Comparison studies of tin deposits (Priamurye, Russia) using the Aitchison's methodology

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Abstract

A study of tin deposits from Priamurye (Russia) is performed to analyze the differences between them based on their origin and also on commercial criteria. A particular analysis based on their vertical zonality is also given for samples from Solnechnoe deposit. All the statistical analysis are made on the subcomposition formed by seven trace elements in cassiterite (In, Sc, Be, W, Nb, Ti and V) using the Aitchison' methodology of analysis of compositional data.

Kew words: compositional data, total variability, Mahalanobis distance, linear discriminant analysis.

The main aim of the research is a statistical comparison study of tin deposits to establish differences between them and criteria of large deposits, and also the analysis of the vertical zonality of Solnechnoe deposit. Revealing the vertical zonality type of large tin deposits is based on three ore mineralization levels –an upper ore level, a middle ore level (a productive horizon) and a low ore level. These ore levels differ by the mineralization intensity and the content of the useful component– Sn, which is determined by different conditions of ore formation: temperature, Eh and pH parameters of ore-forming solutions. We emphasize that there is no clear interface between these levels because the ore-forming process is accompanied by the progressive change of the conditions from the high-temperature saturated solutions at the deep horizons to the low-temperature dilute ones at upper levels of deposits. It is very interesting to reveal how the evolution of ore-forming solutions reflects on the mineral composition.

1 Introduction

The study of ore deposits is of interest both form a theoretical and from a practical point of view, because it allows an approximation to the conditions of their formation and it can reveal criteria for the characterization of large commercial deposits. Those can be used when forecasting ore deposits. This problem is very important for the geology of ore deposits, but it is very complicated because every large deposit is unique and determined by many geological factors. Therefore, one of the most efficient approaches in the study of ore deposits is a statistical analysis and the mathematical modeling. Geochemical data give good results for the reconstruction of formation settings, as well as for the modeling of the evolution of ore-magmatic systems. The use of trace elements permits to analyze the regularity of the magmatic series and to reveal geodynamic settings of ore formation. When reconstructing the geodynamic environments of the ore-magmatic systems, one of the important approaches is the mathematical modeling of geochemical processes by methods based on multivariate statistics. As shown by the previous results (Tolosana-Delgado and others, 2004; Gorelikova and others, 2004), a geometric approach based on Aitchison geometry is very powerful when studying geochemical data. This research concerns tin deposits from Komsomol'sk region of Priamurye (Russia). Within Komsomol'sk ore region, tin deposits are represented by cassiterite-silicate-sulphide ores deposited by thin quartz-tourmaline veins formed as the result of the intensive boron metasomatism. Komsomol'sk ore-magmatic system has been studied in great depth in the Far East.

2 Study area

Tin deposits of Priamurye (Solnechnoe, Festival'noe, Pereval'noe, Pridorozhnoe, etc.) are formed in the age interval 102-84 Ma. Petrochemical and geochemical data of magmatic complexes and ore

associations characterize the Komsomol'sk ore-magmatic system as a heterogeneous mantle-crust. Tin deposits are located in terrigenous rocks of the Jurassic and Cretaceous volcanics. The main ore mineral in veins is cassiterite that formed at the early stage jointly with quartz and early sulphides. The cassiterite content determines a commercial value of tin deposits. As the objects of this study we chose both large deposits (Solnechnoe, Festival'noe, Pereval'noe, Pridorozhnoe) and small ones (Lunnoe, Oktyabr'skoe, Ozernoe, Chalbinskoe).

Within the Komsomol'sk ore region there are three ore clusters: Silinsk, Levo-Khurmulinsk, and Chalba.They are related to magmatism areas with the different magmatism intensity. Morphologically, ore structures are linear stockworks composed of quartz-tourmaline metasomatites cut by quartz vein series with cassiterite, sulphides, and carbonates. The zones have the considerable differences in the composition.

