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Tectonic and magmatic factors of Li-F granites localization of the East of Russia

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Abstract. We have investigated tectonic and magmatic factors of Li-F granites localization of the East of Russia. The study is based on the ideas of Far Eastern geologists about the deep structures of intraplate activity. A model of a source structure with mantle heat sources and ore-forming magmatic complexes was used. We carried out a special metallogenic analysis of the East of Russia as applied to the rare metal-tin-bearing formation of subalkaline leucogranites, including Li-F ones.
Source structures are the main factor in the tectonic and magmatic development of the East of Russia, localization of ore-forming granites and the formation of rare-metal-tin ore regions. On deep layers of source structures there are areas of the mantle and earth's crust decompaction, heat, magmas and fluids sources, as well as granitoid cryptobatholiths. Relatively large massifs of leucogranites, small intrusions of tin monzonitoids and Li-F granites are concentrated near the modern surface. The source structures correspond to the rank of the ore region. The source structures in the South of the region are: Badzhalskaya, Miao-Chanskaya, Ippato-Merekskaya, Hogdu-Lianchlinskaya, Arminskaya, etc.; in the North: Pevekskaya, Kuiviveem-Pyrkakayskaya, Kuekvun-Ekiatapskaya, Iultinskaya, Telekayskaya, Central Polousnaya, Omsukchanskaya, etc. Three types of ore regions have been identified according to the degree of source structures and Li-F granites erosion.
We have also outlined the patterns of source structures evolution and their place in the geological history of ore-bearing granites. A classification of source structures and its comparison with the classifications of regional intrusives and metallogenic subdivisions are proposed. It has been established that, despite the diversity of tectonic, geological and petrological settings in the East of Russia, the intrusions of Li-F granites are regulated by the same tectonic and magmatic factors. The tectonic and magmatic factors of Li-F granites localization in the East of Russia are identified and classified as geophysical, orogenic, geoblock, magmatic, metasomatic and disjunctive.

***Key words*:** localization factors; Li-F granites; source structure; orogen; cryptobatholith; ore region; East of Russia

Introduction. Li-F granites (LFG) were identified in the 1960s as rocks containing rare metal (Ta, Nb, Li, Be, Rb, Cs, REE, W, and Sn) mineralization. The specific mineral composition of LFG and the strategic importance of associated ores have led to a high scientific and practical interest and the development of numerous geochemical, petrological, mineragenic and geodynamic classifications [2, 3, 18].

The Earth crust of the East of Russia includes the massifs of all known granitoids, including the ore-bearing Li-F ones [1]. Significant reserves of tin, tungsten, niobium, indium, bismuth and other rare metals associated with LFG are located in the in the interior of the region. Therefore, it is very important to study the factors of the ore-bearing granites localization.

It is known that magma-controlling ring structures of three granitoid provinces – Novosibirsk-Chukotka, Yano-Kolyma and Sikhote-Alin [1] are observed in the Russian sector of the Pacific belt. Mantle heat flows in the windows of the lithospheric slab rupture are a geodynamic factor in the emergence and development of rare-metal-granite magmatism. The areas of the LFG and the ore regions of the study area are spatially confined to ring structures with negative gravity anomalies [1]. The area of the magmatic formations distribution goes far beyond the boundaries of the active Pacific continental margin, including intracontinental Meso-Cenozoic folded structures and more ancient ones [15, 17]. The aim of the study is to analyze and classify the tectonic and magmatic factors of the LFG localization in the East of Russia.

Research methods. The analysis of the LFG localization factors continues the previously begun study of the deep structure and geodynamic conditions of granitoid magmatism on the basis of

seismic, gravimetric, and geothermal modeling [1]. The work is based on the ideas of Russian geologists about the deep structures of intraplate activity – areas of the lithosphere decompaction within zones of intense magmatism and ore formation [7, 8, 10, 11]. The study of granitoids localization factors is based on the sourcestructure model developed by I.N.Thomson, M.A.Favorskaya, and Y.P.Dezhin for through ring structures with mantle heat sources and ore-forming magmatic complexes [13]. The classification of source structures (SS) is based on the orogens classification by N.P.Mitrofanov [14].

