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DETERMINATION PRINCIPLES OF ORE-BEARING (Mo—W—Sn) GRANITES AND THEIR THERMOBAROGEOCHEMICAL FEATURES

(Fig. 1, Tabs. 3)

A b s t r a c t: Among granitic intrusions, which are accompained or contain greisen-vein mineralization, some may behave as passive wall rock, the other may heat underground water and initiate its convection, the third may be the source of ore-forming solutions. Only intrusions of the last type must be determined as ore-bearing ones. Such intrusions are recognized by means of fluid inclusions studies: composition of the primary inclusions in minerals of ore-bodies was being compared with magmatic fluids composition, which are present in quartz of granites as primary fluid inclusions, syngenetic to melt inclusions. Salt composition of solution and ore-forming elements concentration are established using freezing and laser-spectral methods. It is found that hydrothermal ore-forming solutions distinctively inherit the composition of magmatic fluids. The melt inclusions studies has shown that ore-bearing intrusions, as distinct from barren ones, are characterized by the heightened initial water content ($\geq 4\,\%$ against ≤ 2—3), and intensive distillation into them begins at the early, but not at the final stages of magmatic crystallization. Using worked up thermobarogeochemical criteria new mineral occurrences are found.

Резюме: Среди гранитных интрузий, сопровождаемых или вмещающих оруденение грейзеново-жильного типа, одни могут играть роль пассивной рамы, другие — нагревать подземные воды и возбуждать их конвекцию, третьи — служить источником металлоносных растворов. Лишь последние следует считать рудоносными. Такие интрузии выявлены посредством сопоставления состава первичных флюидных включений в минералах рудных тел с составом первичных (сопутствующих) включений магматического флюида, которые присутствуют в кварце гранитов и сингенетичны расплавным включениям. Солевой состав флюида и содержание в нем рудообразующих элементов определены методами криометрии и лазерной спектроскопии. Установлено, что гидротермальные растворы отчетливо наследуют состав магматического флюида. Изучение расплавных включений показало, что рудоносные интрузии отличаются от ординарных (безрудных) повышенным исходным водосодержанием ($\geq 4\,\%$ против ≤ 2—3), а интенсивная дистилляция в них начинается не на завершающих, а на ранних стадиях магматической кристаллизации. Благодаря использованию разработанных термобарогеохимических критериев выявлены новые рудные объекты.

An idea about special ore-forming role of granitic intrusions is based upon the empirically established fact that certain types of hydrothermal deposits of Mo, W, Sn, Cu, and some other metals are usually situated in (or near) granitic massives. Existent views on the cause of this regularity may be roughly groupped in two alternative conceptions. According to the first of them, ore mineralization is located near the intrusion, because a magmatic melt is the main source of ore-bearing solutions. The second conception assignes to be

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intrusive body the role of a thermal energy source, stimulating convection of non-magmatic waters, which extract metals from the rocks washed and deposit them at geochemical barriers.

It is quite probable that both the principles are realized in nature. But if according to the first conception, the possibility of deposits formation is indeed caused by the melt composition and the peculiarities of magmatic crystallization, then, according to the second one, water and metal contents in country rock come to the fore. As appears from the above-said, in either case a magmatic body is supposed to play an important role, but only the first case gives reasons to consider the intrusion as an ore-bearing one. In this sense of the term the main principle of determination of ore-bearing granites must consist in existence of a clear-cut dependence between the probability of ore-forming hydrothermal system origin and the peculiarities of the magmatic process development.

This principle underlines mineralogical-petrographic and geochemical approaches to subdividing granitic intrusions into ore-bearing and ordinary (barren) ones. But the rocks used in these cases are only "dry residue" of the former magmatic melts and do not reflect their composition in full measure. Moreover, rocks do not give direct information about state of aggregation and phase composition of mineral-forming medium. In a large measure, therefore, there are alternative points of view on many "near-intrusive" deposits origin, including, for example, the well-known tungsten-tin deposits of Cornwall (Charoy, 1980; Alderton—Moore, 1981; Brown et al., 1980).

