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2015 IOP Conf. Ser.: Earth Environ. Sci. 24 012024

(http://iopscience.iop.org/1755-1315/24/1/012024)

Scientific and Technical Challenges in the Well Drilling Progress IOP Publishing
IOP Conf. Series: Earth and Environmental Science **24** (2015) 012024 doi:10.1088/1755-1315/24/1/012024

Metallogenic problems of hydrothermal gold deposit formation: facts and arguments

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Abstract The research problem of substituting existing hypotheses by a well-defined re modeling of the geological processes, which, in its turn, initiate and govern the formation of hydrothermal gold-ore deposits, is becoming more and more relevant. The four existing hypotheses - granitogene, basaltogene (magmagene), metamorphogene, and polygene have been considered and discussed. The interpretation of different hypotheses and analysis of substantiating facts showed the inconsistency of above-mentioned hypothesis-approaches. Up-dated petrological, petrochemical, geochemical data proved the following: generation of metal-bearing fluids in sources of moderate alkali-basalt melts during the late basalt formation stages show recycling Late Riphean to Late Paleozoic convergent antidromic granite diorite dolerite magmatic complexes.

1. Introduction

The attained advanced investigation of ore formation conditions within hydrothermal gold-ore deposits could be associated with such an unsolved problem as metallogenic mineralization dependence to global geological processes.

It should be mentioned that such questions as the sources of ore-gold and foreign- metal impurities, the generation conditions of metal-bearing fluids and the ore path to future deposits could be the evidence base in plotting a geologic-genetic model of fluid-ore-magmatic gold-producing systems, as well as being an effective propspecting criterion in evaluating those commerical gold-ore deposits buried at an accessible depth while excluding eroded deposits.

Granitogene, basaltogene (magmagene), metamorphogene, polygene hypotheses of hydrothermal gold-ore deposit formation were proposed at the turn of 21st century. Probable metal and fluid sources could be granite and/or basalt magma reservoirs (according to magmagene hypothesis); rocks in dynamo-zonal metamorphism areas of hydration and dehydration (according to metamorphogene hypothesis); and/or as numerous sources having been subjected to regional metamorphism , such as sedimentary rocks and silicate melts (according to polygene hypothesis). The diversity of existing hypotheses, being relevant to both gigantic and unique deposits, excludes such a fact as the convergent ore-formation itself, while the existence of such hypotheses only attests either the lack of empirical data or unreliable data.

2. Analysis of hypothesis evidence base

The disadvantages of previous research methods focused on the ore-forming potential in dynamo-zonal metamorphism have been discussed [1]. The decennial integrated analytical data showed a rather apparent tendency, i.e. fully-developed “chaos” of the hypothesis evidence base itself, resulting in this diversity. This “chaos” could be described as different definitions by different authors concerning the pre-gold ore grade (from the first mg/t to multi gr/t) in one and the same ore-hosting black-shale formation, in ultrametamorphic Archean basement complexes and in rather young regional dome structures. Whether sharp positive geochemical anomalies in near deposit wallrock zones formed in metamorphic and/or metamorphosed rocks could be either the cause (assumption) or result of ore formation is even today an open question.

This "chaos" could be explained by the fact that both research approaches and methods were and are irrelative to the stated investigation objectives and tasks. According to V.I. Vernadsky and A.E. Fersman, the aim of these investigations was to show the geological history of chemical elements on the planet and estimate the concentration or dispersion of metals during every formation stage on the basis of quantitative process, as well as to evaluate the subsequent alteration of sedimentary rocks subjected by metamorphic processes and associating mineralization of hydrothermal metasomatic processes. In most cases, host rock metasomatic alterations accompanied by beresite and propylite formation metasomatites are classified as metamorphic processes of hydration, while hydrothermalites are related to biotite-chloritic, chlorite-sericitic, albite-sericitic and other "subfacieses" of greenschist facies [2, 3]. A matter of endless arguments still remains the fact how to determine the total phased gold content.

It is obvious that the out-dated research paradigm should be revoluntionized, i.e from a primitive understanding of geochemistry to a more defined conception of its objectives and tasks. The proposed geological history reconstruction of petrogenic and oregenetic elements (gold and its geochemical accessory minerals – silver and mercury) in the Early and Late Proterozoic black shale formations and in ultrametamorphic complexes within wallrock areas of the following deposits: Kuznetsky Ala Tau (Berikul), North Transbaikal (Irokindinski, Kedrovski, Karalonski), Lensky district (Sukholozhsk, Verninsk), Patom plateau (Chortovo Koryto) indicated that host rock alteration is pertained to zonal metasomatic beresite areolas and propylite metasomatite formations, while the bulk pre-ore metal content shows the syn-ore origin of their anomalies. The obtained data showed the composition-genetic mineralization homogeneity developed in Late Riphean to Late Paleozoic black shales, ultrametamorphic complexes and other crystalline rocks [4].

