GEOLOGICKÝ ZBORNÍK — GEOLOGICA CARPATHICA, 36, 3, BRATISLAVA, JUNE 1985,
Pp. 337—346

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EVOLUTIONAL IGNEOUS GROUPS AND SERIES AND ASSOCIATED RARE-METAL MINERALIZATION

(Figs. 4)

Abstract: Metallogenic analysis of the USSR territory provides evidence that virtual mineralization of magmatic formation is considerably determined by different evolutional groups and series they belong to. The following evolutional groups of magmatism have been recognized for rare-metal mineralization: 2 granitoid — „the long one" — gabbro-diorite — granodiorite; granosyenite — granite — alaskite — alkaline granite (W, Mo, Bi, Nb, Zr, TR and others) and "the short one" — diorite — granodiorite (trondhjemite) — granite — leucogranite (Sn, W, Ta, Cs, Li and others); and 3 alkaline — alkaline-ultramafic (Cr, Pt, Fe, Ti, Al, Zr, Nb, TR, Ba and others); alkaline-mafic (Fe, Ti, Al, Cu, Zr, Nb, TR, and others); and alkaline-salic (Al, Zr, Nb, TR, Rb, Sr, Ba, Pb, F and others). Maximum of rare-metal mineralization associated granitoid suites is related to orogenic and activation zones, island arc, and that of alkaline rocks — to rift zones. There are the following major epochs of endogenic rare-metal mineralization in the USSR: D_{1-2}, T, J_3—K_1 within the rift zones with alkaline magmatism; and PR_1/PR_2, D_{2-3}, C_3—P_1, K_2—P_1 — within the orogenic and activation zones with granitoid magmatism. The groups are divided into 13 series. The following 3 trends are recognized for granitoid groups: normal alkalinity, higher alkalinity and with antidromic termination. The series in alkaline groups are revealed by sodic and potassic specialization of alkalinity. The groups and series of magmatic formation are complementary associated with metasomatic ore-bearing formations. All revealed series are associated with the certain group of rare-metals and they are very different in the scale of development for the same type of ore formation, which sometimes has the similar set of rare-metals. Prognostic metallogenic investigations are based on the reveal regularities and provide the subsequent detailing of the territory. It leads to the recognition of more local potential ore-bearing regions and to the determination of their mineralization (Fig. 5).

Резюме: Металлогенический анализ территории СССР свидетельствует о том, что реальная рудоносность магматических формаций в значительной мере определяется принадлежностью их к различным эволюционным рядам и сериям. Применительно к редкометальному оруденению оказалось возможным выделить 5 эволюционных рядов магматизма: 2 гранитоидных — ,,длинный" габбро-диорит — гранодиорит; граносиенит — гранит — аляскит — щелочногранитовый (W, Mo, Bi, Nb, Zr, TR и др.) и ,,короткий" диорит — гранодиорит (трондьемит) — гранит — лейкогранитовый (Sn, W, Ta, Cs, Li и др.) и 3 щелочных — щелочно-ультрамафический (Cr, Pt, Fe, Ti, Al, Zr, Nb, TR и др.); щелочно-мафический (Fe, Ti, Al, Cu, Zr, Nb, TR и др.) и щелочно-салический (Al, Zr, Nb, TR, Rb, Ba, Pb, F и др.). Максимум редкометальной минерализации, связанной с гранитоидными рядами, приходится на островодужные, орогенные

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и активизационные, а со щелочными — на рифтогенные зоны. Для СССР намечаются следующие важнейшие эпохи эндогенного редкометального рудообразования: в рифтогенных зонах со щелочным магматизмом — D_{1-2}, T, J_3—K_1, в орогенных и активизационных с гранитоидным магматизмом — PR_1/PR_2, D_{2-3}, C_3—P_1, K_2—P_1. Ряды подразделяются на 13 серий: в гранитоидных рядах различают по три варианта серий — нормальной и повышенной щелочности и с антидромным завершением, в щелочных — серии выделяются по Na или K специализации щелочности. Ряды и серии магматический формаций комплементарно дополняются метасоматическими, как правило, рудоносными формациями. Все выделенные серии специализированы в отношении определенной группы редких металлов и резко отличаются масштабами развития однотипных рудных формаций, нередко со сходным набором редких металлов. На выявленных закономерностях базируются прогнозно-металлогенические исследования, ход которых предусматривает последовательную детализацию территорий с выделением все более локальных перспективных площадей с уточнением их рудоносности.

