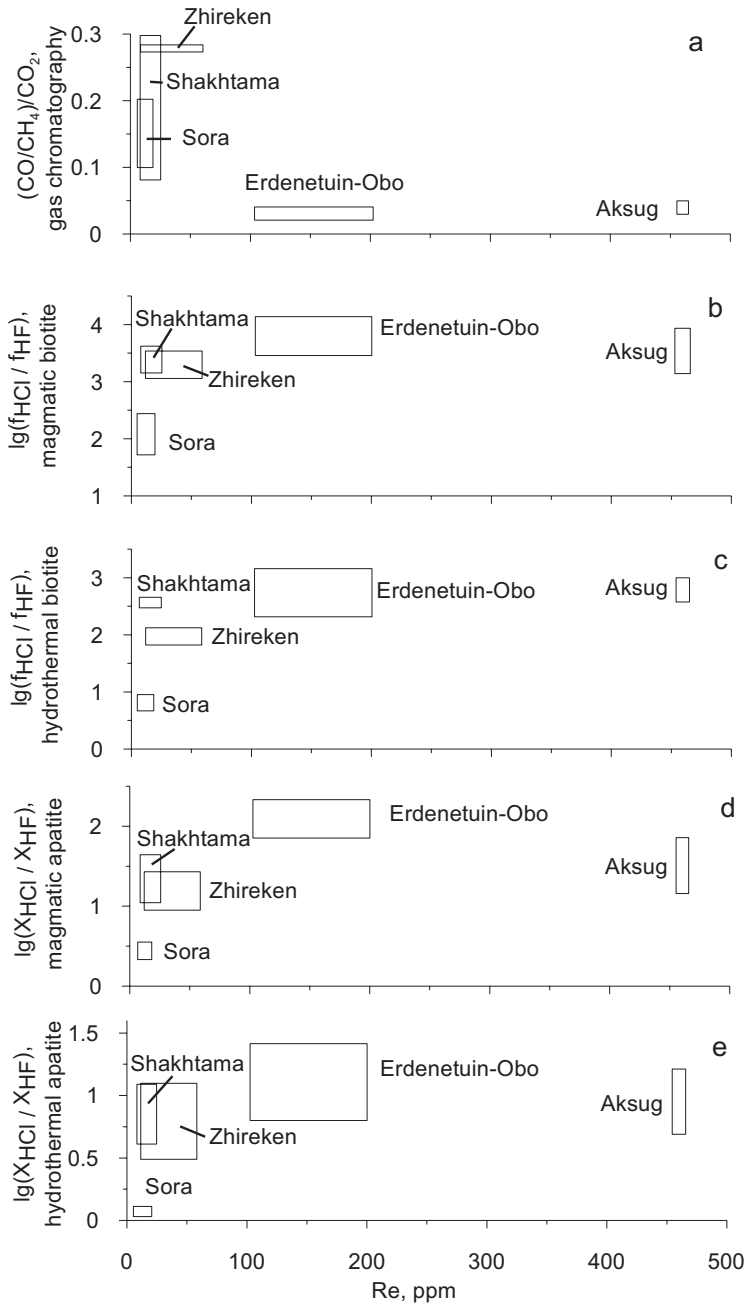
Fig. 11. Characteristics of the fluids associated with porphyry Cu–Mo deposits of Russia and Mongolia as compared to the Re content of molybdenite. (a) $(CO/CH_4)/CO_2$, (b) $fHCl/fHF$ in magmatic biotite, (c) $fHCl/fHF$ in hydrothermal biotite, (d) $XHCl/XHF$ in magmatic apatite, and (e) $XHCl/XHF$ in hydrothermal apatite.

activity if compared to Mo–Cu porphyry deposits. Estimates of fluid composition from biotite and apatite compositions (Sotnikov and Berzina, 1993; Sotnikov et al., 2003a; Table 4, Fig. 11b–e) display an increase in $fHCl/fHF$ value for the studied deposits with relatively high Re contents in molybdenites. The higher Cl

Table 4
Characteristics of the fluids associated with porphyry Cu–Mo and Mo–Cu deposits of Russia and Mongolia (calculated on the basis of biotite and apatite composition and gas chromatography)