The evidence for the granitogene hypothesis is based only on the data of single-version interpretation [5–6]. Bulk magma pockets including granite melts and inherited plutons, as well as granitoid massifs generate sufficient metal-bearing fluids for future commercial gold-ore deposit development.This could be a reason-based choice in considering the possible formation of comparable and/or significant volumes of basalt melts and metal-bearing fluids in the mantle. Water content in granite melts embracing aqueous metasomatic minerals (biotite, amphibole, and other minerals) in mantle xenoliths combines with the lack of water in mantle magmas. The spatial-temporal proximity of deposits to granitoid massifs, mature focused dome-shaped blocks and associations with early pre-ore dikes of acid rocks could be indicators of either genetic or paragenetic interrelationships. Granitoid plutons, blocks, siliceous dyke belts and deposits in the crust are controlled only by deep faults, which are channels for injected early hyperthermal fluids governing crust bedding palingenesis and forming large granitoid-bodies and late metal-bearing fluids, which, in its turn, generate deposits. Therefore, the identified near-pluton zoning of gold-ore mineralization is comparable to near-fault zoning, indirectly associated with plutonic intrusions. The concept that ore-forming fluids are silicate brines (magma) is inconsistent with the existing fact of relatively low fluid concentrations (up to 15…20 % wt of NaCl) within mineral ore vacuoles. Silica debris during host rock metasomatism is up to 50 % wt [7] which indicates the sterility of inflowing metal-bearing fluids in respect to SiO_2. However, the feldspar content in gold ore-bearing quartz veins was probably not the result of granite-inherited veins by generation of metal-bearing fluids in granite melts, but could have been the determined balance of petrogenic components in wallrock metasomic columns by silica, aluminum silicate and sodium diffusion from porous wallrock solutions in the interflowing potassium-calcium fractured solutions during metasomatism and mineralization. In the 1970s the agrument matching of commercial gold-ore deposits to granitoids,which are either metal enriched or metal depleted, introduced the concept of substituting the granitoid metallogenic trend for the potential granitoid mineralization [8].

This substitution furthered the study of applying granitoid minerals in the thermadynamic and physico-chemical regimes of active granite melts and the distribution and evolution of crystallized solid gold content in melts,which show a significant affinity of sulphur, chloride and other elements. In this case, another important factor is to estimate the gold-bearing melt potential, to evaluate the conditions and metal-bearing fluid generation in above-mentioned melts based on petrochemical parameters, as well as other parameters [9–12]. The obtained results are compared with the studied massif granitoids (with or without areal-temporal gold ore associations) in hydrothermal gold deposits and classified as unique, large, average or small. However, there are some emerging fact-based conditions that exclude the possible relevant formulated conclusions concerning the above-mentioned. These are the following: (1) high analyzed data uncertainty that granitoids are the bulk source of residual melts within which metal-bearing fluids could have really generated; (2) no criteria to effectively evaluate that amount of metal-bearing fluids which would be sufficient to produce commercial deposits including differentiated deposits with respect to contained metal mass. In this case, the genetic relation of hydrothermal gold deposits to granites still remains unproved.

Substantiation of magmegene (basaltogene) hypothesis is based on the factual data describing the isotopic content of sulphur in sulphides and carbon in carbonates responsible for meteorite probable cause blast (primeval mantle), associations of gold ores and platinium. There are known factual evidences such as isotopic constitution of sulfides and carbon of carbonate ores associated with meteoric standard (primitive mantle), metal platinum group associations in gold ores, presupposed mantle element impurities - mercury in gold and nickel wallrock metasomatite in chlorites, spatial-temporal association of gold ores with mantle plumes, small-sized basalt bodies– dykes, sills.

3. Results and discussion

Up-dated information was correlated from eighteen deposits of Yenisei, Kuznetsko-Ala Tau, East-Sayan, Northern Transbaikal (Muisk), Lenski gold ore areas within south mountain-folding of Siberian craton margin, including the above- mentioned ones. According to the basaltogene hypothesis, these facts show the principally relative frequency and sequence of events in Late Riphean, Early-, Middle- and Late Paleozoic mineralization, westward-eastward younging deposits.

