(5) The changes in mineral assemblages in the ores are controlled (under constant P–T conditions and solution composition) by hydrodynamic factors. Changes in the filtration regime (increase in one of the flows) results in the precipitation of different mineral associations in the volume of the draining fractures: calcite veins with ore mineralization, mono- and polymineralic ores, or barren gangue material.

(6) Hydrothermal systems of this type can operate over significant time spans if there are replenishable solution resources and a long-lived regional thermal anomaly. Interruptions in the deposition of ore minerals and reactivation of the system in response to tectonic rejuvenation of solution pathways results in the telescoping of ore edifices.

PART 3:
GENESIS OF ORE MINERALIZATION UNDER A TEMPERATURE (PRESSURE) GRADIENT

After simulating ore-forming processes under isothermal conditions, we developed and analyzed a model for the genesis of ore mineralization under a gradient in the temperature field. As illustrative examples, we selected vein base-metal (Pb–Zn) deposits typical of the Sadon mining district in North Ossetia: Kholst, Verkhnii Zgid, Arkhon, and Dzhimi.

Base-metal ore deposits in North Ossetia have been studied since the beginning of their active mining in the 20th century. The descriptions of some of these deposits (Sadon and Zgid) became classic and were included in textbooks and fundamental monographs [Smirnov, 1976, 1978]. There are hundreds of volumes of deposited materials containing detailed descriptions of the structures, mineralogy, geochemistry, data on fluid inclusions, and metallogeny of deposits of the Sadon group. Much of this information was published in monographs, reviewing papers, and dissertations and included the structural setting of the deposits [Nekrasov, 1980], the metallogeny of the area and the ore zoning [*Geology and Mineral Resources of North Ossetia*, 1969; Lyakhov *et al.*, 1994], data on fluid inclusions [Lyakhov *et al.*, 1994; Laz'ko *et al.*, 1981], geochemistry and primary aureoles [Kuikin, 1966; Gorzhevskii *et al.*, 1987; Grigoryan, 1987; Trofimov and Rychkov, 1979, 1988]. The amount of the currently available primary information seems to be sufficient for developing a generalized genetic model of the genesis of these deposits. Synthesis and generalizations of this type were carried out, within the scope of certain geological schemes, by Smirnov [1976]. However, it is now quite obvious that no quantitative collected theory of geochemical processes can be constructed purely intuitively, i.e., based on geologic observations alone, without reference to the laws of physical chemistry. However, no quantitative physicochemical modeling of the genesis of these deposits has ben conducted as yet.

Most steeply dipping veins at these deposits are hosted by Middle–Upper Paleozoic granites. The granite massif is localized near the axial part of the Sadon–Unal anticline. The main rock-forming minerals of the granite are quartz (25–45 wt %), plagioclase (25–40%, oligoclase An_{22-26}), orthoclase and microcline (20–25%), and muscovite and biotite (<7%). The massif is dominated by medium-grained granite. The metasomatic alterations of granite near the veins involve its silification, chloritization, serpentinization, and carbonatization. Granite outcrops are surrounded by thick zones of tuff, fine-grained tuff-breccia, and, more rarely, andesite-dacitic porphyry lavas and Jurassic sedimentary rocks. The ore mineralization is concentrated more in granites than in porphyritic lavas [Nekrasov, 1980]. At the deposit, a significant role is played by the Sadon–Unal fault of pan-Caucasian trend, which truncates the granite in the south. The orebodies fill shear and detachment fractures trending NE and NW and branching from the footwall of the fault. Large east–west-trending faults could serve as ore conduits [Nekrasov, 1980].

According to the data of most researchers, the deposit is of pre-Callovian age, which corresponds to the postkinematic stage of the Cimmerian metallogenic epoch [Khetagurov *et al.*, 1992]. All veins are nearly vertical and vary from 0.1 to 5.0 m or more in thickness. Mining work has expose veins over length intervals of more that 1100 m downdip (Verkhnii Zgid) and more than 4000 m along strike (Sadon). The ores consist of galena, sphalerite, pyrite, chalcopyrite, and pyrrhotite with gangue quartz, chlorite, carbonates, and others. Available geological–mineralogical data and results obtained by studying fluid inclusions [Laz'ko *et al.*, 1981; Lyakhov *et al.*, 1994] indicate that the processes that formed ore mineralization at these deposits were quite uniform and proceeded under similar physicochemical parameters: the overall temperature range was 415–65°C (345–120°C for the quartz–galena–sphalerite mineral stage) at pressures of 230–11 MPa. Numerous analyses of gas–liquid inclusions [Lyakhov *et al.*, 1978, 1994] point to their chloride-dominated composition (>50% chlorides). Schematic geological profiles across the Kholst, Arkhon, and Verkhnii Zgid deposits are shown in Fig. 36.

The primary aureoles of the deposits were examined by several researchers [Kuikin, 1966; Gorzhevskii *et al.*, 1987], who pointed out that the thicknesses of near-vein aureoles only occasionally exceed a few dozen meters. However, the lack of detailed data on the aureoles forced us to conduct additional geochemical examinations in order to identify regularities in the distribution of elements in the nearest space around the veins, where it is reasonable to expect that the effect of chemical interaction between the host granite and hydrothermal fluid should have been at a maximum.

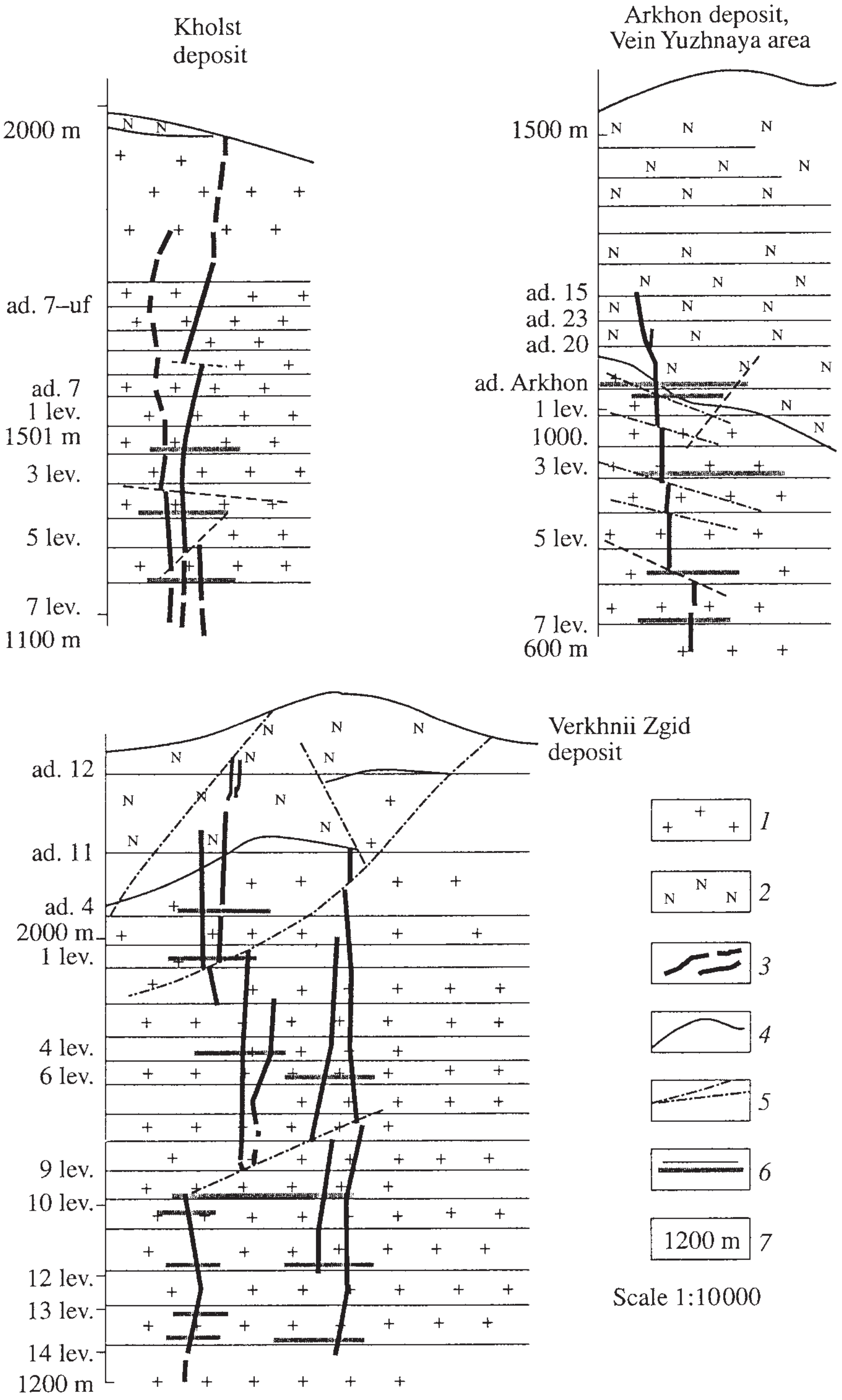

Fig. 36. Geological profiles across the Kholst, Arkhon, and Verkhnii Zgid deposits, Sadon mining district, North Ossetia [Rekhviashvili *et al.*, 1990]. (*1*) Granite; (*2*) porphyry sheets; (*3*) mineralized veins with base-metal mineralization; (*4*) rock contacts; (*5*) faults; (*6*) mining levels (solid lines) and sampling areas (gray shading); (*7*) topographic elevation. Abbreviations: lev.—mining level; ad.—adit.