Solnechnoe deposit is located in a strata of sedimentary rocks of the Jurassic age above the protrusion of a granite batholith within the Mayo-Chan volcanic zone being a part of the Khingano-Okhotsk belt (Korostelev and others, 2001). At the deposit there are two mineralization stages. An early stage is represented by rare-metal greisens with molibdenite, sheelite, arsenopyrite, pyrhotite, pyrite, chalcopyrite, native Bi and Au, Bi sulphotellurides, etc. The age of the molibdenium mineralization is 86-84 Ma. The later productive stage is formed by thick and extend quartz-cassiterite-sulphide veins with wolframite.

Pridorozhnoe deposit is situated in sedimentary rocks of the exocontact and granodiorites of the Silinsk massif and has some tin zones from which we consider Pridorozhnaya and Central. The ore veins have quartz-cassiterite-sulphide composition with sheelite. At the deep horizons there are abundant sulphides especially sphalerite and chalcopyrite that are closely related to carbonates such as siderite and oligonite which could suggest the reverse vertical zonality or the own right cassiterite-sulphide stage.

Festival'noe deposit is located in the meridional linear Perevalnensk ore structure in the Jurassic terrigenous-volcanic rocks of the Cretaceous age. We studied Yagodnaya and Vodorazdel'naya zones which are represented by the copper-tin-sulphide ores. The mineral composition is rather various. Festival'noe Cu-W-Sn deposit is characterized by abundant arsenopyrite, wolframite, sheelite, pyrrhotite, pyrite, stannite, and Bi minerals including the native Bi. It has a low Sb content. The deposit is characterized by a clear vertical zonality resulted from the host rock lithology, namely, at the upper horizons in the volcanic rocks W-Sn-Cu ores prevail while at the low horizons in sedimentary rocks there are W-Sn ones.

Pereval'noe deposit is arranged in the northern part of the Komsomol'sk region within the large Amut syncline composed of the thick volcanic choldamy and amut series of the Cretaceous age. Severnaya zone is the main at the deposit and its extension is more than three km. It composed of quartz-tourmaline-sulphide ores. The mineralization zone has a complicated morphology and is constituted of a thick vein of quartz-chlorite metasomatites cut by cassiterite-quartz veinlets with sulphides among which galena, sphalerite, and stannite prevail. Based on a study of the structural morphological features of ores it could be believed that that the formation of Pereval'noe deposit was proceeding into some stages: 1) the quartz-tourmaline stage; 2) the quartz-cassiterite one with wolframite, arsenopyrite, sericite; 3) qurtz-carbonate-sulphide stage; 4) the calcite one with chalcedony, pyrite, marcasite. Maiskaya zone is positioned in sedimentary rocks and has a lot of tourmaline and arsenopyrite, pyrrhotite, chalcopyrite, and boulangerite with a little content of quartz.

Lunnoe deposit is placed within the northern part of the Amut structure in sedimentary rocks and choldamy volcanics. Tropnaya and Lunnaya zones occur in quartz-tourmaline metasomatites cut by quartz-sulphide ores with disseminated cassiterite. The ores are poor with a low tin content.
Oktaybr'skoe deposit is related to the Pridorozhnaya structure and is shown in series quartz-tourmaline zones in choldamy volcanics and partially in sands. The composition is rather simple and involves quartz, chalcopyrite, pyrrhotite; cassiterite and wolframite are rare. The deposit is small on the tin reserves. We study only Levoberezhnaya zone.

Chalbinskoe deposit is located in the south-western part of the Komsomol'sk region and involves Shirokaya, Poiskovaya, and Marsovaya zones that have a higher temperature of formation and a low sulphide content. It is arranged in the contact zone of a large granite massif. Shirokaya zone occurs in the Jurassic hornfels and has a complex morphology. The mineral composition is various and involves quartz-feldspar, quartz-tourmaline associations with rare cassiterite, wolframite, micas, and sulphides.