Plutons of early palingenic granitoids or mature ultrametamorphic dome structures accompanied by acid rock dikes (aplites, pegmatites, granite-porphyry, felsitic microgranite-porphyry and etc.), beds and dykes of granite diorites (microdiorites, diorite-porphyry), associations of late pre-ore dykes, inter-ore dykes, post-ore dykes of medium-alkali dolerites (figures 1 and 2) were sequentially formed under geodynamical collision conditions in active continental margins or intracontinental rifting in all the areas during tens of millions of years (according to radiological methods). Specified magmatism derivate is controlled by deep faults and combined into convergent antidromic magmatic complexes, the latter of which recurring in space and time indicates their mineragenic type.

Intensifying anisotrophy of mechanical granitoid properties in pre-ore dolerite dykes is often accompanied by quartz veins, as well as early accumulated ore-mineral complexes. Dykes in vein exocontacts embrace beresite growths alternating to porpylites on the periphery. In areas of weakly alternated massive dykes the mineral-chemical composition of these dykes is comparable to similar normative rocks. As this could be found in numerous deposits, confined to granitoid massif complexes, it indicated that residual granite melts did not exist before the injection of early basalt melts; otherwise, if the melts mixed then “mottled” hybrid dykes could have formed and which were undetected in the investigated deposits. It is obvious that in this case non-existinggranite melts could not have been the source of metal-bearing fluids, the early metal-bearing fluid injections after intrusion of early basalt melts into granitoids.

Inter-ore dykes of dolerites cross-cut not only early ore-mineral complexes with decompressed quartz vacuoles in dyke exocontacts, but also veins formed in late ore-mineral complexes with beresite growths in their casings. Black, greenish-black massive, usually, fine/medium -grained, being confined to welded host rock exocontacts, these dykes are converted into metasomatities underlying the host rocks, to a certain extent, either hydrothermally altered or unaffected in their exocontacts. In rare "logan rocks", weakly altered thick dykes, their structure and mineral-chemical composition are related to moderate alkali dolerite, labradorite and aurite with olivine, grothite, titanite impurities (table 1, sample 2).

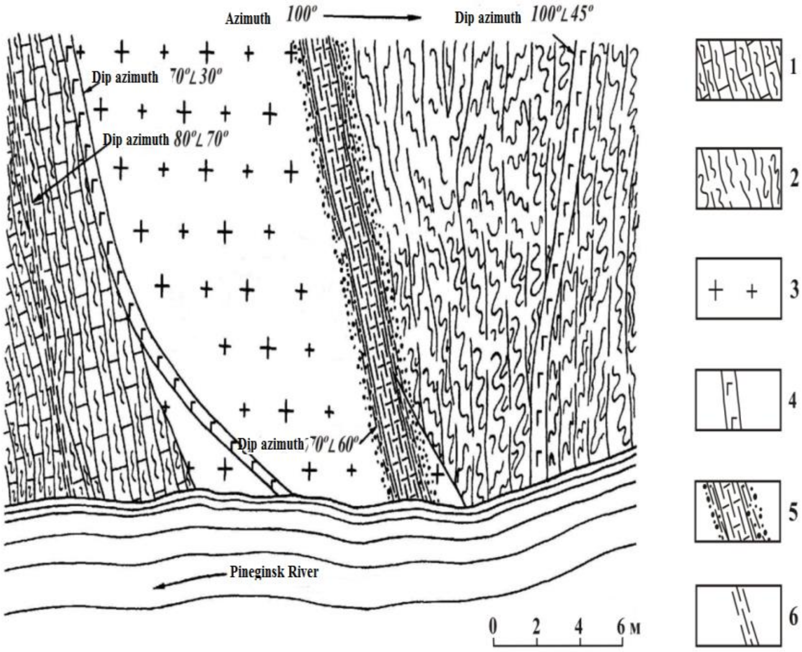

Figure 1. Kedrov deposit: (1) structure-temporal relations of sequentially formed gneiss limestones, (2) carboniferous shales, (3) mature dome structure,diorite-porphyry dykes, (4) dyke of medium-alkali dolerite, (5, 6) sulphide-quartz gold vein with beresite growths and bedded rocks.
Beresite growths, indicating their pre-ore age, are visible on river beds in the vein exocontacts within dolerite dykes