The ingenuity of the suggested scientific method lies in the application of the Far Eastern geologists' ideas about the deep structures of the earth's crust for the new purposes – the reconstruction of the history of granitoid magmatism and the evolution of the magmatic series composition. A fundamentally new scientific approach is the analysis, based on a modern geodynamic data, of the composition of Far Eastern intrusive series completed by ore-bearing granitoid magmatism.

This approach creates a practical opportunity to identify the factors of localization and mineralization level of intrusions and to propose, on this basis, criteria for predicting the largest rare metal-tin deposits in the East of Russia. Since the SS controls the most important ore regions of the area under study, we carried out a special metallogenic analysis. We use the concept of tectonic and magmatic factors of localization, introduced by Yu.A.Bilibin in the study of metallogeny of the North-East and denoting tectonic and geological structure conditions of ore occurrences, as well as features of the composition and evolution of ore-bearing magmatic complexes of a certain formation [4]. This concept is applied to the rare metal-tin-bearing formation of subalkaline Li-F granites [2, 3, 5]. The article briefly discusses the prevalence of LFG in the world, which allows us to consider the identified tectonic and magmatic factors of localization as universal within the Eurasia territory and, first of all, the Transbaikalia and China regions adjacent to the Far East.

Source structures as the main tectonic and magmatic factors in the localization of Li-F granites. The sufficient geological characteristics of the East of Russia are given in works [1, 5]. The granitoid magmatism of the region is characterized by the predominance of moderate collisional conditions occurred during the supra-subduction collision of the Asian plate and island arcs and the formation of transform continental margins. Matter and heat flowing through the lithosphere determined the formation of the SS and completed intrusive series with LFG, arose in the disturbance areas of the subducted Pacific plate. Granitoid cryptobatholiths are located on deep horizons of the SS. Relatively large leucogranites massifs and small intrusions of tin monzonitoids and LFG are located near the modern surface [1, 3, 4, 7-9, 11-13, 15-17, 19, 20].

The source structure is a mantle-crustal central type one, consisting of three stages connected by the matter and energy exchange processes [7, 8, 13-17, 19]. The lower stage of mantle decompaction is a relict of a magma source in the crest of the mantle diapir. The middle stage in the lower and middle crust includes an unconsolidated magma permeable channel with magma sources, the upper one of which has been transformed into a granitoid batholith. The upper stage was formed along with the arched and block dislocations of folded strata, continental volcanism, and multistage intrusive magmatism. This stage includes complexes of leucogranites, monzonitoids, and LFGs with accompanying hydrothermal, metasomatic, and ore formations (see Figure).

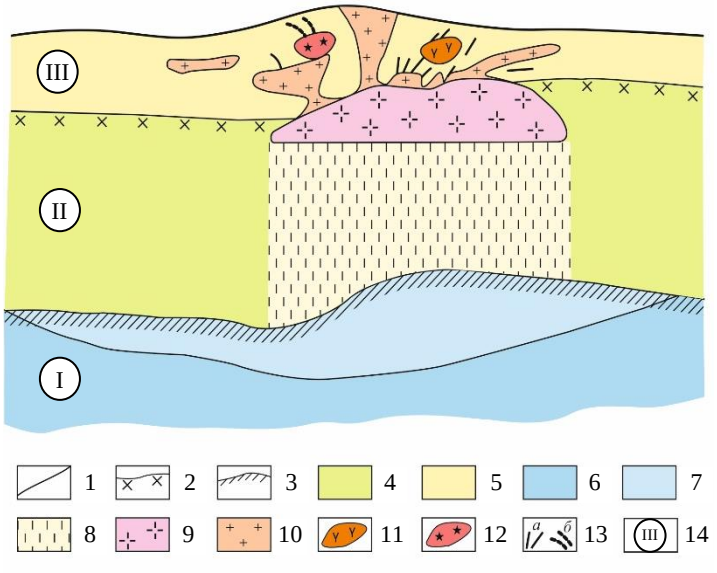
The dimensions of the SS of the East of Russia are 100-400 km across and, with regard to metallogeny, correspond to the rank of the ore region [8, 13, 14]. We have identified three types of ore regions:

• LFG intrusions cut through large massifs of leucogranites (Verkhneurmiysky, Khayargastakhskiy, Arga-Ynnakh-Khaiskiy, Omchikandinskiy, and Severniy) or are localized in their exocontact (Levo-Dzhelakagskiy, Levo-Erikitskiy, and Vostochno-Iultinskiy) and are accompanied by ore-bearing tourmalinite and zwitter located in the host strata;

• independent intrusions of LFG in sedimentary and volcanic strata (Voznesenskiy, Pogranichny, Tigriniy, Zabytiy, Nyutskiy, Sphinx, and Svetliy) with accompanying zwitters and tourmalinites;

• blind LFG intrusions with exocontact ore greisens, tourmalinites and chlorite-bearing metasomatites (Kavalerovskiy, Dusse-Alinskiy, Khingano-Olonoyskiy, Yuzhno-Omsukchanskiy, Deputatskiy, and Iultinskiy districts).

These types differ in the SS erosion degree and show, in general, a weak erosion of the LFG complexes in the East of Russia and a decrease in the erosion from Chukotka and Yakutia towards the Amur and Primorye regions.



Model of a deep source structure with Li-F granites of the East of Russia (according to [7, 8], with additions by the author)

1 – geological boundaries; 2, 3 – geophysical boundaries of the consolidated crust (2) and Moho (3); 4, 5 – layers of the Earth's crust: consolidated (4), cover (5); 6-7 – mantle layers of the normal (6) and anomalous (7) density; 8 – magma-permeable channel; 9-12 – intrusive bodies: granitoid cryptobatholith (9), leucogranite massifs (10), small intrusions of monzonitoids (11) and Li-F granites (12); 13 – deposits associated with leucogranites and monzonitoids (*a*) and with Li-F granites (*b*); 14 – levels of source structure: I – lower, II – middle, III – upper

The formation of the SS began with a rapid magmas and fluids rapidrise from the mantle to the base of the earth's crust. These matter decompacted and broke through the asthenosphere, forming a magma-permeable channel in the earth's crust. Basic material accumulated in the form of lenses in the asthenosphere at the Moho boundary, where primary magma sources were originating. The evolution of the SS develops under the influence of ascending basaltic magma, which initiates the melting of granitoid and metamorphic matter, the formation of transitional mid-crustal granitoid source, early orogenesis, and intraplate intermediate acidity, and basic volcanism. The resulting granitoid magmas "float" along the previously formed channel, differentiate and interact with basic magmas and mantle alkaline fluids. Magmatic evolution leads to the crust leucocratization, the formation of intermediate monzonitoid sources, and the intrusions of monzonitoids and leucogranites on the upper stage of the SS. The latest rare-metal-granite melts result from the interaction of leucogranite magma and transmagmatic fluids. These melts determine the formation of LFG intrusions, accompanying rare-metal-tin metasomatites and deposits. Alkaline basalt volcanoes and rare intrusions of alkaline granites are formed at the final stage of the SS formation. Thus, the SS are the main factor in the tectonic and magmatic development of the East of Russia, the localization of ore-forming LFGs, and the formation of rare-metal-tin ore regions.

Following the classifications [13, 14], a structure expressed on the surface in the form of an orogenic arch with an area of thousands of square kilometers and coinciding with a gravity minimum fixing a batholith hidden at a depth, is taken as an elementary SS (Table 1).

Table 1

Regional taxonomic units of the East of Russia (according to [8, 10, 11])

Taxonomic unit			Area, km^2
Tectonic and magmatic	Intrusive	Metallogenic	
Tectonosphere province	Granitoid province	Ore province	$n\cdot10^5$
Source megastructure	A number of granitoid complexes	Ore region	$n\cdot10^4$
Source structure	Granitoid series	Ore district	$n\cdot10^3$
Part of the source structure	Granitoid complex	Ore cluster	$n\cdot10^2$

Note. n = 1-9.