Poiskovaya zone is represented by a series of echelon-like veins of quartz-tourmaline composition. Marsovaya zone is a funnel-like body of breccia. At the surface there are two small tin plots with a poor cassiterite.

Ozernoe deposit is located in the Pridorozhnaya structure and has essentially polymetal composition with a predominance of galena and sphalerite. The ores are a peculiar kind of type. There are a lot of fluorite in quartz veinlets. Cassiterite is rare mineral in veins. The deposit is very small.

3 Data base

As the objects of this study we chose both large commercial deposits (Solnechnoe [1], Pridorozhnoe [2], Festival'noe [3], Pereval'noe [4]) and small noncommercial ones (Lunnoe [5], Oktaybr'skoe [6], Chalbinskoe [7], Ozernoe [8]). The compositional data set is represented by the geochemical data (288 samples) formed by trace elements in cassiterite (In, Sc, Be, W, Nb, Ti and V). Trace elements are determined by the quantitative spectral analysis.

The main aim of the research is a statistical comparison study of tin deposits to establish differences between them and criteria of large deposits, and also the analysis of the vertical zonality of Solnechnoe deposit. Revealing the vertical zonality type of large tin deposits is based on three ore mineralization levels –an upper ore level, a middle ore level (a productive horizon) and a low ore level. These ore levels differ by the mineralization intensity and the content of the useful component– Sn, which is determined by different conditions of ore formation: temperature, Eh and pH parameters of ore-forming solutions. We emphasize that there is no clear interface between these levels because the ore-forming process is accompanied by the progressive change of the conditions from the high-temperature saturated solutions at the deep horizons to the low-temperature dilute ones at upper levels of deposits. It is very interesting to reveal how the evolution of ore-forming solutions reflects on the mineral composition.

4 Statistical methodology

To analyze this large compositional data set we have applied the Aitchison' methodology (Aitchison, 2986; Barceló-Vidal and others, 2002) to the subcomposition formed by the seven trace elements before mentioned. This methodology is based in the standard statistical analysis in the real space of the clr-transformed data set and the reinterpretation of results in the simplex space.

5 Results

The statistical analysis of data shows a complicated character of the distribution and the correlation between groups of deposits examined. The total relative variability is equal to 4,36, being Nb, V, Ti and Be the components which more contribute to this high variability (Table 1). The biplot of Figure 1 captures only 58% of the total relative variability. In spite of it, it suffices to put in evidence that the eight deposits are not well separated by the trace elements in cassiterite.

Table 1. Variances of clr transformed data

	In	Sc	Be	W	Nb	Ti	V	Total
Global	0,3798	0,4744	0,7848	0,4557	0,8622	0,6443	0,7574	4,3586
Commercial	0,3760	0,3444	0,5465	0,4379	0,7861	0,6545	0,7457	3,8911
Noncommercial	0,3995	0,9688	1,6566	0,4676	1,1252	0,5984	0,7940	6,0102

