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HYDROTHERMAL ORE-BEARING FEATURES OF IGNEOUS INTRUSIVE COMPLEXES

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ABSTRACT
This article is an attempt to generalise information on hydrothermal ore mineralization presence, connected with different petrochemical types intrusive magmatic complexes. In the table ore-bearing intrusive complexes are distinguished and characteristic economic types of deposits are given, main morphogenetic types of ores and types of wallrock alteration, as well as mineral types of deposits are specified. Typical examples are adduced and distribution of each mineral type in Bulgaria is given. The typical ore objects cited usually are ore fields or ore districts with maximum presence of economic mineralization and thoroughly investigated. Metallogenic specialisation of different petrochemical types of igneous intrusive complexes is drawn. Spatial and genetic relations of ores and intrusive bodies are considered. Main types of geodynamic environments, in which discussed hydrothermal deposits were formed, are outlined. It should be underlined that they are mainly Phanerozoic.

INTRODUCTION

The most of hydrothermal deposits are connected temporally and spatially with intrusive (plutonic) complexes, so conclusion that the link between ore mineralization and igneous rocks is genetic one is accepted. It should be mentioned that isotopic data prove also presence of non-magmatic substances – water and dissolved components. This brings up a matter about existing of genuine, not only thermal, but also substantial-genetic relation of ore mineralization with relevant igneous complexes. Conceptions on this till the middle of XX century vary within wide range – from universal ore-bearing granitoid plutons (Emmons, 1936 et al.) to quite narrow specialisation of intrusive complexes (Smirnov, 1937). Meanwhile, till the end of the century a lot of information on this problem was obtained without drawing general conclusion. The recent work represents an attempt along these lines.

SOURCE DATA AND RESULTS

The information on hydrothermal ore-bearing evidence of different petrochemical types igneous intrusive complexes is summarised in the table. Hydrothermal deposits, connected with intrusive complexes from Europe, countries from former USSR, China, Japan, Canada, USA, Australia, Southern Africa, Northern Africa, partially western part of Southern America were taken into account, while for Cu-porphyry deposits, deposits of Mo, Sn, Sb, Hg, Au, U, fluorite – the whole World. The references include only the most important papers on this problem, because of the limited space. Information is quite comprehensive, but is not complete, due to its limited character on deposits in Southern America, Africa, India, Middle East, SE Asia. It should be mentioned that Au and Sb deposits in greenstone belts (mainly Archaean), recently are assumed partially or completely as plutonogenic hydrothermal type. During the past years the predominating opinion is that these deposits in some extent are sub-aqueous, of volcanogenic-hydrothermal type. They are not taken into account in this article due to their controversial origin.

INTRUSIVE COMPLEXES AND RELATED ORE DEPOSITS

1. Ultrabasic complexes
Mainly Phanerozoic (alpinotype) peridotite complexes. Allochtonous bodies in orogens. Ore deposits:
a) Main deposits: chrysotile-asbestos, talc. Widespread in Ural and Appalachian Mt.
b) Subordinate deposits: anthophyllite-asbestos (Ural, RF; Eastern Rhodopes).
c) Rare and very rare deposits: nephrite, magnesite.

2. Basic (gabbro) complexes
Ore deposits: Fe (Mt-skarn, very rare). Subduction zones.

3. Intermediate complexes
Diorite, quartz-diorite, syenite, monzonite, mixed. Subduction zones. Ore deposits:

a) Main deposits
- a_1) Fe: Mt-Sk (carbonate host rocks), Mt-Act (mafic host rocks). Typical for oceanic parts of subduction zones. The former ones are widespread in Ural, the latter – in Turgai, Kazakhstan and in ore belt El Romeral, Chile. Ore-bearing complexes are mainly diorite and syenite, direct, or in regional aspect genetically connected with tholeite-basaltic volcanites.
- a_2) Cu $\pm$ Mo: Mo-Cu porphyry (main), skarn (subordinate), vein-type (rare – Bourgas ore district; dep. Butte, Montana, USA; Cuba). Typical for subduction zones, mainly of Andean type. Deposits are concentrated within two large ore belts: Cordilleran-Andean and Mediterranean (Banat, Romania – Minor Caucasus, Armenia – Iran – Pakistan). The former belt is extremely rich (hundreds of deposits, some of them of world class – El Teniente et al.). Ore-bearing complexes are mainly monzonitoid, syenite, quartzdiorite, often direct, or in regional aspect genetically related with andesite volcanism.

Hydrothermal deposits related to intrusive complexes

Ore-bearing intrusive complexes	Economic types of deposits	Main morpho-genetic type of ore bodies	Type of wallrock alteration	Mineral types of deposits	Typical examples	Occurrence in Bulgaria
1	2	3	4	5	6	7
Ultrabasic (mainly peridotite)	Nephrite	M	Serp ? Tre[1]	Act and/or Tre	Dep. Ospinskoe, Western Sayan, RF Dep. Maritosa, Vermont, USA	
	Asbestos	V	Serp ? Ant	Ant-Asb	O. f. Susertskoe, Ural, RF	Ihtiman Sredna gora Mt.: dep. Belitza, Muhovo, Tzerovo et al. Western Rhodopes: dep. Dorkovo, Kostandovo Eastern Rhodopes: dep. Yakovitza, Avren, Goliamo Kameniane, Kamilski dol et al.
			Serp ? Act, Tre	Tre-Asb, Act-Asb		Eastern Rhodopes: o. oc. Jalti chal, Boturche et al.
				Chrys-Asb	Ore belt Alapaevsko-Bajenovski, Ural, RF – dep. Bajenovskoe Ore belt Thetford, Quebec, Canada – Vermont, USA, dep. Jeffrey Mine	Eastern Rhodopes: ore occurrences Yakovitza, Goliamo Kameniane
				Pic-Asb*		Dep. Brusevtzi, Eastern Rhodopes
	Talc	M	Amph[2] ? T-car	Amph-Tal		Sakar Mt. – dep. Ovcharovo Eastern Rhodopes: dep., Avren, Goliamo Kameniane et al.
			Serp ? T-car	Chl-Tal*	Dep. Seg, Carelia, RF	O. oc. Krainovo, Yambol district
				Tal ± Mag	Dep. Shabrovskoe, Ural, RF	Ihtiman Sredna gora Mt.: dep. Poliantzi, Gabrovitza et al. Western Rhodopes: dep. Pletena, Stanchavitza, Kochan et al. Eastern Rhodopes: dep. railway station Djebel, Genovo, Yakovitza, Boturche et al.
	Magnesite*	M	Serp ? T-car	Mag+Tal, Chl et al.	Dep. Mantudi, Is. Euboea, Greece	Dep. Gornoslav. Assenovgrag district – partly magnesite
Basic (gabbro)	Fe*	M	SK (Mgsk ? Cask)	Mt-Gar, Px, Fo*		Ore field Krumovo, Manastir Heights
			Act	Mt-Act*	Dep. Anzaskoe, Western Sayan Mt., RF	