The upper stage of the SS includes a series of intrusive complexes, zoned metasomatites and ore deposits (see figure). SS of the East of Russia are located within folded belts (Kuiviveem-Pyrkakayskaya in Chukotka, Central Polousnaya in Yakutia, Arminskaya in Primorye), volcanic zones (Omsukchanskaya in Kolyma, Badzhalskaya in Priamurye) and median massifs (Khinganskaya in the Amur region, Voznesenskayain Primorye) and correspond to the ore regions of the same name [5, 7-9].

Elementary SS are part of structures of a higher order – source megastructures, represented on the surface by rounded mega-uplifts with an area of tens of thousands square kilometers. Megastructures are the epicenters of regional deep decompaction of lithosphere at a depth of up to 220 km and mantle diapirs; they are located at the intersection of regional faults that are part of transregional disjunctive systems. The source megastructure controls a number of intrusive complexes, which includes large complexes of granites and leucogranites in the central part of the mega-arch, and the LFG complex along the periphery. In metallogenic terms, each megastructure corresponds to an ore region and covers several ore regions. For example, in the South of the Far East, the Badzhalo-Yamalinskaya source megastructure with the Badzhalskiy and Dusse-Alinskiy cryptobatholiths is known. The megastructure includes the Badzhalskaya, Miao-Chanskaya, Ippato-Merekskaya, Hogdu-L'yanchlinskaya SS and ore regions of the same name. In the north of the region, the Chaunskayasource megastructure based on the Chaunskiy and Kuekvun-Iultinskiy cryptobatholiths and includes the Pevekskaya, Kuiviveem-Pyrkakayskaya, Kuekvun-Ekiatapskaya, Iultinskaya, Telekayskaya SS and the corresponding ore regions. In total, 11 source megastructures are located in the East of Russia, corresponding to the previously identified magma-controlling ring geostructures [1].

The highest hierarchical level of deep structures in the East of Russia are groups of source megastructures, covering regional fragments of the lithosphere – tectonospheric provinces. They correspond to granitoid and ore provinces: Novosibirsk-Chukotkaya, Yano-Kolymskaya and Sikhote-Alinskaya [1, 14, 15].

Tectonic and magmatic factors of localization of Li-F granites. Despite the variety of tectonic, geological and petrological settings in the East of Russia, the LFG intrusions are regulated by the same tectonic and magmatic factors of localization.

Geophysical factor of localization. An important factor in the LFG localization is the transregional Indochina-Chukotka gravity step – a submeridional transition zone from the continental crust to a thin transitional one. The bending of the Earth's crust bottom up to 150 km wide and thousands of kilometers long indicates the zone of the of the lithosphere tectonic stress, expressed in the system of deep faults, as well as the zone of the crust substantial transformation during the Asian-Pacific plate tectonics. In the North of the study region, the Indochina-Chukotka step is marked by the Okhotsk-Chukotka volcano-plutonic belt, and in the South, where this step is more often called the Pogranichnaya step, by the Khingan-Okhotsk volcanic belt [8, 16]. The SS of the East of Russia and the areas of the LFG intrusions are located in the zone of the Indochina-Chukotka step from the Novosibirsk-Chukotka to the Sikhote-Alin granitoid provinces [1].

Orogenic factor of localization. LFG are located in heterogeneous tectonic structures that have undergone tectonic and magmatic activization. Late Jurassic-Early Cretaceous folded complexes formed on passive and active continental margins are predominant. The evolution of the SS is accompanied by the intrusions into ring-type folded-block structures – orogens [13, 14, 19, 20]. Orogenic structures are expressed on the surface as isometric and oval domes of kilometers in size. The localization of the LFG inside the orogens is controlled by faults and bends of folded structures.

Geoblock localization factor. The LFG areas in the East of Russia are located along the borders of the middle massifs – Kuulskiy, Omolonskiy, Kolymskiy, Okhotskiy, Bureinskiy, Khankaiskiy, etc. (Table 2). Geoblocks of ancient stabilization were involved in the Mesozoic collision at the border of the Siberian and North China cratons, stimulating the formation of the SS, orogeny, and granitoid magmatism. At the same time, the Proterozoic basement, overlaid by the Caledonides

and Hercynides, is experiencing tectonic and magmatic activization. The Paleozoic platform cover surrounded by the frame of the middle massifs is locally transformed into orogenic structures with granitoid plutons and small LFG intrusions: Polousnenskoe, Tas-Khayakhtaskoe in the North-East, Badzhalskoe in the Amur region, Spasko-Voznesenskoe in Primorye, etc. [6, 17]. Such ore regions with LFG as Chaunsky in Chukotka, Central Polousny in Yakutia, Badzhalsky in the Amur region, Khankaisky in Primorye, etc., were formed as a result of deep activization of ancient geoblocks.