The purpose of the article is to demonstrate a great informative value for science and practical importance of the recognition, apart from igneous assemblages (magmatic formation) their evolutional groups and series and associated rare-metal industrial mineralization. An evolutional group is defined as a consistent succession of magmatic formations emerging in the course of unidirectional development of large crustal blocks. A series is a variety of evolutional groups which show compositional variations of rocks constituting individual assemblages, mainly at the terminal development stages (Beskin, 1979; Izokh, 1978; Magmatic formation…, 1979; Marin, 1983; Mineralization and…, editor Rundquist). Here we mean the well-known basic Baer's law of classification, i.e. the development of an object proceeds in such a way that features of type arise originally, then successively those of class, genus, species and individuum.

The recognition of group and series is based on the data obtained in compiling metallogenic maps and maps of magmatic formation of the USSR (Magmatic formation…, 1979; Orlova, 1982; Mineralization and…, editor Rundquist).

The following problems relevant to endogenic rare-metal ores were to be resolved:

1. What minimum number of evolutional groups and series reflect the variety of types of rare-metal mineralization?

2. What is the nature of magmatic evolution in terms of different evolutional schemes?

3. How the recognized groups and series can be used in prospecting, survey?

Now we would like to present our main conclusions.

1. The map of structural-metallogenic zones in the USSR show 21 types of zones connected with intrusive magmatism (Mineralization and…, editor Rundquist), including 11 zones with rare-metal mineralization. It is to be noted, that maximum of rare-metal mineralization associated with granitoid suites is related to orogenic and activation zones (partly island arc, late geosynclinal ones) and that of alkaline rocks — to rift zones. The following major epochs of endogenic rare-metal mineralization can be outlined in the USSR (Fig. 1): D_{1-2}, T, J_3—K_1 within the rift zones with alkaline magmatism;

PR_1/PR_2, D_{2-3}, C_3—P_1, K_2—P_1 — within the orogenic and activation zones with granitoid magmatism. Phanerozoic magmatism was largely treated by the authors, who show most prominent age difference in granitoid and alkaline suites and their distribution in time.

2. Virtual mineralization of magmatic formations is considerably determined by different evolutional groups and series they belong to. 5 evolutional groups (Fig. 2) — 3 alkaline (III—V) and 2 granitoid (I—II) and 13 series which differ in the initial members, evolutional trends, extent of occurrence, degree of completeness, have been recognized for rare-metal mineralization. The evolutional groups are shown on the Bowen's ternary diagram that (Fig. 2) is very convenient for such evolutional considerations, since it permits 3 major igneous trends with time to be clearly displayed: increasing acidity (Q), alkalinity (L) and basicity (M); mafic rocks located in the centre of triangle (υ) are particularly important in the analysis of evolutionary trends.

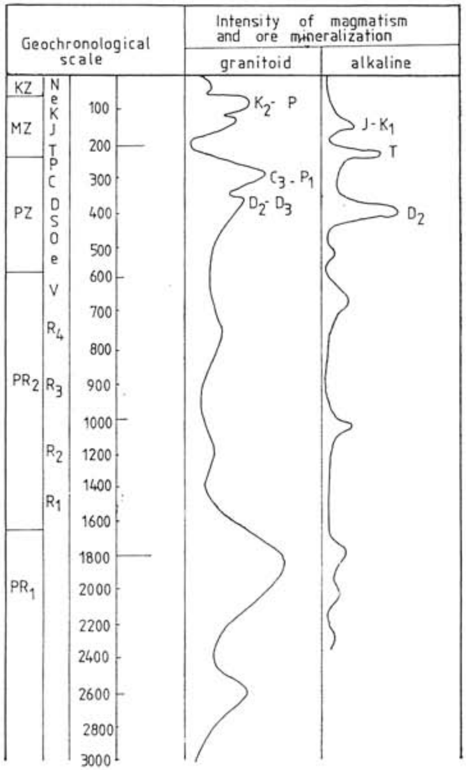


Fig. 1. Intensity of granitoid and alkaline magmatism and associated rare-metal mineralization in the USSR.