The examination of models for the genesis of U ore mineralization (see Chapter 3, Section 3.4) indicates that the filtration-controlled acid leaching of rocks is coupled with the significant redistribution of ore elements contained in these rocks in clarke concentrations. The resulting aureoles have complicated structures, which are highly sensitive to the conditions of interactions in the solution–rock system and depend on the composition of the initial hydrothermal fluid. Our thermodynamic simulations were carried out at 150°C

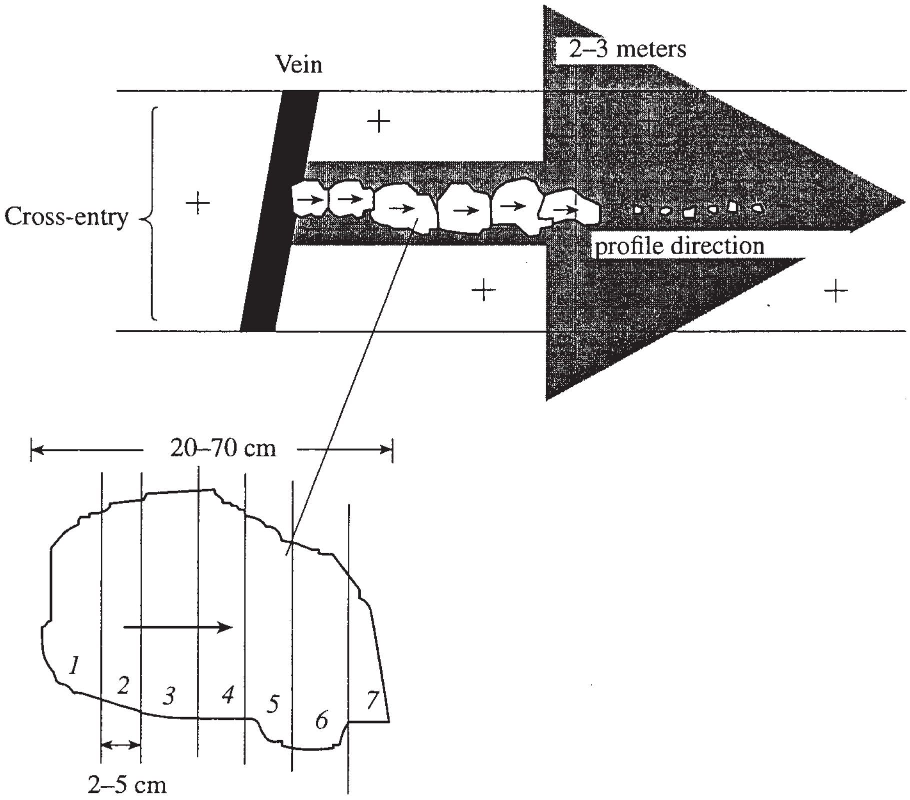

Fig. 37. Techniques of field sampling and subsequent sample processing. Oriented monolithic rock blocks were sampled within 2–3 m from the vein; at the office, the blocks were cut into individual samples with a step of 2–5 cm with a diamond saw; the samples were documented and described, crushed, and powdered (arrows indicate the orientation of the monolithic block and samples relative to the vein; numerals are sample numbers in a given monolithic block). Intervals from 2–3 to 15–20 m were sampled with the discontinuous trenching technique with a step of 0.5–1 m.

in the system liparite–barren solution filtering through it. The simulations point to the existence of a few zones in U and Pb redistribution in the wall-rock liparite and the possibility of shifts in the spatial position of these zones. This led us to suggest that it is also possible to solve the inverse problem, to identify the conditions of ore formation based on the detailed structural data on the aureoles. We were not aware of any other studies centered on examining aureoles by analogous techniques and, hence, were impelled to develop a new system of aureole studying that could reveal (not overlook) details of metal distributions in the wall rocks.

Currently existing techniques of studying primary aureoles make it possible to recover only part of information "recorded" in them. These techniques are usually aimed at achieving purely applied tasks of prospecting geochemistry and only rarely can be used to solve genetic problems. We proposed another approach to reproducing the conditions and mechanisms responsible for the formation of orebodies and primary aureoles at hydrothermal deposits. This approach is based on a combination of the geochemical examination of the fine structures of primary aureoles and analysis, by means of computer thermodynamic simulations, of processes occurring in the hydrothermal system. In other words, proceeding from study of the aureoles, we attempted to reconstruct the development of ore mineralization at the deposit.

CHAPTER 5
REGULARITIES IN THE DISTRIBUTION OF ELEMENTS IN THE NEAREST WALL ROCKS AT HYDROTHERMAL Pb–Zn DEPOSITS

5.1. Methods of Field Research and Processing of Primary Geochemical Data

We developed a method for the detailed examination of fine structures in the primary aureoles: oriented host-granite blocks were continuously sampled over profiles 2–3 m long, then the rock blocks were subdivided into discrete samples with sampling sites spaced 2–5 cm apart [Borisov and Goreva, 1994; Borisov *et al.*, 1995b; Borisov, 1997, 2000a]. The profiles were sampled across the strikes of vein orebodies along the walls of cross-entries, the insets of drifts, or, more rarely, in the roofs of mine workings (Fig. 37).

The very first two pilot profiles were sampled with a step of 2 cm (Figs. 38, profiles *1* and *2*, 41, and 43 also). The mathematical processing of the primary geochem-