Inclusions of mineral-forming medium in crystals give far more complete genetic information in comparison with rock. Therefore, we have approached dilemma under discussion on the basis of fluid and melt inclusions studies in minerals of granites and hydrothermal rocks with tungsten and molybdenum mineralization of greisen-vein type, which accompany some of the investigated intrusions. Inclusions studies were forestalled by geological and mineralogical-petrographic investigations with a view of establishing the succession igneous and hydrothermal rocks formation and the order of minerals crystallization, determining mineral associations and successive generations of individual minerals (Reyf—Bazheev, 1982). For example, Fig. 1 represents the sampling net of Soktuy granite massive measuring 300 km^2. As a result of microscopic study of immersion preparation made from every sample, all inclusions were classified, prevalence of different inclusion types was ascertained, the most representative specimens were selected for making polished plates. The latter were used for establishing primary (secondary) nature of the inclusions and their fittness for heating, freezing and laser-spectral investigations. All these measures make the results, that characterize certain stages of process, to be representative. In this way we have researched more than 20 hypabyssal granitic intrusions, one half of which accompained by considerable ore mineralization and others were barren (ordinary).

The main regularity revealed consists in the following. Only those intrusions are ore-bearing, which separate considerable amounts of fluid-saturated melt as a product of their evolution. On ore veins level injections of such melts are represented by the premineral granite or granite-porphyry dikes, which are formed at the latest intrusive phase. The fluid-saturated state of this dike-

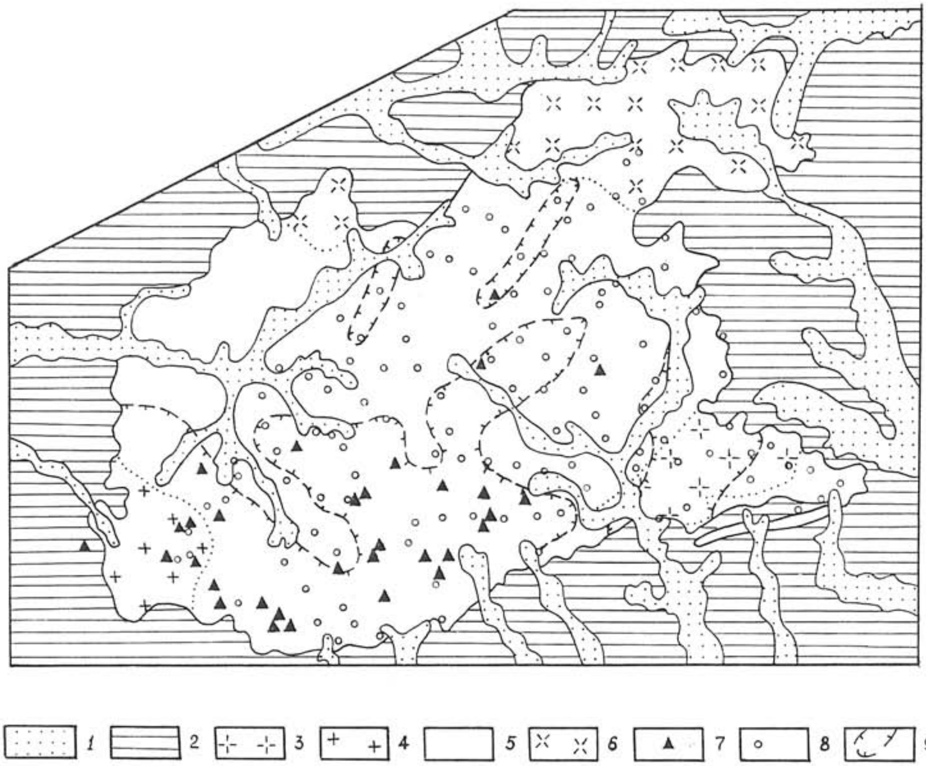

Fig. 1. The sampling net of Soktuy granite massive.
Explanations: 1 — Quaternary sediments; 2 — Mesozoic and Paleozoic sedimentary-metamorphic rocks; 3–6 — igneous rocks: 3 — granite-porphyry; 4 — fine-grained granite; 5 — coarse-grained-granite; 6 — quartz monzonite; 7 — W and W-Sn mineral occurrences; 8 — points of sampling; 9 — outcrop area of fluid inclusions containing two solid phases involving halite.

-forming melt already at early crystallization stage is proved by the presence of syngenetic primary both melt and fluid inclusions ("accompanying", by Y e r m a k o v, 1978) in phenocrysts. Intratelluric nature of the latter is confirmed by their availability in fine-grained rocks of chill zones.