Rare-metal mineralization of the above groups bears some features of both magmatic and post-magmatic origin. Metasomatic complexes associated with the ores (skarns, greisens, feldspatholiths, fenites) form, in turn, the groups succeeding the igneous and complementary to them series (Fig. 2b).

It is to be emphasized that the revealed groups are but parts, maintly terminating fragments of more extensive series evolving over large time-spans, e. g. of major petrochemical series — tholeiitic, calc-alkaline (basalt-andesite-rhyolitic) and alkaline (basalt-trachyte-andesite) treated in works of A. Miashiro, A. A. Marakushev, O. A. Bogatikov and others (Bogatikov, 1980; Marakushev, 1979; Mineralization and ..., editor Rundquist).

3. The localization of alkaline magmatism in zones of transection of long-lived magma-controlling structures is its distinct feature. It usually results in the formation of a single complicated zonal body or volcano-intrusive unit. Rare-metal-REE deposits associated with groups of alkaline suites are characteristic of riftogenic structures, extent of distribution of each group and related mineralization being different in fold areas and platforms (Magmatic

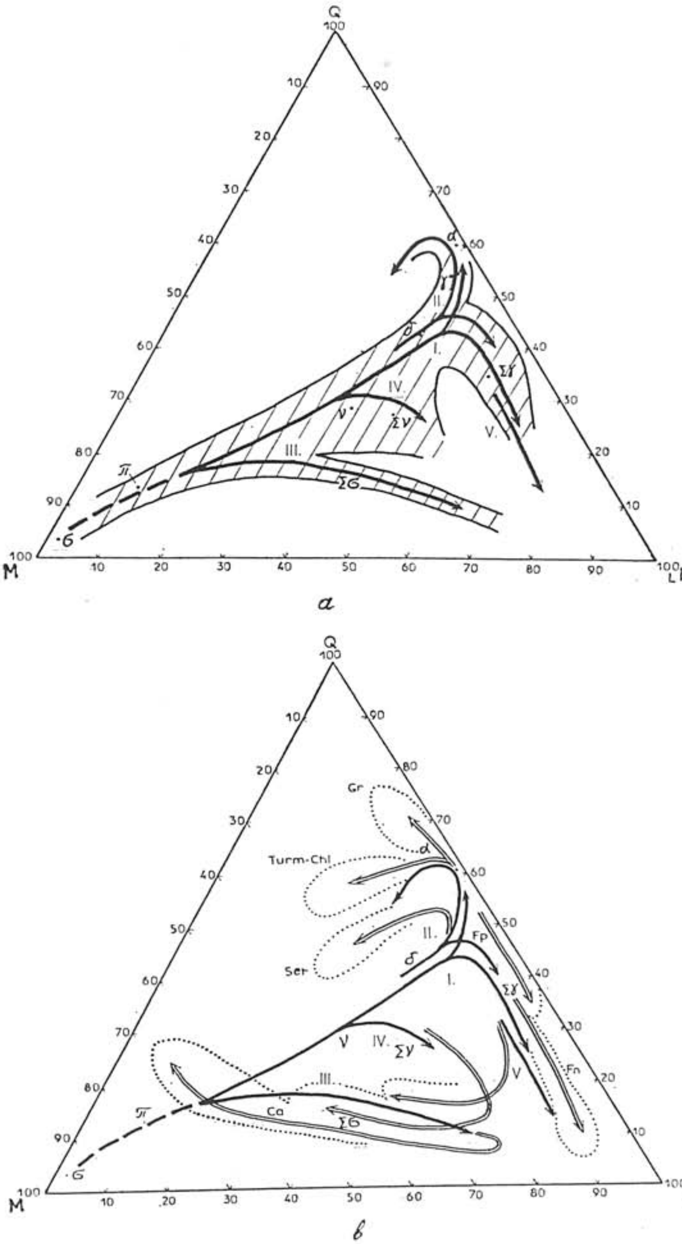


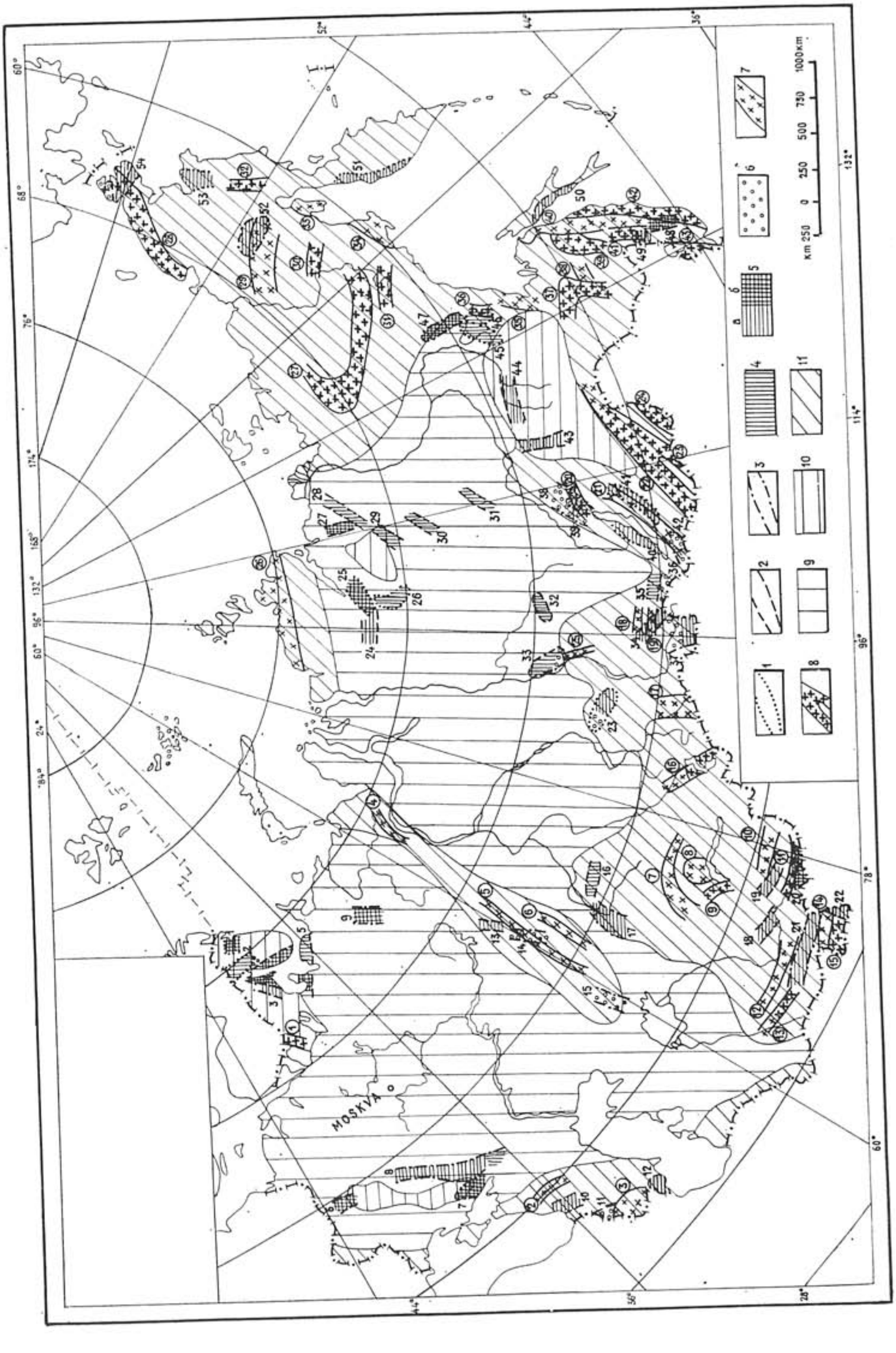
Fig. 2. Major evolutional groups (I—V) of magmatism (a) and complementary metasomatic (b) associated rare-metal mineralization, plotted B o w e n's diagram.
Explanations: σ — dunites, π — pyroxenites, ν — gabbro, δ — diorite, γ — granite, $\Sigma\nu$ — alkaline mafic, $\Sigma\sigma$ — alkaline ultramafic, α — alaskites, $\Sigma\gamma$ — alkaline granite, Gr — greisen, Turm-Chl — tourmaline chloritic metasomatites, Scr — skarns, Fp — feldspatholiths, Fn — fenites, Ca — carbonatites.