Based on the X-ray spectrography method, the following metasomatic minerals of ranging %wt were identified not only in one and the same dykes, but also in different ones: reddish-brown, pinky, earthy-green biotite (up to 60 %wt), ferro-magnesian hornblende (up to 20%wt), actinolite, tremolite, talc, serpentine, zoisite, epidote, magnesian iron chlorite, calcite, dolomite, ankerite, albite, sericite, quartz, apatite, rutile, leucoxene, celestine, barytocelestite, magnetite, pyrite. Two generations of biotite were identified: early generated biotite replaced by chlorites and other metasomes, and late generated biotite forming elongated flakes without replacement features and framing former augite crystals, which, in its turn, have been completely converted into fine- grained chlorite, sericite, carbonate aggregates and other minerals.

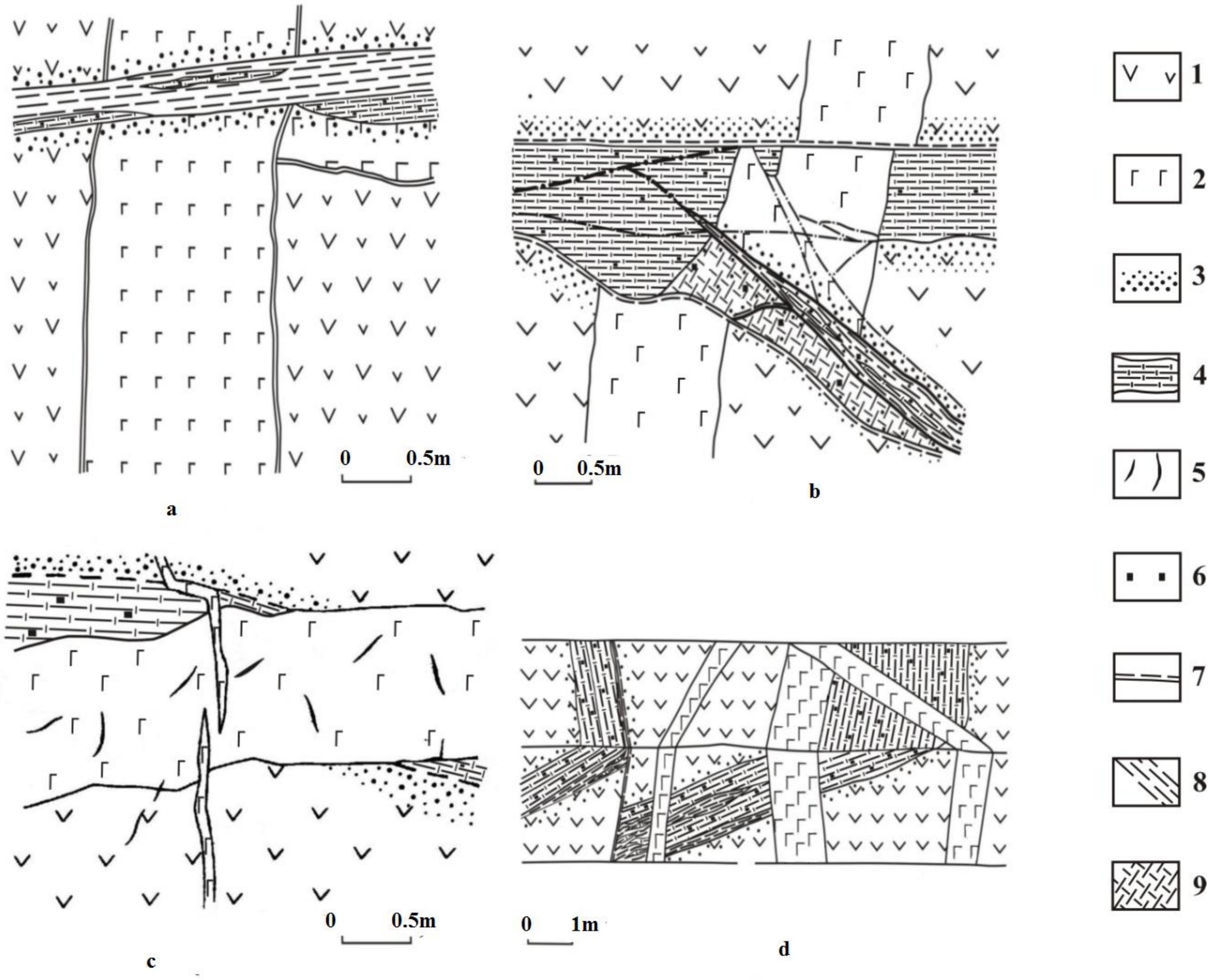

Figure 2. Berikulsk deposit. Structure-temporal relations of gold ores with pre-ore (two generations, *a*) inter-ore (*b*,*c*) post-ore (two generations *d*) dykes of moderate alkali dolerites.
(1) Berikulsk suite blanket basalt porphyries ($Є_1$), (2) dykes of moderate alkali dolerites, (3) beresites, (4) quartz gold veins, veinlets, lenses, (5) carbon-quartz veinlets, (6) pyrite, (7) tectonic wedges, (8, 9) schistosity and rock breaking zones

Based on balance calculations, dolerite chemical compositions during internal dyke metasomatism were identified – silica, sodium output and potassium, carbon dioxide input, sometimes partial replacement of sulphur, phemophile element associations (P, Ti, Mg, and not always Mn, Fe, Ca) (table 1) and gold (up to 3 g/t).

Stated data provides accurate reconstruction of geological processes during the late basaltoid stage of magmatic complex formation.

Metasomatic origin of biotite is proved by its weight (tens %wt) which is incomparable to the late-magmatic biotite wt in moderate alkali dolerite (up to 5 %wt). Hornblende crystals in comparison to late-magmatic hornblende are found in apodolerite metasomatites in the areas of rather intensive metasomatic alteration of dolerites.