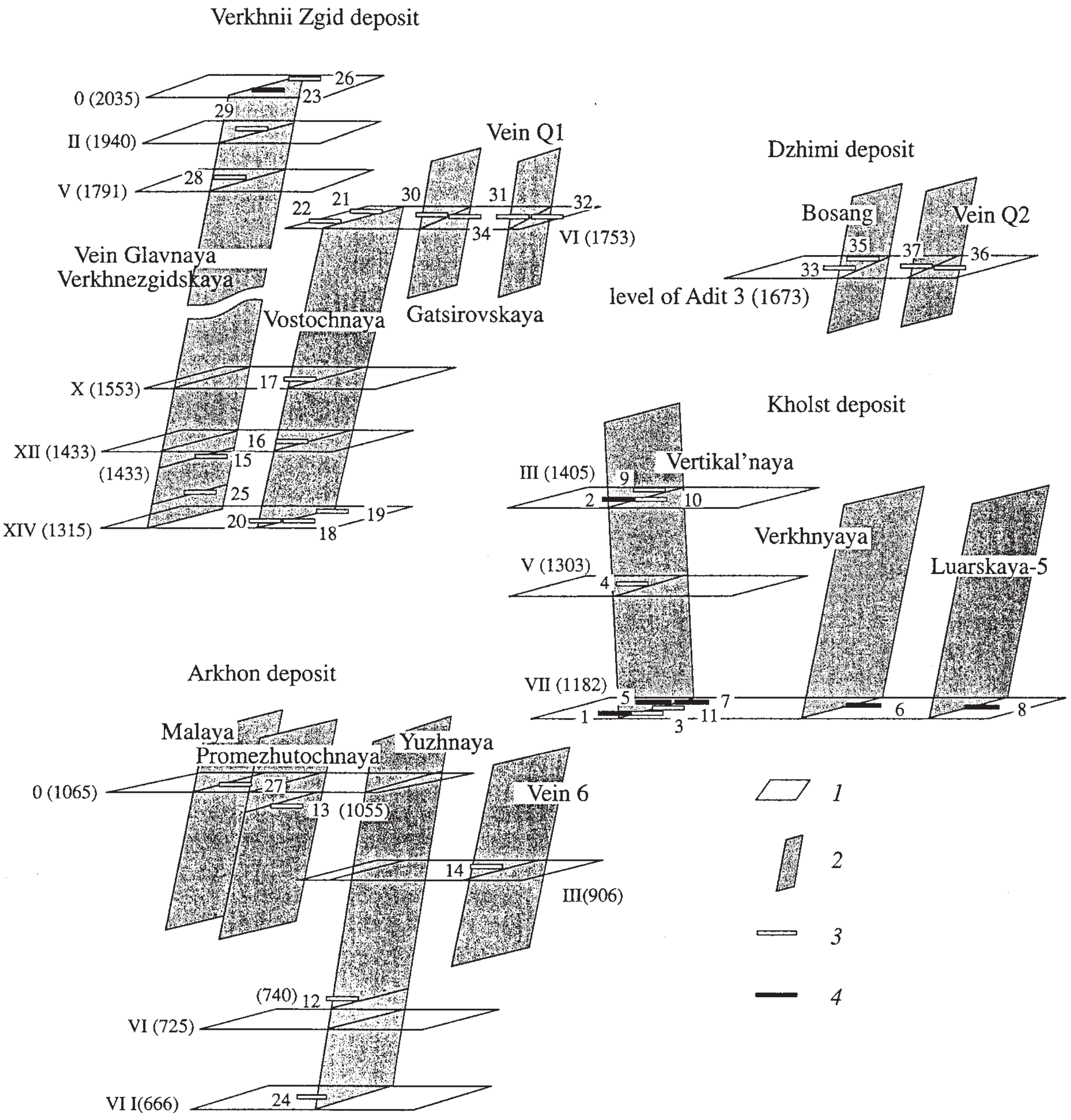

Fig. 38. Schematic diagrams showing the location of the profiles studied for this research at deposits of the Sadon group. (*1*) Levels, numbers, and elevation above sea level are indicated; (*2*) vein body (schematic representation keeping the actual positions of the hanging and foot walls); (*3*) sampling profiles 2–3 m long (continuous sampling) and their field numbers; (*4*) the detailed profile is appended with discontinuous trench sampling (to a length of 20–30 m).

ical data (discretization into equal sampling steps, which was needed for correlation analysis, and treatment with the running window technique) indicates that valuable information is not overlooked even if the sampling step is increased to 5–7 cm. Because of this, most profiles were sampled with an average step of 5 cm; i.e., the sampling density was 35–45 samples per 2 m of the profile on average. The processing of wall-rock blocks at the field office involved measuring and megascopical describing them, cutting them into discrete samples by a stone-impregnated circular saw (all samples comprise a continuous succession, see Fig. 37), and selecting material for oriented thin sections and samples. The primary samples ranged from 0.4 to 1.5 kg. After crushing to fractions of less than mm, the samples were quartered and brought up to 100 g in mass. Samples of this mass were ground in the field on a vibrational grinder. The samples thus prepared were analyzed by quantitative emission spectral analysis or semiquantitative analysis on the Bronnitsy Geological–Geochemical Expedition of the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements and, partly, at the laboratory of the Department of Geochemistry of the Moscow State University. The bulk-rock composition of the vein material at the sampling sites was analyzed by X-ray spectral analysis of composite vein samples at the Department of Geochemistry, Moscow State University.[12] The samples taken along the profiles were also used to measure their filtration characteristics. These measurements began in 1995 with the assistance of V.M. Shmonov of the Institute of Experimental Mineralogy, Russian Academy of Sciences [Shmonov *et al.*, 1996, 2002].

Currently we possess data characterizing 37 detailed profiles across the wall rocks at different topographic levels of 14 orebodies at four deposits (Kholst, Zgid, Arkhon, and Dzhimi). The primary materials comprise approximately 1900 samples (wall rocks and veins), more than 250 hand specimens, and 700 petrographic thin sections and polished sections. Part of the profiles over intervals of 2–20 m were sampled using the dotted trench technique with steps of 0.5 and 1.0 m. The first cycle of data processing involved information on three elements: Pb, Zn, and Cu. Figure 38 schematically depicts the position of the profiles relative to the orebodies. The sampling profiles were unequally distributed between the deposits (11 for Kholst, 5 for Arkhon, 17 for V. Zgid, and 4 for Dzhimi), but all of them characterize the footwalls and hanging walls of the orebodies at their different topographical levels, within the intervals of both the economic ore mineralization and the orebody pinchout. Most of the profiles were run across the Vertikal'naya Vein at the Kholst deposit (nine profiles at three levels) and the Vostochnaya Vein at the Verkhnii Zgid deposit (seven profiles at four levels) (Fig. 38). Geological schemes of the deposits are presented in Fig. 36.

Some samples were taken separately for determining the background concentrations of elements in the country rocks. These samples were usually composed of 10–15 rock chips with a total mass of 5–7 kg, sampled over intervals of 5–10 m in mining work. The background concentrations determined on four samples taken at different levels of the Kholst mine were 0.004 ± 0.0005% for Zn, 0.003 ± 0.0003% for Pb, and 0.002 ± 0.0005% for Cu.

All analyses made in different years were brought to a single sampling by introducing correction coefficients for systematic errors. The analyses were then input into a database (written in Exel) and treated with a set of computer programs (discretization of the concentrations of elements into a single sampling step, running window technique, correlation analysis, construction of plots of the distributions of elements, trends, analysis of the autocorrelation functions, etc.).

Data on the aureoles are appended by the results on the regularities of element distributions and variations in the chemistry of minerals in the vein bodies. We began to thoroughly examine the fine geochemical structures of the veins in 2000, following the progress achieved in developing the methods and accumulation of data obtained by simulating the processes forming filling veins.

5.2. Regularities in the Distribution of Elements

None of the profiles contained rocks without traces of metasomatic alterations (even at distances as great as 200–500 m from the veins). The intensity of the alterations varied, as did the associations of newly formed metasomatic minerals (mostly quartz, sericite, and chlorite). For example, the situation at the Kholst deposit is as follows (units are listed in ascending order). Level VII (lowermost at this deposit): all profiles intersect a rear zone of metasomatically silicified granite, then a zone of sericite–chlorite alterations (often with large, up to 5 mm, muscovite segregations), and a zone of weak silification (traced within 130 cm from the vein), which is the most clearly pronounced in profiles across the hanging wall of the Vertikal'naya Vein (profiles 7, 11, 3). Level V: metasomatic alterations are the same as at level VII, but the silification in profile 4 is more intense than in profiles in the footwall (profiles 1 and 5) of the lower level. Level III: profiles 2, 9, and 10 are noted for the least altered rocks (chloritization alone). The distribution of metasomatic alterations at the Zgid deposit is different. Level XIV (lowermost): sericitization, chloritization, and weak silification (profiles 18, 19, and 20). Levels XII, X, and VI: all profiles (15, 16, 17, 21, and 22) intersect a rear zone dominated by quartz, which gives way to sericite–chlorite metasomatic alterations. Level 0: the strongest silification, which completely transforms the country rocks within 10 m and more from the vein. The data available on the Arkhon deposit characterize only five profiles near different orebodies. The following features are characteristic of this deposit: the most intense silification was detected along profile 24 (lowermost, level VII); the least intense metasomatic alterations are typical of the rocks in profile 13 (level 0). None of the profiles intersected sharp boundaries between metasomatic zones, whose transitions are always gradual (patches, fragments).

The macroscopic descriptions of country-rock hand specimens sampled along the profiles and the examination of the rocks in thin and polished sections indicate that the main modes of Zn, Pb, and Cu occurrence in the veins and aureoles are sulfides. These data also testify to the fact that the rocks contain no stringers with ore sulfides, which could be formed in splay fractures around the main vein. Ore-element sulfides occur in the country rocks mostly in the form of sphalerite and galena dissemination, pockets, and "vermicular" segregations.

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[12] Composite samples were 10-kg rock samples taken over the whole vein interval near the starting sampling site of a profile across the wall rock. These samples consisted of 15–20 chips of the vein material, which were crushed, quartered, and ground.

The analysis of Zn, Pb, and Cu distribution in the wall rocks of steep Pb–Zn orebodies (111 monoelemental samplings for 37 profiles) and comparison between the proportions of the metals in veins and adjacent aureoles allowed us to distinguish the following features of their structures, which were not known before.

(1) All of the Zn, Pb, and Cu aureoles can be subdivided into two types:

A-type aureoles with distributions close to the exponential law (the maximum metal concentrations are found in the very first wall-rock sample, taken near the vein selvage, with these concentrations decreasing away from the vein).

B-type aureoles with metal distributions of other types (maxima of metal concentrations are shifted away from the vein selvages for different distances).