formation..., 1979; Orlova, 1982). A complete evolutional groups (series) of magmatic formations for epi-cratonic rifts can be shown as follows: basalt-dolerite $\longrightarrow$ trachybasalt $\longrightarrow$ alkaline-mafic $\longrightarrow$ alkaline-ultramafic $\longrightarrow$ alkaline-salic suites $\longrightarrow$ alkaline lamprophyres and kimberlites. A shorter series is more common for epi-orogenic rifts: alkaline gabbroids, alkaline basaltoids and basaltoids of normal series $\longrightarrow$ nepheline, calcilite-nepheline and alkaline syenites $\longrightarrow$ alkaline granites $\longrightarrow$ alkaline lamprophyres. Rare-metal mineralization is related only to alkaline suites, so authors consider but fragments of complete evolutional groups. The following 3 groups are recognized: alkaline-ultramafic (III), alkaline-mafic (IV) and alkaline-salic (V) which differ in evolutional "advance" towards the enrichment in more acid and alkaline varieties and in ever-reducing development of the earlier ones. Fig. 3 shows the regions of distribution of different alkaline groups and series and typical associated mineralization.

Two variants in alkaline-ultramafic evolutional group are revealed: sodic (alkaline complexes in north Siberia-P—T; D_{2-3} in Karelia—Kola region etc.); and potassic (C_1 — in north Kazakhstan, J—K_1 in the Aldan etc.). REE-rare-metal (REE, Nb, Ta, Zr etc.) deposits of camaphorite-carbonatite type and Nb-Ti (perovskite) in massifs of Na-series are associated with intrusive and volcano-intrusive rocks of Na- and K-series. Alkaline-mafic evolutional group exhibits also sodic and potassic variants. The former is represented by alkaline complexes: PR_2 — in Karelia—Kola region, D_{2-3} — in Sanguilen etc., the latter are: J_3—K_1 in the Aldan, P_1 — in North Tien Shan etc. Rare-metal (Nb, Ta, Zr) deposits and occurrence of carbonatitic and pegmatitic types are associated with the masifs of Na-series, while Rb, Sr, Zr, Nb, Ba deposits are related to K-series. In alkaline-salic group of foiditic suites three variants can be outlined: those of sodic, agpaite nepheline syenites (type of Khibiny and Lovozero, D_3), potassic (Synnyr, D_3—C), and K-Na, miaskitic (the Urals, P_1). Ores associated with Na-series include Nb, Ta, Zr, REE, those of K-series are characterized by rare-metal-REE (Nb, Zr, REE, etc.) mineralization.

Magmatism of alkaline-ultramafic and alkaline-salic groups is virtually connected only with epi-platformic rifting. Alkaline-mafic group (potassic variant) is linked to epicratonic and epi-orogenic rifting, that of sodic type occurs within both platforms and fold areas. Within the latter, orogenesis is often followed directly by rifting which can coincide in time with the activation. The majority of intrusives of alkaline-salic group of potassic type are associated with rifting in fold areas, the remainder — in platformic areas. Alkaline-salic group of K-Na type is known only in fold areas and close in time to the orogenic or activation stages.

All the three alkaline groups share common features of petrogenetic development, consistent distribution patterns, and the related similar ore formations: rare-metal-REE-carbonatite; rare-metal-albitite; rare-metal-fenite and others connected with the same type of trace elements and REE. Neverthless, each group distinctly differs in its initial members, unidirectional trend and evolutionary range, petrochemical features, PT conditions of the formation and local emplacement environment. This resulted in successive decrease in magmatic deposits proper among ore formations: from alkaline-ultramafic to alkaline-salic group, and in increase of deposits and occurrences of pneumatolithic-hydrothermal and hydrothermal in the same trend, in progressive decrease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of sidero-(and partly)-chalcophile elements and the increase of REE, rare alkalies and Ba.

4. Evolutional groups of granitoid suites are of special metallogenic interest. We do not intend to give a comprehensive account of evolutional series in Phanerozoic terrains, but just to emphasize the possibility of the recognition

Fig. 3. Scheme of zones of alkaline and granitoid magmatism and associated mineralization on the USSR territory.