With the help of the devised technique of laser-microprobe analysis of individual fluid inclusions (I s h k o v—R e y f, 1980; R e y f—I s h k o v, 1982) it was found that the magmatic fluid, trapped by phenocrysts, is characterized by such high concentration of "ore" elements, as hydrothermal solutions are (R e y f—I s h k o v, 1983). In the Tab. 1 the analysis results of the magmatic fluids and ore-bearing hydrothermal solutions analyses are shown in comparison with the data on postmineral solutions. Results of comparative freezing studies of the accompanying fluid inclusions in magmatic quartz and the primary inclusions in quartz of hydrothermal veins are represented in the Tab. 2. Distinct inheritance of the magmatic fluids salt composition by the hydro-

Table 1

The results of laser-microprobe analysis of natural fluid inclusions

Sample number	Object, (host mineral)	Homogenization temperature, °C	Summary volume of analysed inclusions, $n \cdot 10^{-9}$ ml	Metal concentration, gramme per litre of the fluid under PT-conditions of inclusion formation				Other elements (qualitative determination)
				W	Mn	Fe	Mo	
1	2	3	4	5	6	7	8	9
				Magmatic-stage fluids				
611-A-40	Marictikan W-bearing intrusion	730—720	67	21 6—74	144 111—187	98 75—127	<0.7	Mg, Ca
611-A	(quartz)	730—720	270	<7	185 62—555	96 32—288	<0.8	Sn, Cu, Zn, Ti, Mg, Ca
KK-34	Soktuy W-bearing intrusion	295—280	15	<133	0.3 0.1—0.9	18 6—54	<13	Mg, Ca
KK-34	(quartz)		55	45 10—158	0.3 0.2—0.4	75 58—98	<0.9	Sn, Mg, Ca
				Hydrothermal solutions of ore-deposition stage				
D-157-2	(fluorite) Dzhida	260—240	36	22 17—29	98 75—127	250 192—325	<1	Zn, B, Ti, Mg
D-33	W deposit (quartz)	260—240	51	53 31—90	76 33—175	<0.2	<4	Cu, Mg, Ca
D-33		255—240	70	30 21—42	47 20—108	7 4—21	<3	Cu, Mg, Ca

1st continuation of Tab. 1

1	2	3	4	5	6	7	8	9
D-33		255–240	80	125 / 66–238	112 / 25–493	11 / 5–24	<3	Cu, Be, B, Mg, Ca
		Hydrothermal solutions of post-ore-deposition stage						
D-128-5	Dzhida W-deposit (fluorite)	210–200	32	<17	4 / 3–5	267 / 205–347	<1.7	not detected
D-155		185–165	36	<14	1.3 / 1–1.7	123 / 95–160	<1.4	not detected
D-155		220–210	19	<25	0.02 / 0.006–0.07	39 / 11–136	<2.8	not detected
D-27	(quartz)	170–160	150	<3	<0.06	<0.07	<0.3	not detected

Comment: in the columns 5, 6, and 7 above the line – analytical result, under line – the confidence interval for probability of 68 %.

Table 2

Comparative thermometric and freezing character of the magmatic and hydrothermal fluids

Solution trapped type	Tepmerature, °C		Typomorphic phases and their propeties
	homogenization	eutectic melting point	
Spokoynoe ore field			
Magmatic fluids	300	$-25.8 \ldots -22.5$	L_c, S_I ($Np \approx N_L$), $\Delta N = 0.015 \ldots 0.05$
Hydrothermal solutions of:			
deposition stage	315 ... 290	$-26.5 \ldots -23.2$	L_c, S_I ($Np \approx N_L$), $\Delta N = 0.015 \ldots 0.05$
post-deposition stage	270. ... 215	-21.8	are absent
Soktuy ore field			
Magmatic fluids	510 ... 500	$-60.7 \ldots -59.4$	S_I–NaCl; S_2 ($N \leq N_L$); S_3 ($N > N_q$)
Hydrothermal solutions of:			
pre-deposition stage	470 ... 460	$-59.0 \ldots -58.3$	S_I–NaCl; S_2 ($N \leq N_L$); S_3 ($N > N_q$)
pre-deposition stage	685 ... 665	$-24.5 \ldots -23.8$	S_I–NaCl; S_2 ($N \leq N_L$); S_3 ($N > N_q$)
deposition stage	350 ... 340	$-23.2 \ldots -21.8$	S_2 ($N < N_L$)
post-deposition stage	160 ... 150	-21.1	are absent