Figures 40–43 illustrate the distributions of types A and B. The objects examined at all three deposits considered together and at each of them separately are dominated (75–80%) by aureoles of type B (Figs. 39a, 39b).[13]

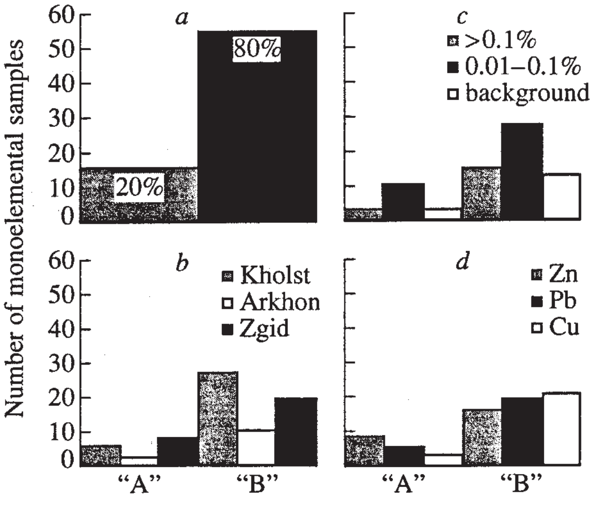

Fig. 39. Frequency of occurrence of two aureole types (as determined from 72 monoelemental samples for 24 profiles). (*a*) General position of the two types of aureoles; (*b*) distribution of the two aureole types between the deposits; (*c*) distribution of the two aureole types in terms of metal content in the main maxima; (*d*) distribution of Zn, Pb, and Cu aureoles between the types.

Figure 41 illustrates Zn distribution that can be ascribed to type A. The Zn concentration near the vein contact attains 0.35 wt % and gradually decreases to the background value within one meter from the vein. The wall-rock alterations comprise a rear zone of weakly silicified granite, which gives way to sericite–chlorite alterations. The Pb and Cu concentrations along the profile are much lower than the Zn concentration, and their distributions belong to type B.

The distribution portrayed in Fig. 42 (type B) is characterized by relatively low Zn concentrations near the vein and enriched (up to disseminated ore with concentrations up to 1.5 wt %) intervals at a distance of 20–30 cm from the vein. Another, lower discernible maximum of intensity occurs at a distance of approximately 50 cm. The distribution patterns of all three metals in this profile are practically the same, but the highest Pb concentration is four times lower that the analogous value for Zn, and the Cu concentration is eight times lower. The metasomatic alteration degree of granite in such profiles is at a maximum: silification, sericitization, chloritization, and carbonatization. The disseminated ore consists of galena and sphalerite pockets. The concentrations of the metals in the aureoles are only very rarely higher than 1%. In the 19 profiles in which the concentration of one of the ore elements is higher than 0.1 wt % (Fig. 39c), values >1% were encountered only in two situations (for Zn in profiles 3 and 4 at Kholst).

Figure 43 presents another illustration of a B-type distribution, which is characterized by metal concentrations at the background level or lower throughout the whole profile (the Zn concentration in the vein adjacent to profile 2 is as high as 5.3 wt %) and clearly pronounced, but weak in magnitude (from $n \times 10^{-3}$ to $n \times 10^{-2}$ wt %), maxima of ore elements at distances between 20 and 60 cm from the vein (all of the maxima are represented by a few points with anomalous concentrations). This aureole demonstrates the spatial separation of maxima in the concentrations of different elements (in the direction from the vein inward the country rock, in the succession Cu—Pb—Zn). The metasomatic alteration degree of granite in profiles of this type is at a minimum (chloritization and sericitization but no silification).

The examples described above do not cover the whole diversity of B-type distributions, and some additional variants will be presented below.

(2) There are no aureoles with only A-type distributions of all metals. This is obvious from the data summarized in the form of a histogram in Fig. 39d. The aureoles commonly include a number of intervals with above-background concentrations (Fig. 44).

A fairly large group is comprised of aureoles (of types A and B) with average concentrations at the background level or below (up to 15% in the samplings, Fig. 39c).

(3) The most widespread aureoles have Zn dominating over Pb and Cu (as classification characteristics, we used the product of the interval length in meters by the concentration in %, i.e., m%, geometric means, and the maxima of concentrations in the aureoles, Figs. 45a, 45b). Among these aureoles, the most common have Zn > Pb > Cu, with aureoles dominated by Zn account-

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[13] Figures 39 and 45 present generalizations based on 72 monoelemental samplings for 24 profiles. Later data on 37 profiles confirm and refine them accurate to 5%.

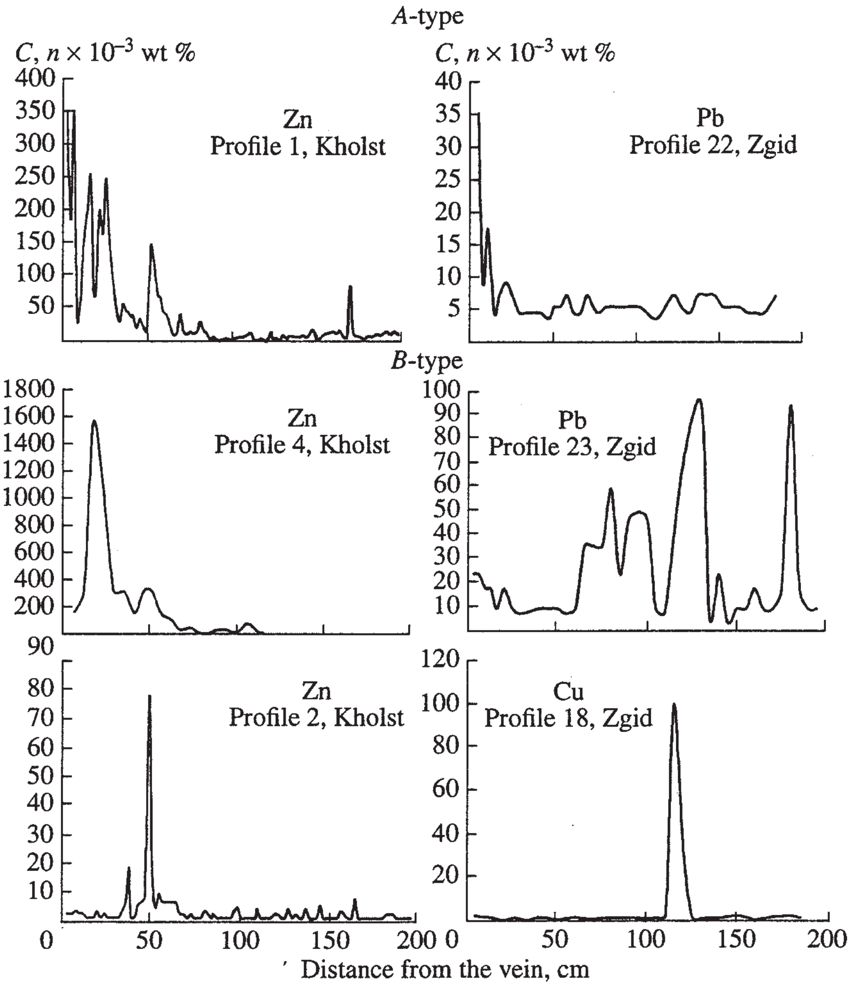

Fig. 40. Examples of two types of Zn, Pb, and Cu distribution in the aureoles.

ing for 65–70%. For the vein intervals adjacent to the aureoles, the numbers of situations when the dominant elements are Pb or Zn are equal. The most persistent relations within these groups are Pb > Zn > Cu (10 of 24 profiles) and Zn > Pb > Cu (9 of 24 profiles) (Figs. 45c, 45d). Only 25–30% of the vein-to-aureole profiles have relations between similar elements in the vein and aureole.

(4) The predominance of Zn in aureoles is characteristic of all of the sampled levels at Kholst and of middle levels at Zgid (levels VI and X) and Arkhon (levels III and V). At the Verkhnii Zgid deposit, the most widespread aureoles are dominated by Pb.

The lower levels at Verkhnii Zgid (XIII and XIV) are characterized by the predominance of Pb in aureoles upon a general decrease in the concentrations of the metals (up to negative anomalies for Zn and, partly, Cu) (Fig. 46). All three profiles near the Vostochnaya Vein at the lower level of Verkhnii Zgid (profiles 18, 19, and 20 at level XIV) display weak aureoles with concentrations near or below the background (the Zn concentrations in the vein are 0.4–3.2 wt % for Zn, 0.5–2.4 wt % for Pb, and 0.01–0.02 wt % for Cu). Only the very f wall-rock samples in profiles 18 and 20 (from the f 10–15 cm) have concentrations above the backgrou up to 0.02 wt % for Zn and up to 0.03 wt % for Pt profile 20; up to 0.015 wt % for Zn and up to 0.03 w for Pb in profile 19.

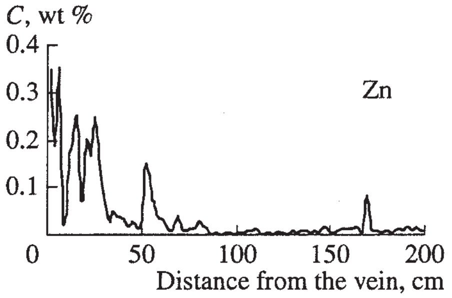

Fig. 41. Type-A distribution of Zn over an interval of continuous sampling of wall-rock granites (Vein Vertikal'naya, footwall, level VII, Kholst deposit; profile 1, 102 samples from a 2-m interval). The background concentrations practically coincide with the abscissa.