Table 2

Tectonic and magmatic factors of Li-F granites localization of the East of Russia

LFG stock*	Granitoid massif	Source structure **	Cryptobatholith	Middle massif
[Iultinskiy]	Iultinskiy	Iultinskaya (I)	Kuekwunskiy	Kuulskiy
Kulyuveemskiy	Severniy	Pyrkakayskaya (I)	Chaunskiy	Kiberovskiy
Kainvaamskiy	Ichuveyemskiy Belt	Pyrkakayskaya (I)	Chaunskiy	Kiberovskiy
Odinokiy	Omchikandinskiy	Central-Polousnaya (II)	–	Omolonskiy
Polarniy	Omchikandinskiy	Central-Polousnaya (II)	–	Omolonskiy
[Deputatskiy]	Deputatskiy	Deputatskaya (II)	Deputatskiy	Omolonskiy
Kesterskiy	Arga-Ynnakh-Khayskiy	Central-Yanskaya (III)	–	Omolonskiy
Jelakagskiy-2	Jelakagskiy	Yuzhno-Yanskaya (III)	–	Omolonskiy
Volshebnik	Levo-Erikitskiy	Chibagalakh-Erikitskaya (IV)	–	Omolonskiy
[Nevskiy-2]	Nevskiy	Yuzhno-Omsukchanskaya (V)	–	Omolonskiy
Orotukanskiy	Vekhne-Orotukanskiy	Orotukanskaya (V)	–	Kolymskiy
[Butugychagskiy]	Zapadno-Butugychagskiy	Ayan-Yuryakhskaya (V)	–	Kolymskiy
Nyutskie stocks	Levonilgysygskiy	Nilgysygskaya (VI)	–	Okhotskiy
Kutepskiy	Kutepskiy	Kutskaya (VII)	–	Okhotskiy
Dozdliviy	Verkhneurmiysky	Badzhalskaya (VIII)	Urmiysky	Bureinskiy
Ongonite dikes	Orokotskiy Belt	Badzhalskaya (VIII)	Urmiysky	Bureinskiy
Obmaniyskiy	–	Khinganskaya (IX)	Khinganskiy	Bureinskiy
Tigriniy	Izluchinskiy	Bikino-Malinovskaya (X)	Bikinskiy	Khankaiskiy
Zabitiy	Priiskoviy	Bikino-Malinovskaya (X)	Bikinskiy	Khankaiskiy
Voznesenskiy	Voznesenskiy	Khankaiskaya (XI)	Voznesenskiy	Khankaiskiy
Pogranichniy	Voznesenskiy	Khankaiskaya (XI)	Voznesenskiy	Khankaiskiy

Notes. *In parentheses – the blind stocks of the LFG. **In parentheses are the numbers of source megastructures according to the author's article [1]. Dash – no data.

Magmatic factor of localization. LFG intrusions and associated rare metal-tin deposits in the East of Russia are located in sialic blocks, tending towards to hidden at depth or partially eroded leucogranite plutons that define the contours of ore regions [2]. In the mantle heat and matter flow during the SS formation, large blocks of the earth crust, hundreds of kilometers in size, are leucocratized and transform into granitoids. Cryptobatholiths formed at the base of the SS and partially exposed by erosion on the day surface, are: Chaunskiy, Kuekvunskiy, Deputatskiy, Badzhalskiy, Bikinskiy, etc. [1]. The bottom of the batholiths lies at depths of 4-16 km [8, 15].