Explanations: 1—6 — zones of alkaline magmatism; 1—3 — boundaries of zones with different petrochemical and geochemical specialization: 1 — sodic, nepheline-apatite — rare-metal (Nb, Zr, TR_{Ce} and others); 2 — potassic calcilite-fluorite — rare-metal (Nb, Zr, Rb, TR_{Ce} and others); 3 — potassic-sodic, apatite-nepheline — rare-metal (Nb, Zr, Rb, TR_{Ce} and others); 4—6 — formational and mineragenic specialization of zones: 4 — alkaline-ultra-mafic (Fe, Ti, Cr, phlogopite); 5a — alkaline-mafic (alumina, apatite, Ba, Sr), 5b — alkaline-mafic combined with alkaline-ultramafic; 6 — alkaline-salic (alumina, apatite); 7—8 — major zones of development of granitoids from different groups: 7 — group I with dominant Mo-W mineralization; 8 — group II with dominant Sn-W mineralization; 9—11 — tectonic structure; 9 — platforms; 10 — shields, 11 — fold areas.

The following zones and ages of alkaline complexes are shown by figures: 1 — Sebliavr-Gremiachinskaya, PR_2, D; 2 — Kola (Kovdor-Khibiny-Salmagar, O-D_2, D_3); 3 — Yelet-Ozerskaya, PR_2; 4 — Onega-Kandalaksha, V, O, D_{2-3}; 5 — Zimneberezhnaya, V; 6 — Volynskaya (Chukotsko-Volskaya), R_4—V, D_3; 7 — Priazovskaya, D_1—C_1; 8 — Prypyatsko-Donetskaya, D_{2-3}—C_1; 9 — Chetlasskaya, R_4—V; 10 — Ajaro-Trialetskaya, K; 11 — Pambakskaya, 12 — Talyshskaya, P; 13 — Niazepetrovskaya, D; 14 — Ilmensko - Vyshnegorskaya, P_1; 15 — Borsuksaiskaya, C_3—P_2; 16 — Kokchetavskaya (Krasnomayskaya), Є?; 17 — Ishimskaya, D_{2-3}; 18 — Northen-Talasskaya, P_1; 19 — Eastern Kirghizian, D_{1-3}, C_3—P_1; 20 — Kokshaalskaya, C_2; 21 — Turkestano-Zardalekskaya, P_2—T; 22 — East Pamirian, N; 23 — Kuznetsk-Alatauskaya, D_2—C_1; 24 — Kamenskaya, P—T; 25 — Gulinsko-Kughdinskaya, T_1; 26 — Bor-Uriakh-Ysseiskaya, T_1; 27 — Kuanamsko-Ujinskaya, D_{2-3}, J—K; 28 — North-Oleniokskaya, MZ; 29 — South--Oleniokskaya, MZ; 30 — Alakitsko-Daldinskaya, PZ_2; 31 — Batuobinsko-Markhinskaya, PZ_2; 32 — Chadobetskaya, T_1; 33 — Yenisei-Angarskaya, PZ_1; 36 — Urikskaya, D_2; 37 — Sanguilenskaya, O, D_{2-3}, P; 33 — North Baikalian, D_3—C_1, P_2—T; 39 — Synnyrian, D_3—C_1; 40 — Baikal-Barghuzinskaya, PR_2, D_{1-2}; 41 — Salenghino-Vishimskaya, T—J; 42 — Jidinskaya, J; 43 — Oliokmo-Charskaya, J_3—K_1; 44 — Central Aldanian, J_3—K_1; 45 — Arbarastakhskaya, R_4—V; 46 — Enaghli-Chadskaya, R_4—V, J_3—K_1; 47 — West-Sette-Dabanskaya, S, D_{2-3}; 48 — South Sikhote-Alinskaya, MZ; 49 — North Sikhote-Alinskaya, N; 50 — West Sakhalinian, N; 51 — West Kamchatskaya, N; 52 — East-Kolymian, P; 53 — Anadyrskaya, N; 54 — East-Chukotskaya, K_1.