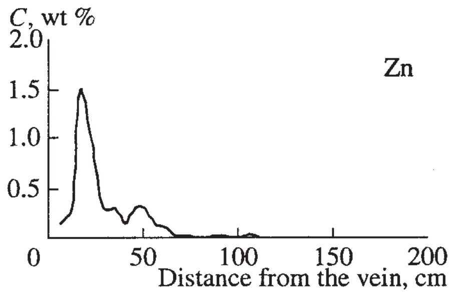

Fig. 42. Type-B distribution of Zn over an interval of continuous sampling of wall-rock granites (Vein Vertikal'naya, footwall, level V, Kholst deposit; profile 4, 35 samples from a 2-m interval). The background concentrations practically coincide with the abscissa.

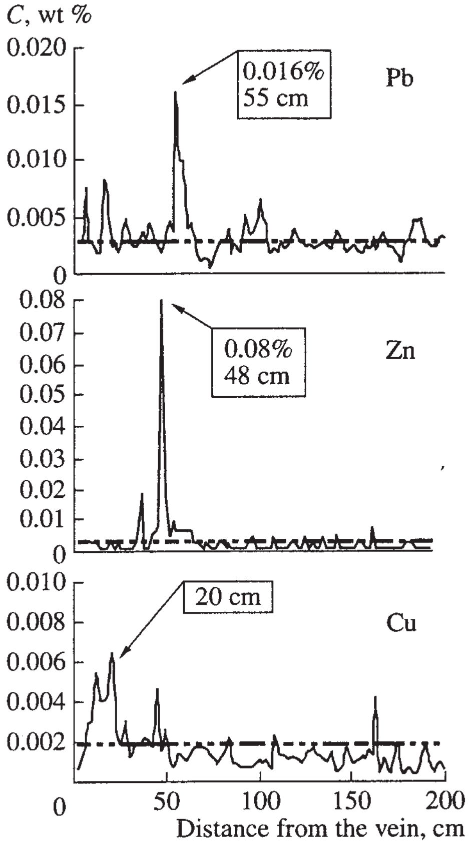

Fig. 43. Type-B distributions of ore elements over an interval of continuous sampling of wall-rock granites (Vein Vertikal'naya, footwall, level III, Kholst deposit; profile 2, 103 samples from a 2-m interval). The dashed line marks the background contents.

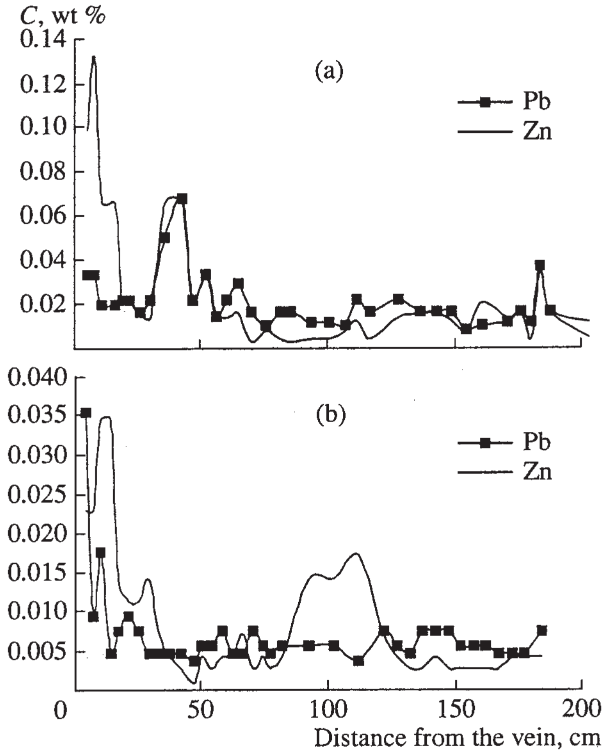

Fig. 44. Distributions of Pb and Zn in the nearest wall rocks of the vein. (a) Vein Luarskaya 5, Kholst deposit, footwall, level VII, profile 8; (b) Vein Vostochnaya, Verkhnii Zgid deposit, hanging wall, level VI, profile 22.

(5) The correlations between the distributions of elements in the profiles can be accurately studied only for the Vertikal'naya Vein at the Kholst deposit (this vein is characterized by the greatest number of profiles at different levels). It has been established that there is a strong correlation between the Zn and Pb distributions in the footwall at levels V and VII, and the pair correlation coefficients r for analogous elements are 0.67–0.94 at significant values of the correlation coefficient (0.36) at a 5% level (Fig. 38, profiles 1, 4, and 5).

The correlations between profiles at level III (profiles 2, 9, and 10) are weak or absent—Pb in profiles 2 and 9, whose $r = 0.1$, and profiles 2 and 10, whose $r = 0.2$; Zn, respectively, 0.12 and –0.01—although the correlation coefficient for Cu in profiles 2 and 10 is equal to 0.47.

There is no correlation between profiles at levels III with those at levels V and VII. For example, r for Zn is equal to 0.07 in profiles 2 and 4, –0.02 in profiles 2 and 1, and –0.1 in profiles 2 and 5.

The distributions of elements in the hanging wall of the Vertikal'naya Vein significantly differ from the distributions in the footwall (correlations are weak or absent). The regularities in the Cu distribution are more complicated and often significantly differ from those for Pb and Zn.

5.3. Discussion of the Results and Formulation of the Simulation Problems

Preparatory to discussing our results obtained for the distributions of elements in aureoles, it is necessary to formulate some starting points, most of which are quite obvious and are confirmed by numerous facts:

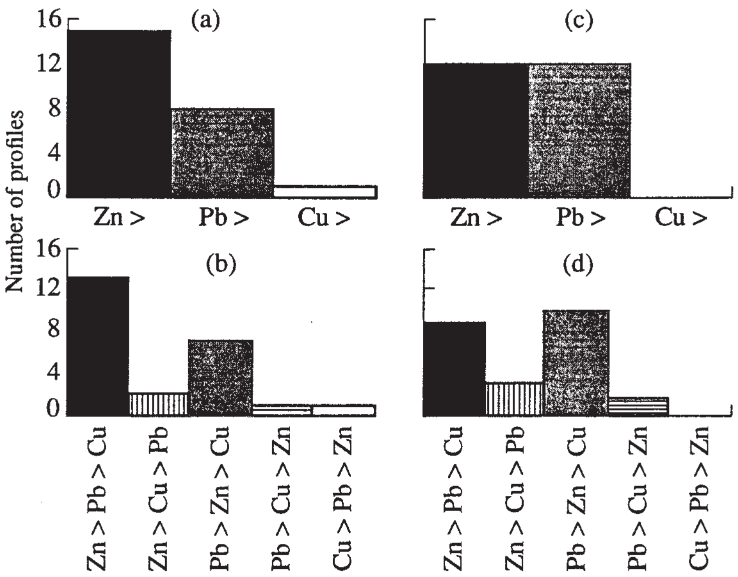

Fig. 45. Occurrence frequency of (a, b) aureoles and (c, d) whole-rock samples of veins. (a) In terms of the predominant metal; (b) in terms of metal proportions; (c) in terms of the predominant metal; (d) in terms of metal proportions

* the deposition of metal sulfides in veins and aureoles implies the coupled migration of the ore elements and sulfide sulfur in the hydrothermal solution;

* the main mode of precipitation of ore elements in the veins and aureoles is their sulfides;

* the ubiquitous development of newly formed (secondary) minerals near veins suggests that the hydrothermal solutions entering the fracture conduits in which the veins develop were relatively disequilibrated with the wall rocks;

* sulfides of metals in the veins and aureoles can be formed as a result of the action of a number of geochemical barriers: a temperature barrier [the solution becomes oversaturated at a decrease in its temperature; temperature gradients as high as 20°C/100 m updip veins were determined by Lyakhov *et al.* (1994) and Laz'ko *et al.* (1981)], an acid–alkaline barrier (rock–water interactions usually lead to a decrease in the solution alkalinity, which inevitably affects the solubility of sulfides), etc.

Below we successively discuss all of the regularities established in the distributions of ore elements in the aureoles and veins and try to identify their genetic implications.

(1) The predominance of type B of the aureoles suggests that metalliferous solutions gave way to barren ones (barren of at least one metal or even all of them) in the process of ore formation.[14] The reasoning is as follows.