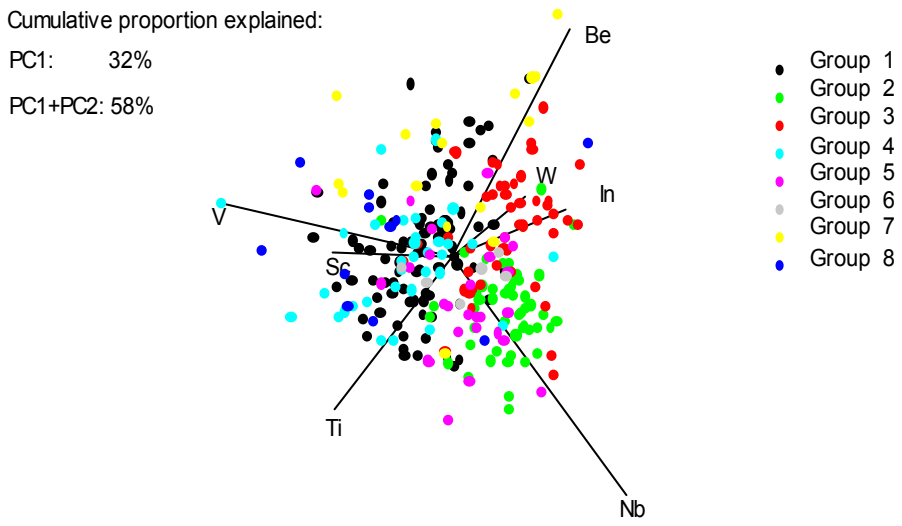

Figure 1. Biplot of all 288 samples (colors corresponds to different deposits)

The squared Mahalanobis distance (MhD^2) between each pair of deposits (Table 2) gives a first approach about the similarity of them. The MhD^2 varies from 2,11 (between Solnechnoe [1] and Pereval'noe [4] deposits) to 18,45 (between Oktaybr'skoe [6] and Chalbinskoe [7] deposits). A step by step discriminant analysis between each deposit and the rest of deposits allows us to establish a rank of deposits from more differentiate to the more similar ones (Table 3). From this two tables it can be concluded that various deposits have both the similar features and the differences ones. Thus, Solnechnoe and Pereval'noe are the most similar because they are related to the same structure. Pereval'noe and Ozernoe deposits seem to be poor differenciate, Pridorozhnoe and Chalbinskoe ones seem to be the most different from other deposits. Chalbinskoe deposit most differs from other deposits because it is characterized by the higher temperature formation and the greisen-like type of mineralization. Festival'noe deposit has a specific ores with a high content of Cu minerals and stannite. Severnaya zone from Pereval'noe deposit has also the distinctive property enclosing cassiterite-feldspar composition of ore. Besides, the lithological factor plays the important role when forming the mineralization. Some zones occur in sedimentary rocks such as Solnechnoe, and another zones are connected with volcanics (Pereval'noe, upper horizons of Festival'noe deposit, Severnaya zone, Ozernoe, Oktaybr'skoe deposits) and magmatic rocks (Pridorozhnoe and partially Solnechnoe deposits). The most contrast differences there are observed in the mineral composition of ores. Chalbinskoe deposit involves high-temperature minerals, ores of Festival'noe deposit have a higher content of Cu, in Severnaya zone there are quartz-micas-feldspar association, within Ozernoe deposit the polymetal mineralization with fluorite prevails. This clearly demonstrates that every deposit has own distinguishing characteristics. And we cannot expect a full similarity of deposits.

Table 2. Squared Mahalanobis distance (MhD^2) between each pair of deposits

MhD^2	Solnechnoe [1]	Pridorozhnoe [2]	Festival'noe [3]	Pereval'noe [4]	Lunnoe [5]	Oktaybr'skoe [6]	Chalbinskoe [7]	Ozernoe [8]
Solnechnoe [1]	--	11,94	5,49	2,11	4,85	7,80	4,25	3,56
Pridorozhnoe [2]	11,94	--	4,64	9,76	6,06	11,30	13,60	17,25
Festival'noe [3]	5,49	4,64	--	5,24	5,79	3,33	8,93	8,54
Pereval'noe [4]	2,11	9,76	5,24	--	3,03	4,94	8,12	0,47
Lunnoe [5]	4,85	6,06	5,79	3,03	--	5,91	11,35	3,52
Oktaybr'skoe [6]	7,80	11,30	3,33	4,94	5,91	--	18,45	4,14
Chalbinskoe [7]	4,25	13,60	8,93	8,12	11,35	18,45	--	6,16
Ozernoe [8]	3,56	17,25	8,54	0,47	3,52	4,14	6,16	--

Table 3. Rank of deposits from more differentiate to the more similar ones. Under each deposit there is the MhD^2 between the deposit and the rest of deposits in the list.