Explanations: L_c — liquid CO_2; S — solid phase; indexes of refraction: N — of crystal, N_L — of solution trapped, N_q — of quartz (host mineral); $\Delta N = Ng - Np$. Mind: homogenization temeprature is not equal to the temperature of mineral formation.

thermal solutions together with the laser-microprobe data indicates that the main source of the ore-bearing solutions is the fluid-saturated magma formed owing to differentiation of the intrusive on the whole.

We believe that a low degree of crysytallization of such fluid-saturated magma creates favourable conditions for the extraction of metals by the coming upwards fluid bubbles and collection of them in apical parts of the intrusion with subsequent mooving off into fractures of wall rock.

Radical distinction of ordinary (barren) intrusions from ore-bearing ones consists in the following: differentiation of them does not cause large masses of the fluid-saturated melt to be separated, although the saturation of residual magma at the last stages of crystallization takes place. This conclusion is based on the results of the study of inclusions in granites which form the main intrusive phases and vein derivates.

Accompanying inclusions are revealed here very seldom and only in the late-magmatic quartz, forming periphery parts of grains and filling interstices between earlier idiomorphic crystals. Such interrelations are peculiar even to granites of final intrusive phases and their vein derivates (aplites). Hence the fluid-saturated state of magma which forms ordinary granitic intrusions arises only at late crystallization stage when the melt is almost exhausted and fills intergranular space of crystalline framework.

We believe in these cases the magmatic fluid separated from intergranular melt to be also metal-bearing. But because of unfavourable conditions for upward migration, a great bulk of this fluid is concealed within rocks and later produces autometasomatic transformation of granites and a slight hydrothermal alteration of them at local sites.

The cause of such essential distinctions between ore-bearing and ordinary intrusions will become intelligible if the data given in Tab. 3 are taken into account. They reflect the results of water content determination in melt inclusions using Naumov's method (1979) with the precision characterized by the relative standard deviation of 15.8 %. It is important to emphasize that inclusions for this procedure were selected in the early-magmatic quartz from granites of the first intrusive phases, therefore the estimations obtained concern initial water content in magmas.

As appears from the above, the ore-bearing intrusions systematically differ from the ordinary ones in hightened initial water content. Detected distinctions are not too great, but they essentially affect phase composition and geological properties of magma and thereby determine the ability of a magmatic system to generate large cumulations of the fluid-saturated melt. We assume that isolation of a compact reservoir of such melt just gives to the magmatic fluids a possibility to form concentrated flows in the above-intrusive zone.

It is establisher that magma with low water content also may be ore-bearing, if it is anomalously enriched with chlorine (about 0.25 % in Mariktikan intrusion). But even in these cases saturation of the magma and separation of fluid at the early stage of crystallization because of low chlorine solubility in granitic melt is a decisive factor.

Here we must remind of Ryabchikov's (1975) and Burnham's (1979) data which argue that crystallization of any relatively large granitic intrusion inevitably results in a transition into fluid of such metals masses, which are enough for ore deposits formation, even when concentration of water, chlorine, and trace elements in the melt are ordinary. But why ore mineralization do not accompain every intrusion?

It is assumed that although each water-bearing intrusion produces metal--bearing fluids, the unusually favourable combination of structural, geological, geochemical, and the other conditions is required in order to mobilize these fluids and collect them into local structure. In other words, even ordinary intrusions are supposed to be potentially ore-bearing, but realization of this potentialities depends on-magmatic factors.

Table 3

Initial water content of ore-bearing and ordinary granite intrusions determined by melt inclusions studies

Intrusions, intrusive phases		Initial water content, wt. %
		1 2 3 4 5 6 7
Ore-bearing (W, Mo, Sn)		
Hudzhir:	II	--------+-+
	III	-------------+-++
	IV	----------++
	V	----------+
	VI	-----------++
Spokoynaya:	I	-----+
	II	---------+-+
Mariktikan		-++
Soktuy		----------++
Zharchiha		---------+++
Akchatau	I	----------+
	II	------------+
	III	-------------+
Ordinary		
Maitas	I	-----+
	II	------+
Hurtugha		------++
Subutuy		----+
Ulegchin		---+
Angyr		----+--+

Nevertheless, the analysis of thermobarogeochemical data obtained has shown that if initial water content of granitic melt exceed 4 %, its crystallization creates (as it were automatically) the conditions for intensive fluid separation only that moment, when favourable drain structure has arisen. Therefore, we believe the magmatic factors to be determinant.