Characteristic	Erdenetuin-Obo	Aksug	Zhireken	Shakhtama	Sora	References
F/Cl in minerals: biotite/apatite						
Magmatic	3.8/7.3	6.1/11.2	6.3/18	3.4/6.9	37.0/>300	Sotnikov et al. (2000a)
Hydrothermal	12/22	15/27	34/37	18/40	125/>300	Berzina et al. (1987), Sotnikov and Berzina (1993)
Volatiles in hydrothermal fluid						
$lg(f_{HCl}/f_{HF})$ Recorded by biotite	2.4–3.1	2.7–2.9	1.9–2.1	2.5–2.6	0.7–0.9	Sotnikov and Berzina (1993), Sotnikov et al. (2003a)
$lg(X_{HCl}/X_{HF})$ Recorded by apatite	0.8–1.4	0.7–1.2	0.5–1.1	0.6–1.1	<0.1	
Volatiles in magmatic fluid						
$lg(f_{HCl}/f_{HF})$ Recorded by biotite	3.5–4.1	3.2–3.9	3.1–3.5	3.2–3.6	1.8–2.4	Sotnikov and Berzina (1993), Sotnikov et al. (2003a)
$lg(X_{HCl}/X_{HF})$ Recorded by apatite	1.9–2.3	1.2–1.8	1.0–1.4	1.1–1.6	<0.5	
$(CO/CH_4)/CO_2$, fluid	0.02–0.04	0.03–0.05	0.28	0.08–0.3	0.1–0.2	Unpublished data[a]

[a] Results of gas chromatography (Institute of Geology, Novosibirsk, Russia).

activity in the fluids of Erdenetuin-Obo and Aksug deposits (Table 4) may suggest that the recorded Re-enrichment in these deposits may be related to the elevated fugacity of rhenium chlorides. These data fit to the experimental results of Xiong and Wood (2001, 2002), displaying that chloride complexity may have played an important role in the hydrothermal transport of Re, in the temperature range of 400 to 500 °C.

The Re contents in molybdenites may have been affected by the temperature or stage of deposition (Giles and Shilling, 1972; Newberry, 1979; Filimonova et al., 1984; Todorov and Staikov, 1985). The slight prograde solubility of ReS_2 in high-temperature (400 to 500 °C) environments means that more ReS_2 is dissolved at higher temperatures (Xiong and Wood, 2002), which may explain the lower Re content in molybdenites deposited at higher temperatures. However this regularity is not consistent over the all range of Cu–Mo porphyry deposits of the world. Popov (1977) showed that there is no correlation between Re content and temperature of molybdenite deposition at the Cu–Mo porphyry deposits of Armenia. The temperature of molybdenite formation (360 to 380 °C) at the Aksug and Erdenetuin-Obo deposits is lower than that of the studied Mo–Cu porphyry deposits (330 to 470 °C) and shows weak negative correlation with Re content in molybdenite (Table 1).

The distinct feature of Cu–Mo porphyry deposits is intense and widespread quartz–sericite alteration of

wall rocks. Mineral associations formed from highly acidic fluids are favorable for the Re accumulation in molybdenites (Ivanov and Yushko-Zakharova, 1989). Filimonova et al. (1984) investigated Cu–Mo porphyry deposits of Kazakhstan and concluded that, within individual deposits, Re contents in molybdenite derived from acid hydrothermal solutions are
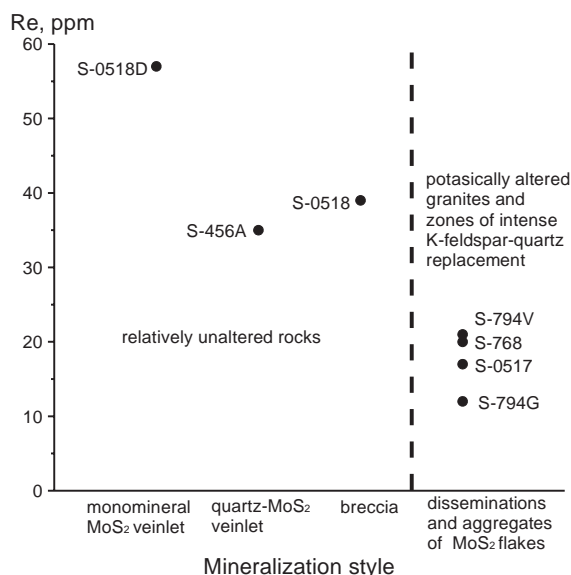

Fig. 12. Plot of mineralization style of molybdenite vs. Re content of molybdenites for the Zhireken deposit.

higher compared to those derived from alkali solutions. A predominance of K-feldspar altered rocks, formed by alkali hydrothermal solutions, is a characteristic feature of Mo–Cu porphyry deposits. Such an environment, dominated by alkali solutions, has the capacity for transporting Re and, as a result, may have caused a decrease of the Re content in molybdenite. Moreover, it seems to be consistent with the higher Re content (35 to 57 ppm) in molybdenites associated with breccia ores or quartz veins and monomineral molybdenite veinlets cutting unaltered granites (Table 2, samples S-0518, S-0158D and S-456A), compared to that of disseminated molybdenites (12 to 21 ppm) found in quartz–K-feldspar metasomatic rocks (Table 2; Fig. 12, samples S-794G, S-0517, S-768 and S-794V).