[1] On contact with gabbro also rodingites are formed (grossular, diopside, chlorites, etc.)
[2] Amph (here and further) – mainly Act, Tre

1	2	3	4	5	6	7
Intermediate mantle (diorite, quartz-diorite, syenite, monzonite, mixed)	Fe	M	SK - Mgsk ? Cask	Mt-Gar, Px, Fo	Dep. Sheregeshskoe, Upper Shoria, RF	
			- Cask	Mt-Gar, Px	Dep. Sokolovskoe, Turgai, Kazakhstan	
			Act	Mt-Act	Dep. El Romeral, Chile	
	Cu ± Mo/Fe	M	SK - Mgsk ? Cask ? Act, Chl, Ep	Chp-Gar, Px, Fo±Mt		Ore field Malko Tarnovo, Strandja Mt.
			- Cask ? Act, Chl, Ep	Chp-Gar, Px ± Mt	Dep. Morenci, Arizona, USA	
		St (Mo-Cu-porphyry)	Bt-KFs-Q	Mol-Chp-Q	Dep. El Teniente, Chile	Dep. Studenetz, Plana Mt.; Panaguirishte ore district: dep. Elatzite, Central Stara planina Mt., dep. Medet, Sredna gora Mt.; Dep. Prohorovo, Sveti Ilia Heights; Dep. Bardtzeto, Strandja Mt. (Malko Tarnovo ore field)
		V	Ser-Q	Chp-Q ± Mol /En, Chal/ Gal, Sph, Au	O. f. Butte, Montana, USA (+ En, Chal)	Bourgas o. d.: Varli Briag o. f., Rossen o. f. (+ Mo), Zidarovo ore field (+ Pb, Zn, Au)
	Au* (diorite complexes)	M	Cask ? Act, Chl, Ep	Au-Sul[3] - Gar, Px	Dep. Nickel Plate, Brit. Col., Canada	
		V	Ser-Q	Au-Sul-Q	Dep. Porgera, Papua New Guinea, Au	
Intermediate, crystal (mainly monzonite, syenite)	U*	V	Ser-Q	Pitch-Sul-Car-Q		Bouhovo ore field. Western Stara planina Mt.
Acid, M-type granitoids (granodiorite plagiogranite)	Fe*	M	Sk (Cask)	Mt-Gar, Px + Sul	Dep. Dashkesan, Minor Caucasus, Azer	Dep. Martinovo, W St. pl. Mt. (controversial origin)
	Co ± Ni*	M	Sk (Cask)	Gla, Cob, Aspy c Co*	Dep. Dashkesan cobalt, M Caucasus, Azer	
			Sk (Cask ? Ab, Tre)	Sma-Sku, Chlo-Gar + Nic, Ram*	Dep. Hovuaksinskoe, Tuva, RF	
		V	Tu-Q+Chl	Gla-Cob-Aspy-Q	Dep. Verhne Seimchanskoe, Far East, RF	
	Cu ± Mo	M	Sk (Cask ? Act, Chl, Ep)	Chp-Gar, Px	Ore field Turinskoe, Ural, RF	
		St (Mo-Cu-porphyry)	Bt-KFs-Q	Mol-Chp-Q	Dep. Chuquicamata, Chile	
	Mo+W*	M	Sk (Cask ? Fs)	She-Mol-Gar, Px*		Ore occurrence Prekop, Western Stara planina Mt.
	W+Au*	V	?	She-Sul-Q+Au*	Dep. Blagoev Kamen, Serbia	
	Au	M	Sk - Mgsk ? Serp	Au-Sul-Fo (Serp), Px	Dep. Suian, North Korea	
			- Cask ? Act, Chl, Ep	Au-Sul-Gar, Px	Dep. Fortitude, Battle Mt., Nevada, USA	
			Jas	Au-Sul-Q	Dep. Cove, Nevada, USA	
		V, St	Tu-Q	Au-Sul-Q*	Dep. Kluchevskoe E Zabaikalie, RF	
			KFs-Q	Au-Q*	Dep Muruntau Tian-Shan, Uzbekistan	Etropole ore field – dep. Svishti plaz (w Aspy), Central Stara planina Mt.