Numbers of samples	Oxide content in % wt (first line). Input-output value of element atoms in standard geometric volume 10000 Å^3 in % to number of their atoms in standard geometric volume of initial dolerite (second line)															
	SiO_2 Si	Al_2O_3 Al	K_2O K	Na_2O Na	CaO Ca	MgO Mg	FeO Fe^{2+}	Fe_2O_3 Fe^{3+}	TiO_2 Ti	P_2O_5 P	MnO Mn	CO_2 C	S*	H_2O^+ H	O	∑ (Δ)
2	49.72	14.94	0.90	3.05	8.47	7.43	8.03	2.86	1.41	0.35	0.19	0.35	0.13	1.81	–	99.64
К-497	38.76 -16.8	10.75 -23.2	4.26 **405**	0.34 -88	10.1 **27**	13.3 **91**	8.79 17	2.69 0.4	2.75 **108**	1.36 **315**	0.21 **18**	1.83 **457**	0.16 **31**	3.40 100	3.3	98.70 (21)
К-588	40.40 -14.2	11.50 -18.7	2.90 **241**	1.09 -62	11.5 **44**	12.2 **74**	6.90 -9.0	4.33 **60**	2.44 **83**	1.04 **213**	0.23 **28**	2.67 **708**	0.26 **111**	1.69 -1,4	2.3	99.15 (19)
К-495	37.83 -22	9.14 -37.2	5.06 **475**	0.27 -91	11.6 **41**	14.0 **94**	7.79 -0.6	3.98 **43**	2.55 **86**	1.37 **303**	0.29 **57**	4.88 **1332**	0.14 11	1.30 -26	-0.6	100.20 (24)
К-562	38.0 -17.1	10.80 -21.6	3.16 **281**	0.39 -86	11.2 **43.6**	15.3 **123**	7.49 1.1	3.88 **47.2**	2.10 **61.7**	1.08 **234**	0.29 **65.6**	2.89 **797**	0.27 **125**	2.54 52	5.5	99.39 (24)
К-486	33.80 -30.6	8.16 -44	2.72 **209**	0.02 -99	12.0 **45**	12.9 **78**	6.87 -12	2.27 -19	1.95 **41**	1.17 **241**	0.33 **77**	14.4 **4107**	0.13 2.2	1.98 12	5.9	98.70 (29)

Table 1. Chemical compositions of moderate alkali dolerite and apodolerite metasomatites of inter-ore dykes and balanced petrogene elements in apodyke metasomatic aureoles of Kedrov deposit

Note (1) Sample 2 – moderate alkali dolerite composition; (2) S* – replaced sulphur; (3) Δ – specific gravity of transported (input and output) substance (sum of petrogene element atoms) in %wt of initial dolerite (sample 2) in standard geometric volume of 10000 Å^3 ; (4) table 1 and table 2 show total chemical silicate analyses of rocks performed in Central laboratory of State Production Association (SPA) "Zabsibgeology" and in West-Siberian Research Centre (Novokuznetsk)

