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Deep structure and geodynamic conditions of granitoid magmatism in the Eastern Russia

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We investigated the deep structure of the lithosphere and the geodynamic conditions of granitoid magmatism in the Eastern Russia within the borders of the Far Eastern Federal District. The relevance of the work is determined by the need to establish the geotectonic and geodynamic conditions of the granitoids petrogenesis and ore genesis in the Russian sector of the Pacific Ore Belt. The purpose of the article is to study the deep structure of the lithosphere and determine the geodynamic conditions of granitoid magmatism in the East of Russia. The author's data on the magmatism of ore regions, regional granitoids correlations, archive and published State Geological Map data, survey mapping, deep seismic sounding of the earth's crust, gravimetric survey, geothermal exploration, and other geophysical data obtained along geotraverses. The magma-controlling concentric geostructures of the region are distinguished and their deep structure is studied. The connection of plume magmatism with deep structures is traced. The chain of concentric geostructures of Eastern Russia controls the trans-regional zone of leucocratization of the earth's crust with a width of more than 1000 km, which includes the Far Eastern zone of Li-F granites. Magma-controlling concentric geostructures are concentrated in three granitoid provinces: Novosibirsk-Chukotka, Yano-Kolyma, and Sikhote-Alin. The driving force of geodynamic processes and granitoid magmatism was mantle heat fluxes in the reduced zones of the lithospheric slab. The distribution of slab windows along the Pacific mobile belt's strike determines the location of concentric geostructures and the magnitude of granitoid magmatism in the regional provinces. Mantle diapirs are the cores of granitoid ore-magmatic systems. The location of the most important ore regions of the Eastern Russia in concentric geostructures surrounded by annuli of negative gravity anomalies is the most important regional metallogenic pattern reflecting the correlation between ore content and deep structure of the earth's crust.

***Key words*:** magma-controlling concentric geostructures; lithosphere; mantle diapir; Moho; gravity anomaly; granitoid magmatism; Eastern Russia

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Introduction. In 1946, Academician S.S.Smirnov revealed the Pacific Ore Belt – one of the main sources of mineral resources in the world. Metallogeny of the Russian sector of the Pacific belt is determined by intense granitoid magmatism at the border of continental and oceanic lithospheric plates [4, 11, 15, 19, 21]. Earlier, the author considered the tectonic development and magmatism in the East of Russia*, including the formation of the Far Eastern belt of lithium-fluoride granites [1, 2]. To improve the concept of the regional tectonic and magmatic evolution, it is necessary to study the local earth's crust structure, as well as the mechanisms of granitoids and ore deposits formation and evolution. The purpose of the article is to study the deep structure of the lithosphere and determine the geodynamic conditions of granitoid magmatism in the East of Russia.

Geological characteristics of the Eastern Russia. The continental margin of Northeast Asia is characterized by a variety of tectonic and petrological conditions, but for more than half a century it has been defined as a single global structure, replete with granitoid magmatism and ore deposits (E.C.Andrews, 1925; E. Og, 1932; P.N. Kropotkin, 1965) . The Russian East is a giant fragment of the Pacific belt – a combination of geostructures and magmatic complexes overlaid the heterogeneous crystalline basement. The polycyclic nature of a regional tectonic and magmatic evolution and ore formation from the early Proterozoic to the end of the Mesozoic is revealed. An age decrease of magmatic formations and an increase in the granitoids basicity along the continent to ocean transition [1, 2, 4, 19, 21, 22, 24, 25] are recorded. Mesozoic endogenous activity in the East of Russia gave rise to the number of tin, tungsten, gold, and other minerals deposits. It is explored (million

* The Eastern Russia is the region that covers the basins of rivers flowing into the Pacific Ocean and the seas of the Eastern Arctic and corresponds to the Far Eastern Federal District.

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tons): Mn 15.1, Sn 2.1, W 0.4, Pb 1.8, Zn 2.5, Cu 0.8, fluorite 16.7, Ti 10.3, B 3.5; (thousand tons): Ag 38, Au 2, Hg 31, Sb 254; Pt 47 tons, in the interior of the Far East.

The granitoid magmatism played an important role in tectogenesis, petrogenesis, and ore genesis of the Eastern Russia. Jurassic-Cretaceous granites occupy 75 % of the granitoid pluton's area [17]. There are four stages of the Mesozoic magmatism history: Jurassic-Early Cretaceous – formation of high-alumina granites batholiths; Early Cretaceous – formation of calc-alkaline granites complexes and granodiorites; Late Cretaceous – formation of subalkaline leucogranites and lithium-fluoride granites complexes; Late Cretaceous – Paleogene – formation of alkaline granites [1].