[3] Sul (here and further) – Py, Chp, Gal, Sph ± Aspy, Pyr

1	2	3	4	5	6	7
Acid, M-type granitoids (granodiorite plagiogranite)	Au	V, St	Ser-Q	Au-Sul-Q	Ore field Mother Lode, California, USA	W St. pl. Mt.: Govejda o. f. (w Aspy, 3.9 t Au mined); C. St. pl. Mt.: dep. Dolna Kamenitza and Negarshtitza, o.f. Etropole (w Aspy, 0.17 t Au mined); Kraishte: o. f. Zlata (w/out Aspy, > 3.9 t Au mined)
	Sb, Au	V	Ser-Q	Au-St-Q ± Berth	Ore belt Yano-Kolimskii, Yakutia, RF, dep. Saralah	Ore occurrence Dobroseletz, Manastir graben, Topolovgrad area (w/out outcrop)
	Sb	V	Ser-Q	St-Q + Berth	O. f. Bruide-Massiak, Massif Central, Fr	
Acid, I_1 type granitoids (granodiorite, granite, mixed)	Pb, Zn ± Bar and/or Fl	M	Sk - Mgsk ? Cask ? Act, Chl, Ep	Gal >< Sph - Gar, Px, Fo (Serp)	Dep. Santa Eulalia, Chihuahua, Mexico	
			- Cask ? Act, Chl, Ep	Gal >< Sph - Gar, Px	Dep. Altyn-Topkan, Tian-Shan, Tajikistan	Ardino ore field, Central Rhodope Mt. (+ Chp)
			- Mnsk ? Q, Mn-cal	Gal >< Sph - Joh	o. f. Dalnegorskoe, Far East, RF	Madan ore field, C. Rhod. Mt. – dep. Mogilata, etc.
			Jas	Gal >< Sph - Q	Ore zone Priargunskaia, Eastern Zabaikalie, RF – dep. Ekatherino-Blagodatskoe Dep. Leadville, Colorado, USA	
		V ± M	Ser-Q ± Sk	Gal ><Sph-Q ± Fl, Bar ± Gar, Px, Joh	O. f. Freiberg, Erzgebirge, Germany O. f. Coeur d'Alene, Idaho, USA	Osogovo Mt.: Ruen o. f. (V, M – Mnsk); C. Rhod. Mt.: Davidkovo o. f. (V), Laky o. f. (V, M – Mnsk), Eniovche o. f. (V, M – Mnsk), Madan o. f. (V, M – Mnsk, one of the largest in the world: 39 dep. >2.41 Mt Pb and >1.99 Mt Zn mined); Sakar Mt.: Ustrem o. f. (> Fl, Bar) – relation with magmatism uncertain
	Pb, Ag ± Fl	M	Car (Ank, Sid) *	Agss-Gal-Q	Dep. Szabadbattyián, Hungary (+ Ank)	
				Agss-Gal-Fl-Q		? Dep. Chiprovtzi, Western Stara planina Mt. (+ Sid) – relation with magmatism uncertain
		V	?	Agss-Gal-Q	O. f. Linares – La Carolina, Spain	
			Arg-Q	Agss-Gal-Fl-Q*	Dep. Garahov, Cz	
	Bi*	M	Sk (Cask ? Tre,Act, Car)	Bis-Biss-Q + Gar, Px, Tre, Act, Car*	Dep Ustasarai, Tian-Shan, Uzbekistan	
	Fl*	V	Arg-Q	Sul(Gal, Sph)-Fl-Q	Dep. Pakozd, Hungary	
Acid, I_2 type granitoids (granite, granodiorite, mixed)	Mo ± W/Pb, Zn	M	Sk - Cask ? Mu	Sche-Mol-Gar, Px	Dep. Verhnee Kairati, Central Kazakhstan	
			- Cask ? Act, Chl, Ep	Mol-Gar, Px	Dep. Yangzi Changzhi, Liaoning, China	
				Sche-Mol-Gar, Px	Dep. Tyrnyauz, Greater Caucasus, RF	
		St, V	Gr	Mol-Q	Dep. Orekitkanskoe, E Zabaikalie, RF	O. f. Babiak, Western Rhodope Mt.
				Wol-Mol-Q	Dep. E Conrad Central Kazakhstan	
			KFs-Q	Mol-Q	Dep. Climax, Colorado, USA	
			Ser-Q	Mol-Gal, Sph-Q*	Dep. Bugdainskoe, E Zabaikalie, RF	
	W + Mo/Pb, Zn	M	Sk - Cask ? Mu	Sche-Gar, Px	Dep. Fujigatani, Is. Honshu, Japan	

1	2	3	4	5	6	7
Acid, I_2 type granitoids (granite, grano-diorite, mixed)	W + Mo/Pb, Zn	M	Sk - Cask ? Fs	Sche-Gar,Px	Dep. Sangdong, South Korea O. f. Macmillan Pass, Yukon-NW Ter. Can	Ore occurrence The Seven Rila Lakes, NW Rila Mt.
		V, St	Gr	Wol-Q	Dep. Antonovogorskoe, E Zabaikalie, RF	Dep. Polski Gradetz, Manastir Heights
				Mol-Wol-Q	Dep. Akchatau, Central Kazakhstan	
				Hüb-Q*	Dep. Bom Gorhon, W Zabaikalie, RF	
			KFs-Q	Sche-Py-Q*		Dep. Grancharitza, Western Rhodope Mt.
				Sche-Aspy-Q*	Dep. Barruecoparado, Spain	
				Hüb-Gal, Sph-Q*	O. f. Djidjinskoe, Eastern Zabaikalie, RF	
			Ser-Q	Sche-Py-Q*	Dep. Boguti, Central Kazakhstan	
	Fl*	V	?	Sul (Gal, Sph), Fl-Q		Yugovo ore field, Central Rhodope Mt.
Acid, S type granitoids (mainly granite)	Sn ± W/Be	M	Sk - Mgsk ? Cask	Cas-Gar, Px, Fo	Dep. Brooks Mountain, Alaska, USA	
			- Cask	Cas-Gar, ± Ves, Px	Dep. Moina, Tasmania	
				Cas-Gar, Px + Chryb*	Ore field Lost River, Alaska, USA	
		V, St	Gr	Cas-Q	Dep. Lailishan, Yunnan, China	
				Wol-Cas-Q	O. f. Altenberg, Germany – Cinovec, Cz	
				Cas-Wol-Q	O. d. Nanling, SE China – dep. Xihua-shan; Dep. Panasqueira, Portugal	
	Sn + Li ± Ta*	V, St	Gr	Lep-Cas-Q*	Dep.Trasquillon, Spain	
			Ab	Tan-Lep-Cas-Q	Dep. Montebras, France	
	Sn + Sul[4] +Cu/Pb, Zn±W	V, St	Tu-Q ± Chl, Hüb, Cham	Wol-Cas-Tu-Sul-Q	Dep. Ilin-Tas, Yakutia, RF	
				Cas-Tu-Pyr +Chp/Aspy/Py+ Chp-Q (Tür)	RF: ore zone Derbeke-Negliahinskaya, Ya-kutia – dep. Alis Haia; O. d. Kavalerovskii, Sikhote-Alin, dep. Dubrovskoe (Lifudzin)	
				Cas-Chp-Tu-Q	O. d. Cornwall, England – dep. Dulcote	
			Ser-Q	Cas-Gal, Sph-Q*	O. f. Krasnorechenskoe, Far East, RF	
	Be ± Fl	M	Sk (Cask ? Mu)	Hel-Fl-Mt-Gar,Px	Dep. Iron Mountain, New Mexico, USA	
		V	Gr	Ber, Bert-Q + Fl	O. f. Lake George, Colorado, USA	
			Fl, Mu[5]	Phe, Fl	Dep. in former USSR	
			Serp ? T-car	Ber, Phl	Dep. in former USSR	
	U ± Ag, Bi, Ni, Co	V	Ser-Q ?	Pitch-Ars-Sul-Car-Q (5-ел. формация)*	O. d. Schneeberg-Yahimov: dep. Schnee-berg – Germany, dep. Yahimov – Cz	
			Desilification ? Ab, Cal, Q ? Hem	Pitch-Q ± Fl	O. f. Morvan, Massif Central, France	