The decrease in Re content in molybdenite from zones of intense potassic alteration is also a characteristic feature for the Sora deposit. The minimum Re contents are fixed in molybdenites from central parts of breccia ore zone and zone of intense occurrence of quartz–molybdenite veins and veinlets (Fig. 13). It is

typical, that zones of intense potassic replacement are best developed within central parts of breccia ore zone and vein zone.

The Re distribution in molybdenite from porphyry Cu–Mo deposits is thus controlled by a complex interplay of several factors, including the composition of ore-forming solutions and host rocks, sources of the material, total molybdenite amount, temperature of deposition and variations of physical and chemical conditions of crystallization (fO_2, Cl activity, P, T).

8. Conclusions

Our compilation of new and previously published data leads to the following conclusions:

1. The maximum Re contents of molybdenite from Cu–Mo and Mo–Cu porphyry deposits of Siberia and Mongolia (460 and 199 ppm Re) were found in the Cu-rich (Cu/Mo=30 to 70) deposits of Aksug and Erdenetuin-Obo. The Re contents in
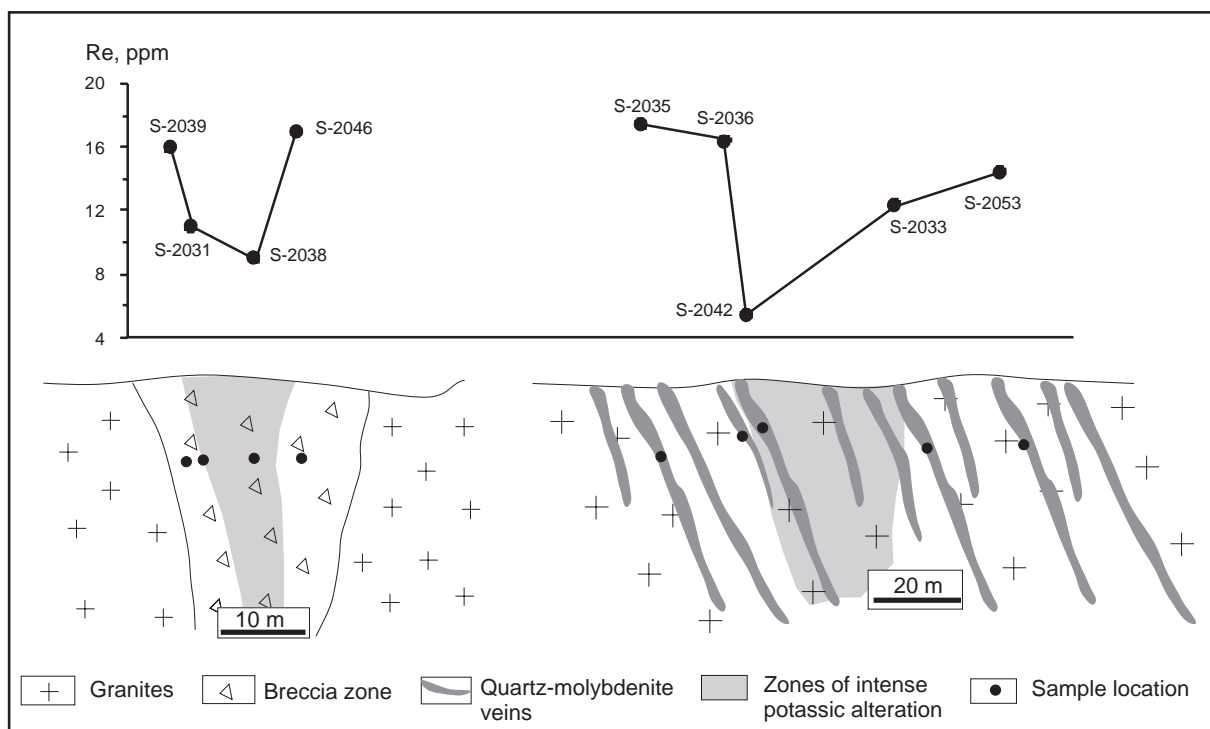

Fig. 13. Distribution of Re in molybdenite from the breccia zone (left) and zone of intense quartz–molybdenite veining (right), Sora deposit.

Mo-rich (Cu/Mo<1–4) deposits (Zhireken, Shakhtama, Sora) are only a few tens of ppm.

2. Major controlling factors of the Re distribution in molybdenite from porphyry Cu–Mo deposits may be the composition of parent magmas, the concentration of Re in ore-forming fluid and variations of physical and chemical conditions of crystallization (fO$_2$, pH, Cl activity, P, T).

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