The data presented allow to formulate the main thermobarogeochemical features of ore-bearing intrusions:

1. High (≥ 4 %) water content in the melt inclusions which are found in early-magmatic quartz of granites of the first intrusive phase indicates the possibility of fluid-saturated melt to be accumulated at the depth of this

intrusion. This indication must stimulate looking for outcrops of such magma at the contemporary erosion level as stocks and dikes.

2. Availability of accompanying fluid inclusions in the early-magmatic quartz of certain granitic intrusion indicates that it has been the source of magmatic metal-bearing fluids. The size of this granitic body allows to judge how deeply this intrusive system has been eroded. If the erosion has opened only dike- and stock-like juts of underlying pluton, the probability of ore deposit discovery (including blind ones) is the greatest. If at surface a big massif of ore-bearing granites has outcropped, a considerable part of ore bodies is supposed to be eroded.

Using these criteria we have estimated several areas for tungsten and molybdenum mineralization of greisen-vein type. One of six was considered to be highly perspective because fragments of granite-porphyry were found here, which contain the phenocrysts of quartz separated from the fluid-saturated melt. No direct indications of ore mineralization at this prospect were known. Nevertheless, by the following detail search a molybdenum deposit of stockwork type was discovered here. Large-scale prospecting made by a geological party on other prospects has confirmed our thermobarogeochemical data about their unperspectivity as regards tungsten and molybdenum mineralization.

In conclusion, we should like to note that confirmation of the prognoses based on the reported criteria not only indicates their applicability for solving practical tasks, but also proves that the discussed factors and mechanisms do cause the ore productivity of granitic intrusions, with regard to W and Mo at least.

REFERENCES

ALDERTON, D. H. M. — MOORE, F., 1981: New determination of tin and tungsten in granites from south-west England. Mineral. Mag. (London), 44, 335, pp. 354—356.

BROWN, G. C. — CASSIDY, J. — OXBURGH, E. R. et al., 1980: Basement heat flow and metalliferous mineralization in England and Wales. Nature (London), 288, 5792, pp. 657—659.

BURNHAM, C. W., 1979: Magmas and hydrothermal fluids. In: Geochemistry of hydrothermal ore deopsits. 2-nd ed., H. L. Barnes ed., John Willey and Sons, New York, Chapter 3.

CHAROY, B., 1980: Deuteric phenomena and associated fluids in granitic rocks. Metallogenic developments. Sci. Terre. Inform. geol., 13, pp. 23—40.

ИШКОВ, Ю. М. — РЕЙФ, Ф. Г., 1980: Лазерно-спектральный микроанализ жидкой фазы индивидуальных включений. Геохимия (Москва), 9, pp. 1407—1412.

РЕЙФ, Ф. Г. — БАЖЕЕВ, Е. Д., 1982: Магматический процесс и вольфрамовое оруденение. Наука, Новосибирск, 158 pp.

РЕЙФ, Ф. Г. — ИШКОВ, Ю. М., 1982: Возможности использования лазерного микроанализатора для изучения состава жидкой фазы индивидуальных включений. В кн: Использование методов термобарогеохимии при поисках и изучении рудных месторождений. Недра, Москва, pp. 14—25.

РЕЙФ, Ф. Г. — ИШКОВ, Ю. М., 1983: Первые результаты прямого определения концентрации рудообразующих элементов в магматическом дистилляте вольфрамоносных интрузий. Докл. Акад. Наук СССР, 269, 3, pp. 725—728.

РИЯБЧИКОВ, И. Д., 1975: Термодинамика флюидной фазы гранитных магм. Наука, Москва, 232 pp.

ЕРМАКОВ, Н. П., 1978: Информационные ряды и значение сопутствующих включений в минералах интрузивных пород и руд. In.: Термобарогеохимия земной коры и рудообразование. Наука, Москва, pp. 5—10.

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