The fact that there are mineralized veins and adjacent aureoles with distributions of type A implies that ore minerals in the veins were produced by solutions possessing relatively high concentrations of metals (which corresponded to saturation or oversaturation concentrations relative to sulfides under given conditions). These fluids, equilibrated with the vein mineral assemblages, were not in equilibrium with the country rock. Interacting with the latter, these fluids produced *deposition aureoles* in the wall rocks by means of infiltration- or diffusion-controlled mass exchange (the driving force of the former is concentration gradients, and main factor of the latter is rock–water reactions). Deposition aureoles should always develop when metalliferous mineralized solutions (metalliferous solution flow through a fracture conduit) are in contact with the

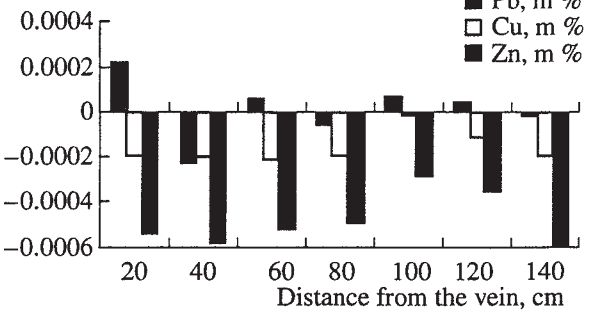

Fig. 46. Distribution of ore elements in the host granite of the Vein Vostochnaya footwall (Verkhnii Zgid deposit, level XIV). Plotted on the *x* axis is the distance from the vein (20-cm intervals), plotted on the *y* axis is the product in this interval over the metal concentration in this interval minus its background concentration.

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[14] Here and below, the term *ore-bearing solution* is understood as a solution that is saturated or oversaturated in ore elements and sulfide sulfur with respect to sulfides of these metals at a given temperature and pressure; the concentrations of ore elements in a *barren solutions* are a few orders of magnitude lower than the saturation concentrations.

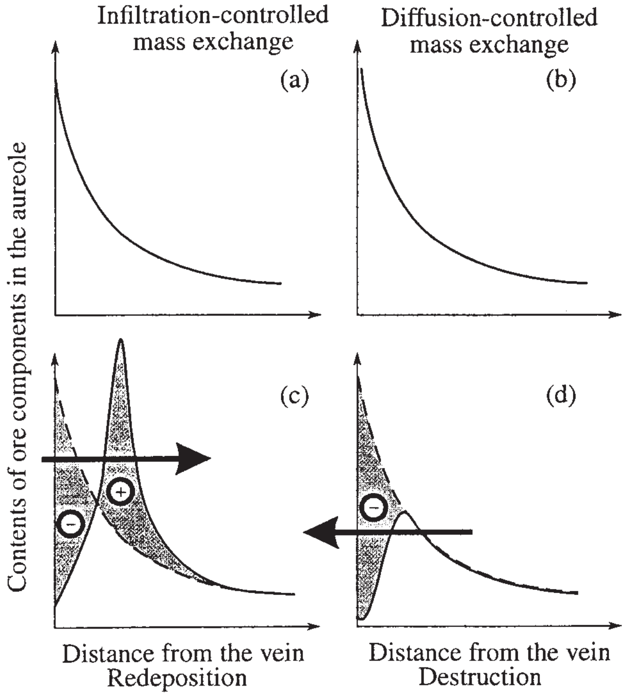

Fig. 47. Scheme for the transformation of deposition aureoles into redeposition and destruction aureoles. (a, b) Deposition aureoles (A-type distributions) produced by infiltration- or diffusion-controlled mass exchange; (c) redeposition aureole developing in place of a deposition aureole (a) when the barren solution filters through the country rocks (filtration direction is indicated with an arrow); (d) destruction aureole developing in place of a deposition aureole (b) during diffusion exchange with the barren solution (the arrow indicates the direction of the diffusion flux of ore components). The shaded areas with the minus and plus signs in Fig. 47c are equal. The shaded area with the minus sign in Fig. 47d corresponds to the amount of metal removed to the fracture conduit. The ordinate axis shows the content of the ore component in the aureole, the abscissa axis is the distance from the vein.

rock over a long enough time period. It is reasonable to hypothesize that deposition aureoles (metal distributions approaching type A) are original, i.e., produced early during the ore formation process (Figs. 47a, 47b).

Distributions of type B can develop as follows. We believe that the most realistic hypothesis is the systematic transformation of aureoles of type A into aureoles of type B (redeposition of metals similar to that simulated in our models for the Chauli deposit, see Chapter 3). Let a metalliferous solution that produced a type-A aureole (Figs. 47a, 47b) become barren because of the possible evolution of its composition during the mineral stage (as was demonstrated in Section 2.4 and in [Borisov *et al.*, 1995; Borisov and Shvarov, 1996]) or during the closing stages of the hydrothermal process. The interaction of this solution with a preexisting deposition aureole should inevitably result in the transformation of the latter into an aureole of type B. The infiltration of this (now barren) solution away from the vein should be associated with the dissolution of sulfides in the inner portion of the type-A aureole and the development of *redeposition aureoles* (with a shift in the concentration maxima away from the vein but the preservation of generally elevated concentrations of the metals throughout the aureole). Figure 47 schematically demonstrates how the development of an aureole according to this scenario involves the dissolution of the ore material near the vein and its redeposition at a distance from the vein.

The greater the interaction time, the farther away from the vein the concentration maximum of the ore component. Diffusion-controlled mass exchange produces *destruction aureoles* (the overall concentrations in the rocks decrease, and the residual maximum concentrations can be preserved at a distance from the vein; that is, "recede" from it). Figure 47d shows a possible result of an exchange of this type.

(2) The variant discussed above corresponds to the isothermal transformation of an aureole of type A. It is necessary to consider the possible structure of the aureole that should develop under a gradient in the thermal field in the country rocks. Obviously, the percolation of a hydrothermal solution flow heated to 350–400°C along a fracture conduit results in the heating of the wall rocks by means of conductive heat transfer. The depth at which the deposits in question were produced was 2.5–3.0 km [Nekrasov, 1980]. The country-rock temperature of the hydrothermal ore deposition should have been about 100–150°C (at a temperature gradient of 35–50°C/km). This temperature difference may also have affected the structure of the developing aureole.

At diffusion-controlled mass exchange, the structure of the destruction aureole does not differ significantly from that considered above (see Fig. 47d). The situation during infiltration-controlled mass exchange can be more complicated. When the solutions filter into the wall rocks, conductive heat transfer is complicated by a convective component. The higher the filtration velocity, the briefer the time needed for a temperature plateau (a zone of constant temperature, which is equal to the solution temperature in the fracture conduit) to develop in the wall rocks. The plateau abuts the vein, and the temperature of the rock and the solution percolating through it should decrease outside the plateau to the ambient rock temperature [Golubev and Sharapov, 1974]. Temperature profiles of this type can be induced by both metalliferous and barren solutions. This interaction between a metalliferous solution and the wall rock can follow a scenario different from that in the isothermal situation. As earlier, the near-vein region may be characterized by the development of a deposition aureole, which is formed under the effect of high-temperature water–rock reactions. However, the boundary of the temperature plateau can be marked by a solution-oversaturation front and, hence, by the deposition of sulfides, i.e., the development of another maximum in the concentrations of the ore components. The transfor-

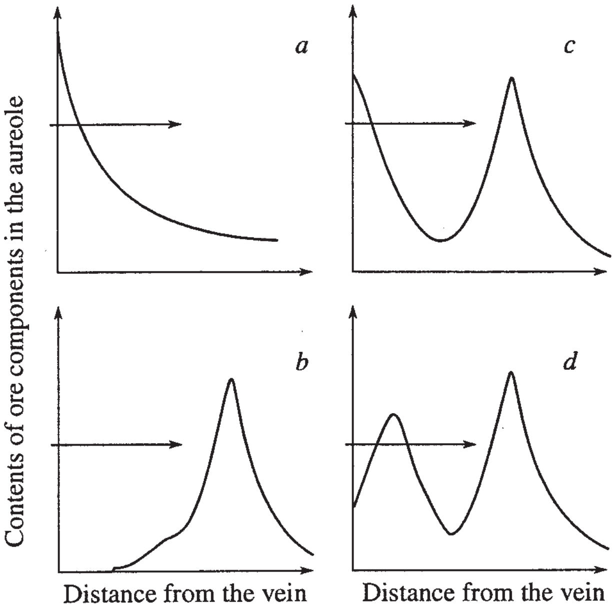

Fig. 48. Possible scenario of the evolution of infiltration redeposition aureoles with time. (*a*) Early aureole with an A-type distribution of the ore component; (*b*) redeposition aureole that is transformed from aureole (*a*) during the filtration of barren hydrothermal solution; (*c*) development of aureole (*b*) during the filtration of a new portion of ore-bearing solutions; (*d*) redeposition of aureole (*c*) during the filtration of barren solution of the second generation.

mation of such an aureole under the effect of a barren solution may result in two redeposition maxima, which are shifted away from the vein. The amplitude of the second (temperature) maximum should depend on the temperature gradient: the higher the gradient, the more intense the sulfide precipitation.

Aureoles of such structure are quite common, for instance, the Zn distribution in the aureoles of profile 4 in Fig. 42 and profile 22 in Fig. 44b. This can, perhaps, be regarded as evidence that many aureoles are formed by fluid infiltration in the thermogradient field of the wall rocks.