Chalbinskoe [7]
└ 6,45 →
Pridorozhnoe [2]
└ 4,54 →
Festival'noe [3]
└ 3,91 →
Oktaybr'skoe [6]
└ 3,61 →
Lunnoe [5]
└ 3,52 →
Solnechnoe [1]
└ 1,97 →
Ozernoe [8]
└ 0,47 →
Pereval'noe [4]

The comparative analysis of commercial (Solnechnoe [1], Pridorozhnoe [2], Festival'noe [3], Pereval'noe [4]) and noncommercial (Lunnoe [5], Oktaybr'skoe [6], Chalbinskoe [7], Ozernoe [8]) tin deposits gives the following results. The squared Mahalanobis distance between the two groups is very small (MhD^2 =0,8066) and therefore the two groups are not well separated. The centers of the two groups (Table 4) and the biplot of Figure 2 confirms this result. Nonetheless, they differ on the amount of some trace elements such as Ti and V, more abundant in noncommercial deposits. Moreover it should be pointed out that the total variability of the noncommercial deposits is higher than the total variability of the commercial ones (6,01 versus 3,89). It means that the compositions of commercial deposits are more homogenous than those belonging to noncommercial deposits (Table 1). The relative variability of Sc, Be, and Nb is higher in noncommercial than in commercial ones.

Table 4. Centers of global, commercial and non commercial deposits

	In	Sc	Be	W	Nb	Ti	V	Residual
Global	0,1192%	0,1134%	0,0112%	15,7181%	1,2796%	6,6695%	0,3993%	75,6897%
Commercial	0,1117%	0,1083%	0,0101%	15,7280%	1,2639%	6,0929%	0,3642%	76,3208%
Non commercial	0,1508%	0,1338%	0,0164%	15,5860%	1,3316%	9,2806%	0,5591%	72,9418%

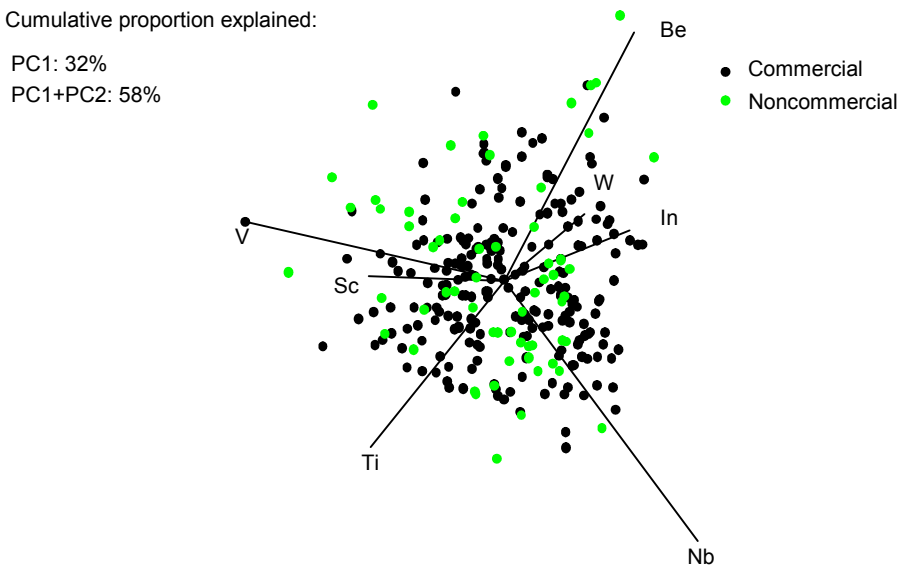

Figure 2. Biplot of all 288 samples (the two colors corresponds to commercial and noncommercial deposits).

The comparative analysis of the three levels -upper, middle and low- of the 71 samples from Solnechnoe deposit in central zone yields the following results. From Table 5 we observe that the centroide of samples from middle level differs from the other two centers by the small relative amount of W. The centers of upper and low levels mainly differ mainly in the small relative amount of Be in the low level. In spite of that, the three levels are note well separated just as can be deduced from Table 6: the squared Mahalanobis distances are very small and the misclassification rate (from a linear discriminant analysis) are very high.