[4] Sul (here): Pyr + Chp/Aspy/Py, Chp
[5] Greisen in carbonate rock

1	2	3	4	5	6	7
Acid, S type granitoids (mainly granite)	B*	M	Sk - Mgsk	Kot-Fo, Px	Dep. Hol Gol, North Korea	
				Lud-Mt-Fo, Px	Dep. in former USSR	
			- Cask ? Ep	Dat-Gar, Px + Dan*	Ore field Dalnegorskoe, Far East, RF (with Pb-Zn ores)	
	Fl*	M	Cask ? Gr	Mu-Fl-Cal+Gar,Px,Cas	Dep. Solnechnoe, Central Kazakhstan	
		V	Arg-Q	Fl-Q±Sul (Gal, Sph)	O. d. E Zabaikalie, RF - dep. Solonechnoe	
Alkaline granite	TR*	M	Sk (Cask ? Act, Chl)	Bas-Mt-Gar,Px*	Dep. Båstnäs, Sweden	
	Nb	Dis	Ab	Pych-Col + Cas, Zir	Jos Plateau, Nigeria – dep. Bukuru	
Agpaite	Nb, Zr*	Dis	Fen	Zir-Pych*	Dep. Vishnevogorskoe, Ural, RF	
Miaskite	Be, Nb, Th, TR*	St	Fen	Pych-Bary + Eud	O. f. Sill Lake, Quebec, Canada	

Explanations

Economic types deposits: correspond to the main economically important component(s). Slashes between second order components with episodic appearance manifest their alternative presence. In case of more than one economic types deposits, connected with certain type magmatic complex the order is from higher to lower temperature of ore-forming. By the same reason aposkarn type deposits are situated before vein type and stockwork. In both cases typomorphic (economically significant) mineral parageneses are formed at similar temperature conditions, but in aposkarn deposits the beginning of ore-forming processes is at higher temperature.

Spreading:

═══ – widely spread (>100 ore fields, or separate deposits)

——— – widespread (30-100 ore fields, or separate deposits)

.... – limited spreading (11-30 ore fields, or separate deposits)

Not underlined – rare (6-10 ore fields, or separate deposits)

* – very rare (<6 ore fields, or separate deposits)

Morphogenetic ore types: **- V** – veins and/or linear stockworks; **- M** – metasomatic replacement bodies; **- St** – stockwork (veinlet-disseminated); **- Dis** – disseminated only.

Wallrock alteration types – the types of wallrock alteration (approximately from higher temperature to lower one) are as followed: skarn (magnesium skarn, calcium skarn, manganese skarn), amphibole (mainly actinolite, tremolite), actinolite, fenite, albitite, greisen, tourmaline-quartz ± chlorite, potassium-feldspar-quartz, biotite-potassium-feldspar-quartz, sericite-quartz, serpentine, jasperoid, hematite, carbonatisation, talc-carbonatisation, argillizite-quartz. Minerals are listed in ascending order of quantity. Differentiation is done based on typomorphic (specific) parageneses in pre-ore metasomatic alteration. Pre-ore metasomatic alterations most often are common and comparatively intensive.

Mineral types of deposits – differentiation are based on main ore and gangue minerals in the deposits. Minerals with low content, but economically significant (typomorphic) are also taken into account: for an example Au, Cas, Wol, Mol, etc. Mineral types of deposits are distinguished by the same manner as ore formations in sense of Breithaupt, Schneiderhöhn et al. In this case the object of classification is ore field, not separate deposits within them, because not such deposits, but ore field as a whole manifest peculiarities of concrete ore-forming process, including mineral type of ore. That's why in the table ore fields are given, except for individual deposits. Minerals in mineral types are in ascending order of their amount. Comma separates minerals with almost equal quantity. Abbreviations of minerals most often correspond to first letters of mineral names in English (see abbreviations).

Typical examples – ore fields with maximum concentration of ores and well studied have been selected. When deposit is individual (separate) – it is specified. For Bulgaria, in cases when economic mineralization is lacking, main ore occurrences are specified.