(3) Metalliferous solutions may give way to barren ones several times during a single mineral stage in the course of evolution of a hydrothermal system. This can account for the fact that aureoles commonly include a series of over-background concentrations of metals with near-background concentrations in between. A possible evolutionary scenario is presented in Fig. 48. Changes in the character of the solutions (alternating series of metalliferous and barren solutions) can also be brought about by pulses of tectonic activity, when the conduits of solutions to the ore-controlling tectonic structure are reactivated or modified.

The aureoles examined at the deposits also suggest that the concentrations of Zn, Pb, and Cu never decreased in the hydrothermal solution synchronously or this solution never became barren of all metals simultaneously. As can be seen in Fig. 44b, Pb enriches the region near the vein selvage, while the Zn aureole is partly redeposited. Analogous situations with metal redistributions are typical of other profiles: profile 1 demonstrates Zn deposition and Pb redeposition aureoles, profile 13 shows deposition for Zn and redeposition for Cu, etc. Further support for this concept comes from the fact that there are no aureoles in which distributions of all metals belong to type A alone.

(4) Not all aureoles ascribed to type B seem to have been formed by the mechanisms described above. A relatively large group (up to 15% of the monoelemental samplings, Fig. 39c) comprises aureoles whose metal concentrations are either below the background or are no more than one to three times higher than it. A distinctive feature of these aureoles is negative values of the products of the interval length over the metal concentration minus the background concentration (m %). Negative m % values are typical, first of all, of Zn and Cu and are rarer for Pb. Aureoles of this type are primarily those in three profiles (18, 19, and 20) in the lowermost level XIV at Verkhnii Zgid and the aureoles of two profiles (2 and 10) of level III at Kholst. Aureoles of this type usually belong to the aureoles characterized by the removal of components.

Aureoles of this kind could be conceivably produced by the following two mechanisms:

**destruction aureoles* [see (1) in the discussion above] are produced by means of diffusion-controlled exchange with a barren hydrothermal solution;

**leaching* or removal *aureoles* are produced by means of mass exchange between the country rocks and fluid flow that percolates (through the pore space of the rocks) to the fracture conduit.

There are two facts in conflict with the former mechanism: (a) when the aureoles of metasomatically altered rocks are sufficiently thick (up to 2.15 m in profile 18 and up to 20 m in profile 2), it is reasonable to expect more intense metasomatic alterations of the country rocks than those actually observed (for example, granite silification is not pronounced at all); (b) high contents of ore components in veins in contact with these aureoles, a feature that is difficult to explain bearing in mind the long residence time of barren solutions.

The latter mechanism (infiltration-driven development of *leaching aureoles*) seems to be more preferable. It finds support in the low intensity of metasomatic alterations of the rocks, because the percolating pore solution flow is in relative equilibrium with the rock in terms of all of its components, and this solution can bring about at most very weak alterations near the vein (see Chapter 3). Also, this model does not contradict the occurrence of mineralized vein adjacent to the leaching aureole.

It should be mentioned that leaching aureoles can, perhaps, be formed in two different environments: they can either transform unaltered country rocks or modify preexisting aureoles of types A or B.

Of course, the facts and considerations presented above provide merely indirect evidence in support of the existence of pore filtration flows percolating to fracture conduits. Recent years witnessed the amassing of extensive information pointing to the important role of fluid flows that pass through rocks during the hydrothermal ore-forming process [Safonov *et al.*, 1982; Korotaev *et al.*, 1992; Korotaev, 1994]. Traces of these flows are zones with negative anomalies in the rocks hosting the lower portions of vein bodies at several deposits of the Sadon group ("ore" cuts), whose boundaries at significant distances from the veins were identified by the distributions of K, Rb, Ni, Mo, Ba, Be, Sn, and Cr [Khetagurov and Rekhviashvili, 1977; Rekhviashvili *et al.*, 1990].

(5) The discovery of leaching aureoles at the lower levels of V. Zgid and middle levels at Kholst has raised the questions as to why there are no leaching aureoles in the profiles at the lowermost (VII) level of Kholst or the middle levels at V. Zgid, and whether this reflects some regularity or is purely accidental.

Available data cannot provide a direct answer to this question. However, it is possible to make some hypothetical supposals.

It is currently universally admitted that the west-trending Sadon–Unal normal fault, which limits the area of vein base-metal deposits in the south, played the role of a conduit of mineralized fluids. There are no deposits in the fault zone itself, and all of them are localized in its splay shear or detachment fractures that generally trend to the north (northwest or northeast) and are spatially restricted to the footwall of the fault. There is good reason to believe that the junction zone between the Sadon–Unal normal fault and westerly fractures was the most favorable for the development of the deposits, i.e., loci with certain specific conditions. The events that took place in the junction zones could conceivably have evolved according to many scenarios, the most probable of which could be as follows. Waters of any genesis should have circulated in the Sadon–Unal fault zone during the predeposition time. The intrusion of stocks and dikes of the andesidacite association in the Middle Jurassic and significant tectonic motions (which resulted in shear and detachment fractures) created prerequisites for the initiation of the hydrothermal process: intrusions of the andesidacite association provided the required heat source, and tectonic motions created a zone of shattered rocks. The zone of shattered rocks is understood here as a zone of any strong tectonic deformations in the rocks (fracturing, fragmentation, mylonitization, etc.). The heated and virtually barren solutions of the Sadon–Unal fault filtered through the permeable zone of shattered granite (junction zone), with the flanks of the flow affecting less disintegrated rocks that hosted the ore-controlling tectonic structures. Thus a mobilization zone of a variety of components (including metals and sulfide sulfur) was formed. This zone can be referred to as the *root* zone, but it is elongated updip the Sadon–Unal fault and, perhaps, comprised not only the roots (i.e., the lowermost portion) of the deposit. The intensity of the mobilization processes associated with reactions between the primary (barren) hydrothermal solutions and country rocks should have decreased updip the junction zone and away from the heat sources, closer to the paleosurface. This idea is indirectly supported by data on the lengthwise zoning of orebodies at the Sadon deposit [Grigoryan, 1992]. "It has been established that the maximum gradient in the concentrations of most of the aforementioned elements (including those composing the ore mineralization) is determined in the direction from the lower levels of the southwestern flank, adjacent to the regional ore-controlling Sadon–Unal fault of pan-Caucasian trend, to the upper levels of the northeastern flank of the deposit."

Hence, as a *working hypothesis*, we assume that the Sadon–Unal normal fault was a conduit not of the ore material (the solutions that moved along it were practically barren) but of solutions. Then, the junction zone between the fault and its splay fractures and faults could be the main region where the mobilization of ore elements and sulfide sulfur probably took place. If the splay faults drained the solutions of this region, they can be regarded as ore-controlling and ore-hosting structures.

Proceeding from this hypothesis, it is reasonable to expect that the leaching aureoles can, in principle, be found at different levels of the deposit near the Sadon–Unal normal fault. Aureoles of this type can be found at a greater distance of the Sadon–Unal fault at deeper levels of the deposit than at its shallower levels (because of a decrease in the intensity of the process updip the normal fault).

Let us consider the leaching aureoles at the deposits described above. Aureoles at the Kholst deposit were encountered at level III, in profiles 2 and 10, at a distance of only 100 m from the Sadon–Unal fault. The profiles of level V (profile 4) and VII (1, 3, 5, 7, 11, and others) are located 500–600 m away from the main fault. The leaching aureoles at V. Zgid were detected at level XIV (profiles 18, 19, and 20), i.e., at the smallest distance from the Southern Fault (the westward continuation of the Sadon–Unal normal fault).