The numbers in circles show the following zones: 1 — Priladozhskaya, PR_{1-2}—R; 2 — North Caucasus, PZ_3, KZ; 3 — Meghrinskaya, K_2—P; 4 — North Urals, PZ; 5 — East Urals, PZ; 6 — Cis-Urals, PZ_3; 7 — Central Kazakhstan, PZ_3; 8 — Pribalkhaskaya, PZ_3; 9 — Maykulskaya, PZ_2—PZ_3; 10 — Cis-Iliyskaya, PZ_2—PZ_3; 11 — Soukul-Sarijanskaya, PZ_3; 12 — Central Tien Shan, PZ_3; 13 — South Tien Shan, PZ; 14 — North Pamirs, K_2—P; 16 — Kalba-Narymskaya, PZ_3; 15 — South Pamirs, J_3—K_2; 17 — Mountain Altai, PZ_2—PZ_3; 18; 19 — East Sayan, PZ_1—PZ_2; 20 — North Baikal, PR^2_2—R; West Cis-Baikal, PZ_3—MZ; 22; 23 — Central Cis-Baikal, PZ_3—MZ; 24 — East Cis-Baikal, PZ_3—MZ; 25 — Yenisei, PR_2; 26 — Taimyrskaya, PR_2, PZ_3; 27 — Polousnensko-Kolymskaya, J_3—K_1; K_2—P; 28 — Chukotskaya, K_2—P; 29 — Oloiskaya, K_2—P; 30 — Omsukchanskaya, K_2—P; 31 — Upper-Kolymian, J_3—K_1; 32 — Kariakskaya, P—N; 33:34:35— — Prloknotskaya, J_3—K_1; 36 — Sette-Dabanskaya, R, K—P; 37 Bureinskaya, PZ, K—P; 38 — Umaltinskaya, PZ, MZ; 40 — Amurskaya, J—K_1, K_2—P; 39 — Komsomolskaya, K_2—P; 41 — West Sikhote-Alin, K—P; 42 — Primorskaya, K_2—P; 43 — Hankaiskaya, PZ, MZ.

of to major, up to a point, polar groups of intrusive associations. Group 1 is represented by gabbrodiorite-granodiorite, granosyenite, syenite-granite-alaskite-alkaline granite suites of intrusive rocks exhibiting agpaite trend and rather common (sometimes extensive) earlier mafic members. Group 2 is relativly short, falling into diorite-granodiorite, trondhjemite-granite-leucogranite range and showing plumasite trend, mafic members are virtually absent. It is to be noted that the same "traditional" granitoid suites may be located at two branches — in 1st and 2nd series, and characterized by different mineralization; group 1 and 2 can be tentatively called Mo-W and Sn-W, respectively.

Due to great metallogenic importance of the above groups the analysis of their distribution pattern in the USSR was made. Fig. 3 shows the zones of long group of granitoids (oblique hatching) with mineralization of Mo-W group, well-exampled by reference regions — Central Kazakhstan, the Urals, West Transbaikal and that of Sn-W group (crossing hatching) — by the Verkhoyansk—Kolyma, East Transbaikal, Kalba—Narun regions. Wide distribution of S-granites with high ($\geq$708) initial crustal $^{87}Sr/^{86}Sr$ ratios within the stanniferous provinces, and predominantly I-granites which iow ($\leq$ 706) hybrid mantle-crustal $^{87}Sr/^{86}Sr$ values have been reported in numerous publications. Sn-short group of associations is an evolutional branch of magmatism showing a relatively slight mantle-crustal mass transfer, being occurred at the terminal stages of the group emergence, whereas the series is a mantle-crustal evolutional branch with rather intense mantle-crustal mass transfer. The blocks with Sn-W group of formation are characterized by a kind of destructive development, i. e. by a repeated reworking of the crust lacking considerable thickening, whereas the development of the Mo-blocks exhibits a constructive pattern with successive growth of continental crust due to dominant production of I-granites in these zones. In this case the granitoids suites as though terminate the long lasting volcanism of island arc-type.

A specific evolution pattern of later members permits three trends, i. e. normal alkalinity, higher alkalinity and with antidromic termination to be revealed in the two evolutional granitoid groups (Beskin, 1979; Marin, 1983; Mineralization and ..., ed. Rundquist). The evolutional series of higher alkalinity and those with antidromic termination show the most contrast types of ore-bearing formations. The following succession of mineralization is established for the Mo-blocks: Fe-Cu skarn ⟶ Cu porphyry ⟶ Cu-Mo porphyry ⟶ Mo-W skarn-greisen and Mo-W quartz-vein-greisen. Then Mo-W stockwerk beresite followed by Au, Mo, Au-Sb argillisite mineralization took place with the antidromic trend and with increasing role of dykes. When magmatism exhibits increasing alkalinity trend a passage to Mo-W stockwerk humbeite and then to feldspatholithic deposits with Mo, Nb complex rare--metal mineralization occurred.