Table 5. Centers of the three levels of samples from Solnechnoe deposit

	In	Sc	Be	W	Nb	Ti	V	Residual
Upper	0,0870%	0,1150%	0,0170%	18,6650%	0,6650%	6,4820%	0,4230%	73,5450%
Middle	0,0900%	0,1240%	0,0060%	11,8210%	0,6710%	7,8910%	0,5470%	78,8490%
Low	0,0610%	0,0930%	0,0060%	17,0520%	0,6070%	7,3560%	0,7520%	74,0720%

Table 6. Squared Mahalanobis distance (MhD^2) and misclassification rate between each pair of levels in Solnechnoe deposit

MhD^2 Misclassification rate (%)	Upper level	Middle level	Law level
Upper level	--	3,07 28,6%	4,08 22,3%
Middle level	3,07 28,6%	--	4,64 17,5%
Law level	4,08 22,3%	$,6417,5%	--

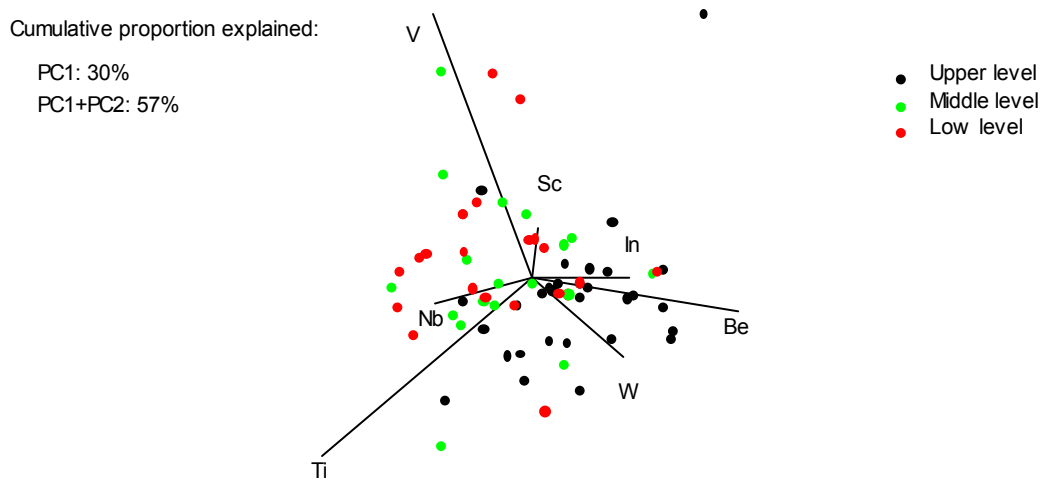

Figure 3. Biplot of 71 samples from Solnechnoe deposit (the colors corresponds to the three origin levels of samples).

6 Conclusions

The mathematical analysis performed emerged that every deposit is characterized by the peculiar features and there are more similar deposits and more distinctive ones. The first results of the hierarchical discriminant analysis of tin deposits from Komsomol'sk region elucidated that the dissimilarity between deposits are explained by different geological factors such as the distance from the magmatic chamber, the host rock lithology, and the conditions of ore-forming processes. These factors influence on the mineral composition of veins. The main aim of this study is to clear up the common features inherent in tin deposits of this region and separate the essential characteristics typical of commercial deposits as compared with noncommercial ones. The challenge of this problem lies in the combined effect of all geological factors influencing on the mineral composition. The similarity of tin deposits is graphically confirmed by the biplots and the composition of deposits' centers. But there are essential differences between commercial and noncommercial deposits which appear in relative variability of Sc, Be, Nb and the centers of some elements such as W, Ti, In. This study could be consider as a preliminary work. The task of the further research is revealing the criteria of large commercial tin deposits.

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