Abbreviations – ore objects:

Dep.	deposit	**O. f.**	ore field
O. oc.	ore occurrence	**O. d.**	ore district

Abbreviations – minerals:

Act	Actinolite	Chl	Chlorite	Hüb	Hübnerite	Ram	Rammelsbergite
Agss	silver sulphosalts	Chlo	Chloanthite	Ilv	Ilvaite	Saf	Safflorite
Amph	Amphibole	Chp	Chalcopyrite	KFs	K Feldspar	Sca	Scapolite
Aniv	Anivite	Chryb	Chrysoberyl	Kot	Kotoite	Ser	Sericite
Ant	Anthophyllite	Chrys	Chrysotile	Lep	Lepidolite	Sma	Smaltite
Ars	arsenides	Cha	Chalcedony	Lud	Ludwigite	Sche	Scheelite
Asb	Asbestos	Chal	Chalcocite	Mag	Magnesite	Sku	Skutterudite
Aspy	Arsenopyrite	Cob	Cobaltite	Mic	Microcline	Sp	Specularite
Ax	Axinite	Col	Columbite	Mol	Molybdenite	Sph	Sphalerite
Bar	Barite	Dan	Danburite	Mt	Magnetite	St	Stibnite
Bary	Barylite	Dat	Datolite	Mu	Muskovite	Sul	sulphides
Bas	Bastnäsite	Di	Diopside	Nic	Nickelline	Tal	Talc
Ber	Beryl	En	Enargite	Or	Orthoclase	Tan	Tantalite
Bert	Bertrandite	Ep	Epidote	Phe	Phenakite	Ten	Tennantite
Berth	Berthierite	Eud	Eudidymite	Phl	Phlogopite	Tet	Tetrahedrite
Bis	Bismuthinite	Fl	Fluorite	Pic	Picrolite	Tre	Tremolite
Biss	Bi sulphosalts	Fo	Forsterite	Pitch	Pitchblende	Tu	Tourmaline
Bt	Biotite	Gal	Galena	Pre	Prehnite	Tür	Türingite
Cal	Calcite	Gar	Garnet	Py	Pyrite	Ves	Vesuvianite
Car	carbonates	Gla	Glaucodote	Pych	Pyrochlor	Wit	Witherite
Cas	Cassiterite	Hel	Helvite	Pyr	Pyrrhotite	Wol	Wolframite
Cham	Chamosite	Hem	Hematite	Px	Pyroxene	Ws	Wollastonite
				Q	Quartz	Zir	Zircon

Abbreviations – wallrock alterations:

Ab	albitite	Car	carbonate (Ank, Sid)	Jas	jasperoid	Tu-Q-(±Chl)	tourmaline-quartz (±chloritisation)
Act	actinolite	Cask	calcium skarn	KFs-Q	K-feldspar-quartz	Ser-Q	sericite-quartz
Arg-Q	argillisite-quartz	Fen	fenite	Mgsk	magnesium skarn	Serp	serpentine
Bt-KFs-Q	biotite-K-feldspar-quartz	Gr	greisen	Mnsk	manganese skarn	Sk	skarn
		Hem	hematitisation	T-Car	talc-carbonate		
				Tre-Act	tremolite-actinolite		

Abbreviations – geographic names:

Au	Australia	C. Rhod.	Central Rhodope mountain	Fr	France	NW Ter.	North West Territories, Canada
Azer	Azerbaijan	C. St. pl.	Central Stara planina mountain	Is.	island	W St. pl.	Western Stara planina mountain
Brit. Col..	British Columbia, Canada	Cz	Czech Republic	M Caucasus	Minor Caucasus	RF	Russian Federation
Can	Canada			Mt.	mountain(s)		

b) Rare deposits: Au (single deposits mainly in Asian sector of Pacific metallogenic belt).

c) Very rare deposits: U (only one ore field – Bouhovo, Bulgaria). This brings up a matter of genuine genetic relationship of ore mineralization and the intrusive complex.

4. Acid[1] complexes:

Acid intrusive complexes should be distinguished to **M**, **I** and **S** granitoids (Chappel and White, 1974). Type **I**, i. e. granitoids with intrusive protolithe could be detached into two subtypes – $\mathbf{I_1}$ и $\mathbf{I_2}$, depending on ore deposits connected with them. The latter subtype according to its ore-bearing features (Mo, W) corresponds to type **I** in classification of mentioned above authors. The former subtype also manifest specific ore-bearing features: Pb-Zn+Ag, Bi. Pb, Ag and Bi are typical crustal elements and their mobility in supergene conditions is very low. Due to this their content in sedimentary rocks (pelites, sandstones) is also low. Therefore $\mathbf{I_1}$ subtype granitoids, analogues to subtype $\mathbf{I_2}$, also originate from intrusive protolithes with crustal character.

4.1. M type granitoid complexes – granodiorite, andesine-bearing trondhjemite (plagiogranite in Russian literature). Sometimes small plutons + a lot of dykes mainly with plagiogranite composition: ore field Muruntau, Uzbekistan – 4 dyke belts with 148 dykes. Subduction zones, collisional orogens (rarely, small and not so rich deposits). Typical for intrusives is low K content (K_2O usually less than 2%). According to petrogenetical classification of Didier *et al*. (1982) they could be referred to **M** type granitoids (mantle and mixed). According to classification of Barbarin (1990) they could be assigned to $\mathbf{H_{LA}}$ type (mixed, Ca-alkaline, low-K, high-Ca, subduction zones) and to $\mathbf{T_{IA}}$ type (tholeitic, subduction zones). It is well seen, that both classifications determine this type of granitoids as formed in subduction zones. It should be mentioned that Au-bearing granitoid complexes are also formed in collisional orogens. Variscan Au-bearing granitoid complexes in Bulgaria (Western Stara planina mountain, Kraishte) are of this type. Ore deposits:

[1] Their petrogenetic classification according Chappel and White (1974) is used in the table.

a) Main deposits

- a_1) Au (with high fineness): vein (main), skarn (second order), jasperoid (rare). Typical mainly for oceanic parts of subduction zones. Regions with high economic significance (500 – 1000 t Au and more): Sierra Nevada, California, USA; Australia, state Victoria, (dep. Bendigo, etc.)

- a_2) Au (with high fineness) $\pm$ Sb (stibnite): almost entirely vein. It seems that they are typical for peri-cratonic part of subduction zones (Yakutia, Bolivia).

b) Second order deposits: Sb (stibnite), vein.

c) Rare deposits:

- c_1) Fe (Mt-Sk)

- c_2) Cu (Chp-Sk).