The Sn-blocks show a different succession of mineralization: rare-metal ⟶ Sn-bearing pegmatites ⟶ W-Sn. Sn skarn ⟶ rare-metal greisen and vein deposits with W, Sn. The subsequent antidromic trend resulted in the wide distribution of Sn-tourmaline-chlorite and then in Sn-Pb-Zn and Sb-Hg argillisite deposits. As alkalinity increased, the series was being completed by the formation of rare-metal feldspatholithic, "apogranitic" deposits or rare-metal (Li, Cs, etc.) pegmatites.

Now we shall drop the analysis of the evolutional groups and turn to application the revealed patterns to prospecting metallogenic investigations. The latter consists in a successive detailed study of areas in order to reveal more and more local perspective domains with their mineralization being precised.

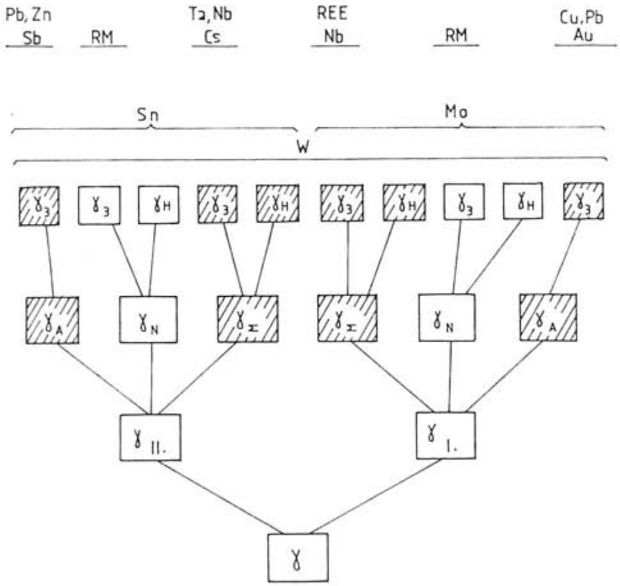

Fig. 4. Classification chart of granitoids and associated mineralization (see context).

Fig. 4 shows a summary of the subdivision of the granitoid magmatism zone. At is can be seen, they first of all, fall into two major types (γ_{I} and γ_{II}) corresponding to the long and short evolutional groups respectively. The granitoid zones of the first type are usually characterized by higher crustal thickness, extensive magnetic ($\varkappa \leq 500\,\gamma$) granitoids with low ($\leq 706$) mantle-crustal $^{87}Sr/^{86}Sr$ values (mainly, I-granites). The further detailization of perspective areas within the zones recognized is based on the determination of a granitoid series type, i. e. normal (γ_N) or higher alkalinity (γ_Σ) or with antidromic termination (γ_A). Prospecting more local potential ore-bearing regions requires a degree of completeness (γ_3) (with late subalkaline or alkaline rare-metal granites of extensive dykes and minor intrusions ranging in composition) or incompleteness (γ_H) of each granitoid series to be taken into account. The subsequent analysis to reveal prospecting ore fields and deposits is based on detailed studies of the granitoid massifs, defining a magmatic formation they belong to, character of apical surface, level of erosion, intensity of petrographic ore-forming processes, etc. (B e s k i n , 1979; I z o k h, 1978; Magmatic formation . . ., 1979; M a r i n, 1983).

Thus, the possible answer to the beginning of the article is that major industrial rare-metal mineralization in the USSR is connected with ore-bearing granitoid and alkaline suites which are integral parts of 5 evolutional groups and 13 series. The revealed evolutional groups and series are of great practical importance, since virtual mineralization of magmatic formations is not only a function of their composition but it depends largely on a certain evolutional group or series they belong to.

One of main tasks in further rare-metal mineralization studies is a more detailed investigation of palaeotectonic environments, geodynamics, predetermining the emergence of the outlined groups and series.

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Manuscript received October 1, 1984

The autors are responsible for language correctness and content.