Dependency of metasomatic dyke alteration to host rock alteration indicates the dyke fluid conductivity, which, according to the physical law, is possible only in thermal bodies located in relatively cold environment.Therefore, usually hot vertical dykes, as well as faults and channels, provided those paths where hot solutions rose from generation areas with the melts in time and these generated dyke melts have no time to cool, so cold dykes could not have accumulated the hot solutions. Gold and phemophile element anomalies, including contrast anomalies, indicate the fact of metal-bearing fluids. The inherited potassium-sulphur-carbon dioxide profile of interdyke apodolerite metasomatism, phemophile element anomalies, determining the petrochemical diversity of basalt melts, and gold near-ore metasomatites-beresites near deep fault framings (table 2) proved the fact that apodolerite and near-ore metasomatites formed (and ores) as a result of the behavior of one and the same metal-bearing fluids, the sources of which were moderate alkali basalt magma pockets.

Mineral zone, subzone	Output-input value of element atoms in % to number of their atoms in parent rocks in standard geometric volume of 10000 Å^3												Δ
	Si	Al	K	Na	**S^***	**C_o**	**Ca**	**Mg**	**Fe^{2+}**	**Fe^{3+}**	**Ti**	**P**	**Mn**	
Irokin deposit Granite migmatite melting, AR (3)														
Vy(5)	0	0	-10	-10	+	20	20	0	0	10	10	50	-60	1.2
Vi(6)	0	0	-10	0	+	220	70	30	30	70	20	110	0	3.1
Ch (9)	-10	10	-40	40	0	500	70	60	0	60	-10	210	-50	6.9
A (8)	0	0	-20	-10	+	**870**	**10**	**60**	**20**	**50**	**70**	**250**	**10**	4.5
Rz (7)	-10	10	20	-90	+	**2400**	**200**	**220**	**100**	**230**	**250**	**650**	**30**	18.8
Kedrov deposit Carboniferous feldspar-quartzose shales of Kedrov suite, PR_2 Metasiltsandstone (1)														
A (1)	-17	4.9	**248**	-34	+	**1905**	**33**	**1053**	**282**	**340**	**82**	**300**	**374**	18.0
Rz (1)	-39	8.8	**445**	-93	+	**6913**	**880**	**1781**	**447**	**125**	**73**	**672**	**347**	43.0

Table 2. Petrogene element balance in zonal host rock metasomatic aureoles of mesothermal gold deposits in Southern Siberia

Note: 1) Mineral zones and subzones of near-ore metasomatic aureoles: Vy, Vi – subzones of moderate and intensive frontal zone alterations, C, Ch, A and Rz – carbon, chlorite, albite, back zones, respectively; 2) S^* – sulphide sulphur, C_o – oxidized carbon (carbonate), + –
S input , if its content in parent rock is lower detection limit assay; 3) in brackets – number of samples, which are involved to calculate the average; 4) Δ – specific gravity of transported (input and output) substance as percentage of substance mass of parent rock in standard geometric volume 10000 $Å^3$

The deficiency of biotite and hornblende in near-ore beresites resulted in the substitution crystallization of the only potassium carrier in fluids by low-temperature sericite governed by extra heating of filtering fluids in hot dykes and cooling progressively as the fluids enter the mineralization area. Recrystallization of high-temperature biotite within inter-dyke metasomatism in succession to low-temperature metasomatic minerals (chlorite, sericite, carbonate and others) is correlated to increasing crystallization temperature of early quartz generation in succession to each ore-mineral complexes within ore bodies, comparable to the formation temperature of late generated quartz of each preceding complex. Above-mentioned facts in combination with alternating melt and metal-bearing fluid injections focus on the pulsing regime of hydrothermal systems, observed within today's volcanic activity areas.

4. Conclusion

The stated facts and data indicating the composition-genetic mineralization homogeneity in crystallized and black shale substances [4], form a conformed assemblage, which, in its turn, could be a basis for the geologic- compositional-genetic model of gold within antidromic-granite-diorite of fluid-ore-magmatic complexes. The described assemblage extends beyond the existing hypotheses (granitogene, metamorphogene, polygene). Therefore, fact-based evidence for the above-mentioned depends on the possible supporting facts of mineralization convergence, i.e. ore-producing potential of granite magmatism and/or regional metamorphism heating. However, this is practically impossible.

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