4.2. I_1 type granitoid (crustal) complexes – granodiorite, granite, mixed. Subduction zones and mainly collisional orogens (postcollisional stage). With increasing of K content in the plutons usually ratio Pb/Zn in ores also increase: from ~ 1 in deposits connected with granodiorite intrusives to 2-3 in deposits connected with granite intrusive. Deposits with almost entirely Pb ores also appear (as Linares – La Carolina, Spain). According to classification of Didier *et al.* (1982) discussed granitoids could be assumed as $\mathbf{C_i}$ type (crustal, intrusive). They could be also compared with $\mathbf{H_{LO}}$ type, according the scheme of Barbarin (1990) – potassium Ca-alkaline (high-K, low-Ca). Some discrepancy is observed – there are no ore-studies data proving that discussed granitoids are of mixed origin (mantle-crustal), as it is specified in this classification (Barbarin, 1990). Ore deposits:

a) Main deposits: Pb $^{>}_{<}$ Zn – vein (main), skarn and jasperoid (second order). Typical for subduction zones (most often between ocean and continental margin) and late (post-nappe) stage in development of collisional orogens. Within subduction zones are widespread in Cordillera Mt., USA and Far East, RF. In collisional orogens such deposits are well expressed in Tian-Shan Mt. (Kazakhstan, Uzbekistan, Tajikistan), Erzgebirge, Germany, Rhodope Massif (Osogovo Mt., Central Rhodope Mt.), etc.

b) Rare deposits: Pb, Ag $\pm$ Fl – vein, metasomatic replacement with carbonate (ankerite, siderite) metasomatites. Granitoids are with extremely high K content.

c) Very rare deposits:

- c_1) Bi (bismuthinite, Bi sulphosalts)

- c_2) Fl (fluorite+sulphides, mainly galena) – vein, metasomatic replacement in carbonate rocks.

4.3. I_2 type granitoid complexes – crustal granite, granodiorite and mixed. Subduction zones (peri-cratonic parts), collisional orogens (restricted quantity) – postcollisional stage. Ore-bearing intrusives are enriched in K, compared with the former types (**M** and $\mathbf{I_1}$) and ratio K_2O/Na_2O varies from ~ 1.3 to 2.3 and more. According data for Mo and W deposits in Cordillera Mt. (USA, Canada), Eastern Zabaikalie, RF, and NE China K_2O content in ore-bearing granitoids varies from ~ 4.00 % to ~ 6.30 %, while Na_2O – from ~ 3.00 to ~ 4.00 %, rarely to 4.80 % (Pokalov, 1972; Naletov, 1981; Mineral Deposits of China, 1990, etc.). According to classification of Didier *et al.* (1982) discussed granitoids could be also referred to $\mathbf{C_i}$ type (crustal, intrusive). An indication for this is low Re content (typical mantle element) in molybdenite (Popov, 1977) – n.10 ppm in discussed deposits, compared with n.100 ppm in molybdenite from Cu-porphyry deposits with no doubt mantle origin. Ore deposits:

a) Main deposits: Mo $\pm$ W and W $\pm$ Mo – stockwork and vein (main), skarn (second order). Minerals: Mo – molybdenite; W – wolframite, rarely hübnerite, scheelite (skarn deposits). In subduction zones most often are situated close to the cratonic parts. Two regions of widespread deposits could be pointed: Mo (the Rocky Mt., USA – dep. Climax, et al.); W (Eastern Zabaikalie, RF). Within collisional orogens such deposits are comparatively rare, but in Central Kazakhstan significant accumulation is observed.

b) Second order deposits: W + Py, rarely Aspy – vein and stockwork (main), skarn (second order). No significant accumulation in separate region is observed. Bulgaria – dep. Grantcharitza, Western Rhodope Mt.

c) Very rare deposits:

- c_1) W, Pb, Zn (hübnerite,galena, sphalerite)

- c_2) Fl (vein, metasomatic).

4.4. S type granitoids - crustal granite complexes. Subduction zones (usually close to peri-cratonic parts), collisional orogens (restricted quantity). Compared with $\mathbf{I_2}$ type granitoids these have lower and more stable K and Na content: K_2O from ~ 4.30 to ~ 5.00 %; Na_2O – from ~ 2.80 to ~ 3.30 %. Ratio K_2O/Na_2O varies from ~ 1.3 to ~ 1.8, rarely to 1.9 (data on ore-bearing granitoids from Far East, RF, SE China, SW England, Alaska et al. – Naletov, 1981; Mineral Deposits of China, 1990, etc.). Petrogenetically discussed granitoids are crustal, sediment **S** type, according Chappel and White (1974), $\mathbf{C_S}$ (crustal, sediment) according Didier *et al.* (1982), crustal, oversaturated in Al ($\mathbf{C_{ST}}$, $\mathbf{C_{CA}}$, $\mathbf{C_{CI}}$ – Barbarin, 1990). Ore deposits:

a) Main deposits

- a_1) Sn, Sn $^{>}_{<}$ W – vein and stockwork (main), skarn (rare). Minerals: Sn – cassiterite; W – wolframite, scheelite (skarn deposits). Mainly in subduction zones of Japan type. Maximum accumulation in SE China, Birma, Malaysia, Indonesia. In collisional orogens with restricted distribution (Erzgebirge, Germany, Czech Republic).

- a_2) Sn + sulphides (chalcopyrite, pyrrhotite, etc.) – cassiterite-sulphide deposits. Within subduction zones are comparatively widespread in Yakutia and Sikhote-Alin range, RF, while in orogens – in Cornwall peninsula, England.

b) Second order deposits: U (pitchblende) – vein. Some data prove that U is almost entirely leached from granite. They are typical for orogens and are well expressed in Central Europe

(Massif Central and Armorican Massif, France) – pitchblende; Erzgebirge (Germany, Czech Republic) – pitchblende + Co-Ni arsenides and sulphides, Ag и Bi minerals (5-element formation).

c) Rare deposits: Be + Fl – vein (beryl, bertrandite), apo-skarn (helvite), apo-carbonate-greisen (phenakite); Be + Sn – skarn (chrysoberyl); Be + phlogopite – veins among ultrabasite (beryl).

d) Very rare deposits:

- d_1) Sn + Li ± Ta – vein (cassiterite, lepidolite, tantalite)

- d_2) Fl – vein, metasomatic replacement

- d_3) B – skarn (kotoite, ludwigite, datolite,danburite).