LFG are located above the granitoid cryptobatholiths, sometimes in their apical protrusions (Table 2). The Pravurmiyskiy, Kesterskiy, Pyrkakayskiy, Tigrinskiy and other complexes of the LFG and large rare metal-tin deposits (Pravourmiyskoye, Kesterskoye, Pyrkakayskoye, Tigrinoye and others) are located within the Badzhalskaya, Central-Yanskaya, Pyrkakayskaya, Bikino-Malinovskaya SS. Only one Bureino-Badzhalskaya sourse megastructure includes such large ore regions of the East of Russia as Badzhalskiy, Komsomolskiy, Aesopskiy, Dusse-Alinskiy, and Yam-Alinskiy.

Metasomatic factor of localization. The formation of LFG complexes is always preceded by complexes of pre-ore metasomatites. Pre-ore propylites of biotite, actinolite, and epidote facies arise during the formation of rare-metal-granite magma in the source structure under the influence of mantle fluids [3, 6]. Propylites compose zonal domes. Mainly thin high alkaline biotite-bearing metasomatites –

biotitites, are concentrated in the cores of these domes. LFG intrusions which formed later are correspondingly localized in biotitite fields, which create a specific geochemical background for subsequent hydrothermal processes. The intrusion of LFG is accompanied by the formation of multi-stage metasomatic complexes, including ore-bearing zwitters, tourmalinites, and chlorite-bearing metasomatites. Zwitter-tourmalinite complexes are characterized by uniform localization conditions, zonal distribution with regard to LFG, common acid-base evolution, ore and geochemical specialization [1].

Disjunctive factor of localization. Deep disjunctive disturbances that connect magma sources and arise during magma transport are an important factor in the formation of the SS and localization of LPG [9, 14]. Regional control of magmatism is carried out by trans-regional fault systems in the zone of the Indochina-Chukotka step and along the boundaries of the middle massifs – Itun-Ilan-Kurskaya, Arsenyevsko-Tastakhskaya, Tanlu, etc. Throughout the Mesozoic period, longitudinal deep faults had magma-controlling role: Kuvetskiy and Chaunskiy in Chukotka, Adycha-Tarynskiy and Inyali-Debinskiy in Yakutia, Kurskiy and Khinganskiy in the Amur region, Arsenyevskiy and Centralniy in Primorye, etc. [16]. Block deformations and intrusions in the upper staged of the SS of the East of Russia were accompanied by the formation of transverse, radial and ring fault structures: Ichuveemskaya and Telekai-Iultinskaya in Chukotka, Balygychan-Sugoiskaya and Chokhchuro-Chekurdakhskaya in Yakutia, Tigrinaya and Orokotskaya in the Far East, and others. Local faults determined the placement of small LFG intrusions in the marginal or exocontact zones of leucogranite plutons.

Comparison with other regions. Li-F granites were described by V.I. Kovalenko in 1969-1971 in the study of small intrusions of microcline-albite granites in the tungsten-tin ore deposits of Mongolia. Then LFG were found in Kazakhstan, Western Europe, and the territories of Transbaikalia and China adjacent to the Far East [2]. At present, a fundamental similarity has been established in the tectonic and magmatic conditions of LFG formation and localization in the East of Russia [1, 6, 9], Transbaikalia [2, 3] and China [18, 20]. An important practical aspect of the described similarity between the LFG of the East of Russia and adjacent regions is the possibility of creating an effective complex of predictive and evaluative indicators of tungsten-tin and rare-metal ore content. Thus, the similarity of the tectonic and magmatic factors of LFG localization provides new opportunities for prospecting large and unique deposits of W, Sn, Nb, Ta, Li, Be, Rb, Cs, and REE [3, 12, 17, 18].

Conclusions. On the territory of the East of Russia, there are numerous deep-seated source structures with mantle roots, which is the main factor in the localization of Li-F granites. Deep structures are expressed on the modern surface in the form of orogenic structures and volcano-plutonic areas. Source structures are superimposed on tectonic structures of different ages with different types of the Earth's crust and are the generator of complete intrusive series. Tectonic and magmatic factors of Li-F granites localization include: geophysical, orogenic, geoblock, magmatic, metasomatic and disjunctive factors. The proposed research method can be used for regional prediction of deposits.

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