(6) The weak correlations between the distributions of metals in the veins and aureoles (only 25% of vein–aureole profiles show equal proportions of metals) and the dominance of Zn in the aureoles (up to 65–70% of the profiles) led us to suggest that the Zn concentration in the metalliferous solutions was higher than the Pb and Cu concentrations. Because of this, Zn could be accumulated in the aureoles in greater amounts. Moreover, it is quite probable that the quantitative propor-

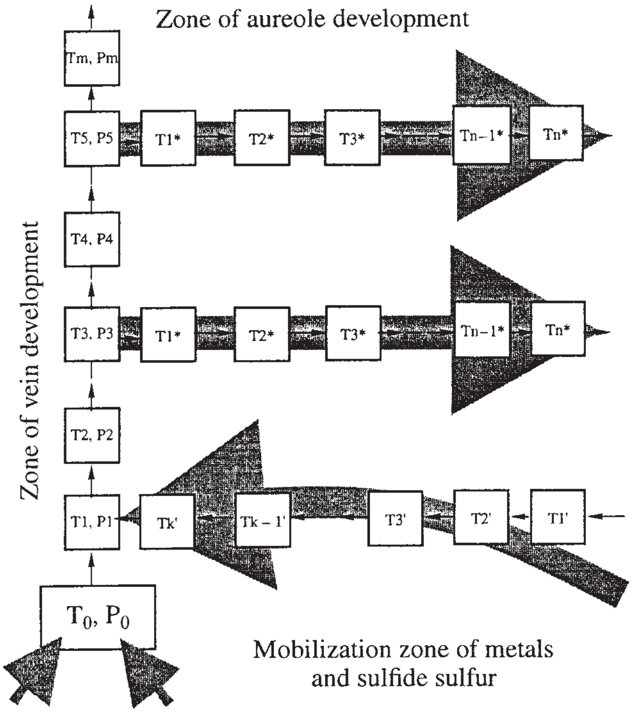

Fig. 49. Elements of the genetic model and a scheme of the thermodynamic simulations for the zones where the initial hydrothermal solution is produced, aureoles develop, and filling veins are formed. The *mobilization zone*, in which ore components are extracted from granite, the initial hydrothermal solution of the hydrothermal system is formed, and leaching aureoles are produced. The *zone of vein development*, in which an ascending flow of hydrothermal solutions from the mobilization zone forms veins. The *zone of aureole development*, in which aureoles develop in the wall-rock granite: deposition–redeposition aureoles develop in the upper part of the rock sequence (arrows indicate the directions of solution flows away from the fracture conduit) or leaching aureoles are produced (arrows indicate the directions of solution flows toward the fracture conduit). Squares marked with T and P are stepped reactors describing this geological model in the equilibrium dynamic simulation (see Chapter 6 for details).

tions between the metal concentrations in the aureoles were predetermined by the contents of these metals in the source (granite), and these proportions could be modified (enhanced) by the selective extraction of the metals. Since we assumed, based on the information reported above, that the source of the ore components was the host granite, whose proportion of the metals was determined as Zn > Pb > Cu, similar relations between the metals can be also expected in the aureoles. Our idea about the source of the ore components is corroborated by data on the Pb isotopic composition [Amov *et al.*, 1988], which suggests that Pb of the deposits in the Sadon group was extracted from the host granite. A higher Zn concentration than those of Pb and Cu was also determined in experiments on the dissolution of sulfides of these metals in the presence of the monzonite buffer at 300–500°C and 0.5–2 kbar [Hemley *et al.*, 1992].

Above we reported data suggesting that metalliferous solutions gave way to barren ones in the course of ore formation. This could have caused the weak correlations between the proportions of the metals in the veins and adjacent aureoles. When moving along a fracture conduit partly filled with gangue and ore minerals, the barren solution reacted with them. The minerals could be partly or fully dissolved and redeposited somewhere along the general direction of fluid movement through the fracture. The replacement of some ore minerals by others (for example, sphalerite by chalcopyrite and galena), their dissolution, and zonal structures were described by several researchers dealing with vein minerals at these deposits [Zlatogurskaya, 1960; Kandaurov, 1988; Dobrovol'skaya, 1989; Bortnikov *et al.*, 1991].

However, only metal redeposition and accumulation occurred in the aureoles. Because of this, the veins should be dominated by Pb and Cu (Zn is removed), while the adjacent aureoles are dominated by Zn (which is only accumulated and redeposited but not removed).

(7) The totality of geochemical data led us to propose elements for the genetic model of ore and aureole formation (Fig. 49). The model involves a probable scheme for fluid filtration flows in fields with thermal gradients, with this scheme determined by a combination of the ore-controlling and fluid-conducting joint structures.

In the root part of the deposit (the junction zone between the Sadon–Unal normal fault and splay shear and detachment fractures in its footwall), ore components are mobilized during reactions between the primary barren solutions and granites. This process gives way to metalliferous solutions that are initial for the hydrothermal system. These processes can also manifest themselves by producing *leaching aureoles* (type B), which occur at different levels of the deposit.

The fracture conduit in which the vein orebody develops is dominated by the ascending motion of high-temperature metalliferous solutions. The local lateral spread of part of this solution away from the fracture conduit can take place at different levels of the deposit, at which *deposition* and *redeposition* aureoles (types A and B) are predominant. The partial contraction of the solutions from the pore space of the granite to the fracture conduit (a process that also results in the development of *leaching aureoles*) can be expected where there are flows from the regional fault or local solution flows between closely spaced fracture arrays. This genetic scheme is presented in Fig. 49.

5.4. Conclusions

The analysis of regularities in the Zn, Pb, and Cu distributions in the wall rocks of steeply dipping Pb–Zn orebodies and in mineralized veins led us to draw certain conclusions and deduce a series of genetic implications.

(1) The results obtained on the fine structure of aureoles of Pb, Zn, and Cu distribution developing in the wall-rock granite around veins indicates that they can be used to reconstruct elements of rock-water interactions in the ore-forming hydrothermal system and propose a scheme of a model for the genesis of the ore and aureoles.

(2) The region where a variety of elements (including ore elements and sulfide sulfur) are mobilized can be spatially restricted to the junction zone between a regional fault and its splay shear and detachment fractures, in which vein orebodies develop.

(3) The deposits studied within the scope of this research are dominated by aureoles whose maxima of metal concentrations are shifted away from the vein selvages for different distances (aureoles of type B). There are no aureoles whose Zn, Pb, and Cu distributions are close to the exponential law alone (type A). The dominance of type-B distributions suggests that ore formation was associated with a change from metalliferous to barren solutions (at least in terms of any one metal or even all of them).

(4) The switch from metalliferous to barren solutions could occur more than once over the mineral stage during the evolution of the hydrothermal system. The decrease in the concentrations of Zn, Pb, and Cu or the barren character of the fluid in terms of these components occurred asynchronously for all metals. The weak correlations between the distributions of the metals in veins and aureoles and the dominance of Zn in the aureoles led us to propose that the Zn concentration in the metalliferous mineralized solution was higher than the Pb and Cu concentrations.

(5) The probable mechanisms responsible for the origin of the primary aureoles at vein deposits were deposition, redeposition, and leaching.

(6) We have demonstrated that in aureoles, ore elements are mostly redeposited and accumulated (the only exception is leaching aureoles), while in veins ore elements can be partly or fully dissolved and redeposited along the general vector of fluid movement in the fracture conduit.

(7) The totality of geochemical data led us to propose elements for the genetic model of ore formation and the development of aureoles. These elements comprise, first of all, a probable scheme of fluid filtration flows in the ore-forming hydrothermal system.

CHAPTER 6

EQUILIBRIUM–DYNAMIC MODELS FOR THE MOBILIZATION OF ORE COMPONENTS AND THE DEVELOPMENT OF ORE MINERALIZATION AND ALTERATION AUREOLES AT VEIN BASE-METAL DEPOSITS

Based on the geological model that is underlain by the results of geochemical studies at Pb–Zn deposits (see Chapter 5), let us now consider equilibrium–dynamic models for the main elements of the ore-forming system: regions where metals are mobilized, where metals are transported and veins develop, and where aureoles develop.

As before, our methodological approach involves the analysis of models for the genesis and evolution of the hydrothermal systems (from the region where the ore material is mobilized to the regions where ore mineralization is formed and aureoles grow) as a chain of an interrelated and self-adjusting sequence of events [Borisov and Goreva, 1994, 1995a; Borisov *et al.*, 1995b; Borisov and Shvarov, 1995, 1996, 1998; Borisov and Kudryavtsev, 1996, 1999; Borisov *et al.*, 1997, 2002; Borisov, 2000a, 2000b, 2000c].

6.1. Model for the Mobilization of Ore Components

One of the very first stages in simulating ore-forming processes is the specification (or determination) of the load of ore components of the probable initial hydrothermal fluid. Inasmuch as it was established (see the results listed in Chapter 5) that a possible source of ore components can be the host granite, the main task of the first phase of simulations is to test this possibility and identify the principal factors that control the mobilization of metals from a natural granite. For this purpose, we examined a series of models for the mobilization of ore components over broad ranges of temperature, pressure, and the composition of the primary (barren) hydrothermal solution.

6.1.1. Model formulation and simulation techniques

Let us recall (based mainly on literature data) the main thermodynamic parameters of the hydrothermal system that can be used to specify our simulation conditions and parameters.

(1) Temperature generally varies over the interval of 415–65°C (the quartz–galena–sphalerite ore stage spans a range of 345–120°C) [Laz'ko *et al.*, 1981; Lyakhov *et al.*, 1994]. The paleodepth at which the deposits were formed corresponded to 2.5–3.0 km [Nekrasov, 1980]. The temperature of the country rocks during ore formation could be 100–150°C (at a temperature gradient of 35–50°C/km). Our models deal with mobilization processes at different temperatures, but the basic leaching model was assumed to operate at 370°C (i.e., 25°C higher than the maximum for the quartz–galena–sphalerite ore stage).