5. Alkali complexes:

5.1. Alkali granite complexes. Cratons, "hot spots". Mantle. Ore deposits: rare – Nb (columbite, pyrochlor) + Zr (zircon), Sn (cassiterite).

5.2. Agpaite complexes. Cratons, "hot spots". Mantle-crustal? Ore deposits – very rare:

a) Be, Nb, Th, TR_{Ce}; only one ore field – Sill Lake, Quebec, Canada. Ore-forming elements are geochemically contrast – Be, typical for deposits, related to **S** type granitoids and Nb, common for deposits, connected with alkali intrusives. Be minerals are specific – barylite, eudimite; as well as Nb ones – pyrochlor enriched in TR_{Ce}, Th.

b) Nb, Zr (pyrochlor); only one small deposit (Vishnevogorskoe, Ural, RF).

5.3. Myaskite complexes. Ore deposits (very rare): Nb, Zr (pyrochlor, zircon).

CONCLUSIONS

1. Metallogenic specialisation of igneous complexes and genetic relationship of ores with intrusives

Metal plutonogenic deposits are connected mainly with intermediate and acid intrusive complexes and partly with basic and alkaline intrusive complexes. Separate petrochemical types of intrusive complexes manifest quite distinct metallogenic specialisation according to main and second order deposits, expressed as follows:

- Ultabasic intrusive complexes: asbestos and talc. It should be mentioned that chrysotile asbestos and talc deposits also are formed at metasomatic replacement of rich in Mg carbonate rocks under the influence of hydrothermal solutions, related with intrusive complexes. Typical examples: chrysotile asbestos – dep. Aspagashskoe, Siberia, RF, talc – dep. Hopfersgrün, Germany.

- Basic intrusive (gabbro) complexes (rare) – Fe.

- Intermediate intrusive complexes: Cu, Fe ± Mo (molybdenite is enriched in Re – n.100 ppm).

- **M** type granitoids: Au, Sb + Au, Sb.

- **I_1** type granitoids: Pb, Zn, Ag, Bi (Pb $^{>}_{<}$ Zn + Ag, Bi; Pb+Ag; Ag; Bi).

- **I_2** type granitoids: Mo, W (Mo $^{>}_{<}$ W).

- **S** type granitoids: Sn, W, U, Fl, Be, B (Sn $^{>}_{<}$ W, Sn, Sn + Be, Be ± Fl, U, B, Fl). U deposits connected with granitoids have some specific features. In many cases (Massif Central, France – Geffroy, 1971) the presumption that U ores are precipitated by late hydrotherms, alien to the granitoids. From the other side the granitoids themselves represent source for U, mainly isomorphically included in K-feldspar

Barite deposits connected with granitoid complexes are established, although rarely and with uncertain genetic relationship. They contain usually (except barite) also Q, Cal and insignificant amount of sulphides ± Fl. Examples: dep. Badamskoe, Tian-Shan, Kazakhstan (M); dep. Chordskoe, Greater Caucasus, Georgia (V); in Bulgaria: vein deposits in Central Stara planina – Trudovetz, Visok and Kashana.

In some cases among granite plutons mainly lens-like bodies of piezo-optic quartz without sulphides are established. Probably these are allo-hydrothermal formations (leaching of SiO_2 from granitoids and then precipitation). In Bulgaria of this type seems to be quartz mineralization in Sakar granite pluton (dep. Glavanak, Hliabovo, etc. Sakar Mt.).

- Alkaline intrusive complexes: Nb $^{>}_{<}$ Ta, TR, Th. A case apart is ore field Sill Lake, Quebec, Canada, where in ores associate Be, typical for deposits related to **S** type granitoids and Nb, Th, TR_{Ce}, characteristic for deposits connected with alkaline intrusives.

Deposits transitional between mentioned above types most often represent element of zonality in ore fields. As a rule they are small by ore volume. Only in single cases ore fields with Mo, W and Sn ores are significantly enriched in Pb and Zn.

A distinct disperse is outlined for fluorite deposits – they are connected with **I_1**, **I_2** and **S** types intrusive complexes. Different deposits are accompanied by specific second order elements: Pb (galena) – in deposits connected with **I_1** type granitoids, Mo (molybdenite) – in deposits with **I_2** type granitoids, Sn (cassiterite) – in deposits with **S** type granitoids.

The geological and isotope data obtained, let us distinguish three types of genetical relationship between mineralization and certain intrusives:

a) Mineralization in direct genetic connection with intrusives, in sense that hydrothermal solutions are generated by magma, generating intrusives. Certainly as such type chrysotile asbestos, connected with auto-serpentinisation of ulrabasic rocks could be assumed. These mineralizations are not widespread and rarely economic significant accumulations are formed (dep. Abzakovskoe, Ural, RF). It seems, that direct connection with intrusive complexes have some deposits of Sn, W, Mo, Be, Li, Nb, Ta.

b) Mineralization mainly in indirect (paragenetic) relationship with intrusive complexes. Isotope investigations of H and O prove, that in many cases water in one or another degree is with non-magmatic origin. Lead isotopes in rocks and sulphides (mainly galena) in ores show similarity – a fact, that demonstrates common genesis of ores and intrusives.

c) Mineralization for which intrusives play a role of educt (allo-hydrothermal mineralizations). From this type are asbestos, talc, nephrite and magnesite deposits, which accompany allo-serpentinisation of ultrabasic rocks, or metasomatic alterations overimposed on serpentinites. It is assumed that hydrothermal fluids are connected with late intrusive magmatism. Such hydrothermal fluids always precipitate sulphides, while in deposits discussed, sulphides in practice are lacking. So more considered is an opinion that hydrothermal fluids are squeezed out from rocks during the ultrabasic sheets obduction in orogens. Quite similar is the case with asbestos deposits of non-alkaline amphibole (anthophyllite, partly tremolite and actinolite). They are usually connected with ultrabasic rocks among metamorphites in amphibolite facies. Obviously in this case metamorphic hydrothermal fluids form asbestos mineralization.

Significant influence of host rocks on the volume of ore mineralization is traced out in Fe deposits – when host rocks are mafic ones, the total quantity of Fe in ore strongly increases, well expressed in Mt-Act type deposits. It could be also presumed that Ni and Co in relevant deposits are leached out from deep-seated ulrabasic rocks. This is the only way to explain association Co, Ni, U in 5-element formation. Probably different sources (mantle and crustal magma) lead to the strange geochemical association Be and Nb (+ Th, TR_{Ce}) in mentioned above ore field Sill Lake, Quebec, Canada.

Extracting of metals from older deposits is also possible. Probably this is the way of forming of single ore fields of Mo, W and Sn with significant presence of Pb and Zn. Very well is expressed the influence of host rocks in relation to petrogenetic elements. It is distinct in case of carbonate host rocks – the quantity of carbonate minerals in ores significantly increases. From the host rocks some elements that represent impurities in rock-forming minerals are leached. In Madan ore field for an example altered wallrocks are with lower Co content, than non altered ones. Significant changes in chemical composition of ores are not observed.

2. Spatial connection of ores with intrusives

Ores in most of hydrothermal deposits are situated within the intrusives themselves or/and close to them. Ores of Pb, Zn and Sb represent an exception. In case with Pb and Zn deposition of ores could accomplish at 1 km and even more from the intrusive body, sometimes associating with dykes. Sb ores represent even extreme case – because of their low deposition temperature (less than 220° C) they are precipitated even farther from intrusives. So, if the erosion had outcrop the intrusive, the ores could be entirely destroyed. Controversial, if the ores are outcropped by erosion pluton might not outcrop at the surface. The situation with barite and fluorite deposits is similar.

3. Connection of mineralization with metasomatites

Nephrite: Serp → Tre; Asbestos: Serp → amphibolisation (Act, Tre); Talc: Serp → T-Car; Fe (Mt) deposits: accompanying skarn (in carbonate rocks), Act (in mafites); Cu: in carbonate rock aposkarn, rarely apo-carbonate jasperoids, in silicate rocks Bt-KFs-Q (Cu-Mo-porphyry deposits), Ser-Q (vein deposits); Au: in carbonate rocks aposkarn rocks, rarely apo-carbonate jasperoids, in silicate rocks most often Ser-Q, rarely Tu-Q and KFs-Q; Pb >< Zn: in carbonate rocks aposkarn ores, but also often apo-carbonate jasperoids, in silicate rocks Ser-Q; Pb, Ag ± Fl: in carbonate rocks Car (Ank, Sid), in silicate rocks Arg-Q; Mo: in carbonate rocks aposkarn ores, in silicate rocks Gr, more rare KFs(Or)-Q, rarely Ser-Q; W: in carbonate rocks aposkarn ores, in silicate ores Gr, more rare KFs-Q, very rare Ser-Q; Sn: in carbonate rocks aposkarn ores, in silicate rocks Gr; Sn + S: Tu-Q±Chl, rarely (with Pb-Zn) Ser-Q; Be: in carbonate rocks aposkarn ores, rarely Fl-Mu apo-carbonate Gr, in alumosilicate rocks Gr, in ultrabasites Serp → Phl; B: aposkarn ores; Sb: Ser-Q; U: Ser-Q, Hem; Fl: in carbonate rocks aposkarn ores, in silicate rocks Arg-Q?; Fl + Sul (mainly Gal): Arg-Q; TR: aposkarn ores; Nb: Ab; Nb, Zr: Fen.

4. Geodynamic environments of forming

Plutonogenic hydrothermal de4posits are formed in following types of geodynamic environments:

- Subduction zones – deposits connected with basic and intermediate intrusive complexes.

-Subduction zones and collisional orogens – deposits connected with $\mathbf{I_1}$, $\mathbf{I_2}$ and **S** type granitoid intrusive complexes. Probably the case with deposits connected with **M** type granitoid intrusive complexes is similar, but deposits in subduction zones predominate.

- Orogens – deposits included in allochtonous ultrabasic bodies (mainly peridotite complexes).

- Cratons – “hot spots”: deposits connected with alkaline intrusive complexes.

5. Metallogenic epochs

Hydrothermal deposits, connected with intrusive complexes are almost entirely Phanerozoic. Single pre-Phanerozoic metal deposits are also established, mainly in the Baltic shield: Sn – ore field Pitkiaranta, Carelia, RF; Mo and W±Mo – respectively ore field Knaben and dep. Ersdallen, South Norway. During the Phanerozoic deposits are typical for all metallogenic epochs. At the end of Alpine metallogenic epoch (after Oligocene) they strongly decrease. The only exclusion is Southern part of Pacific metallogenic belt, where Au plutonogenic deposits with age 5 – 10 Ma (Upper Miocene) are formed: dep. Porgera, Papua New Guinea, 7 – 10 Ma (420 t Au); Dep. Masra, Philippines, 4.7 Ma (28 t Au).

Connected with intrusive complexes hydrothermal deposits in Bulgaria are formed in Late Palaeozoic (Variscan epoch – Western Stara planina, Kraishte), Late Mesozoic (mainly Srednogorie and Strandja zones) till Oligocene (Rhodope Massif).

6. Economic significance of plutonogenic hydrothermal deposits

1st place: Mo, W, Sn, Cu (equally with copper sandstones), Asb, Tal, nephrite

2nd place: Sb – after stratiform deposits, Nb (Ta) – after carbonatite deposits.

3rd place: Pb, Zn (+ Cd, Ag. Bi) – after stratifiorm and massive sulphide deposits, Au – after gold-bearing conglomerates and massive sulphide deposits, U – after elision-hydrothermal and infiltration deposits, Be – after pegmatite and volcanogenic-hydrothermal deposits.

Without considerable economic significance (as separate deposits): Bar, piezo-optic Q, Co, Ni Li, TR, Zr, Ag, Bi.

7. Economic significance for Bulgaria

1st place: Pb, Zn (+ Cd, Ag, Bi), Cu, Asb, Tal.

2nd place: Fe – after siderite (Kremokovtzi), Au – after massive sulphide (copper-pyrite) deposits.

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