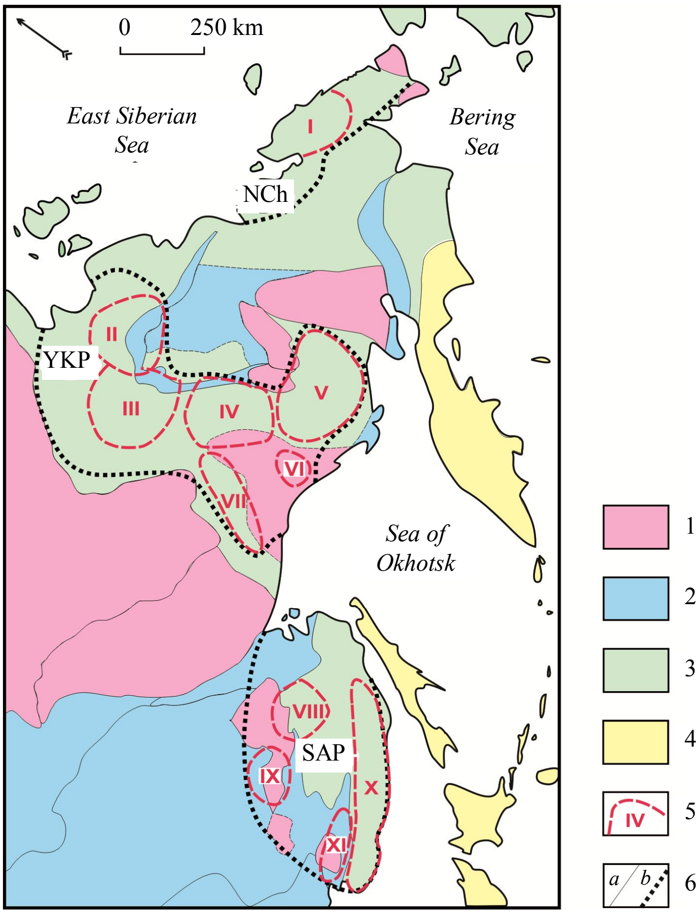
Research methods. Occurrences of Pacific granitoid magmatism and ore genesis reflect the deep transformations of the earth's crust material during the interaction of the Eurasian, Pacific, and Hyperborean lithospheric plates. The key to understanding the tectonic and magmatic history of the region is to study the lithosphere's deep structure and the geodynamic conditions of its development. For these purposes, the author used methods of geological mapping and regional correlation of granitoids, formation analysis, interpretation of deep seismic sounding data, gravimetric survey, geothermal exploration, and other geophysical data along geotraverses of the Russian East. The author's materials on granitoids of ore regions were used. Data on the composition, structure, and geodynamics of the Eastern Russia lithosphere were obtained from the materials of the State Geological Map [1] and areal geological mapping [18], monographs, and thesis papers of N.L.Dobretsov [7], Yu.F.Malyshev [6], Yu.A.Pavlov [12], L.M.Parfenov [11], A.M.Petrishchevsky [13], V.G.Sakhno [16], A.S.Egorov [8], multi-authored monograph of Far Eastern geologists [3, 19, 21], employees of ITIG [4, 5], VSEGEI [17]. Valuable information on the regional technosphere was obtained from foreign published research results [22-25]. The author used the geodynamic models of Yu.Ya.Vashchilov [14], A.I.Khanchuk [21], V.E.Khain [20], A.S.Egorov [9], supplemented by the concept of ore-magmatic systems by N.P.Romanovsky [15].

Magma-controlling concentric geostructures of the Eastern Russia. The massive Late Mesozoic magmatism of the Russian East, which spread deep inside the Far Eastern continental margin, is associated with the mantle activity and the rise of magmas in the upper horizons of the earth's crust. These events are associated with the Pangea disintegration and the horizontal movement of lithospheric plates. The crust extension was accompanied by the volcanic belts formation, and massive granitoids intrusions in the orogenes [1, 16, 24]. Pacific magmatism was replaced by Central Asian Permian-Triassic one, which occurred on the outskirts of the Emeishan and Siberian trap provinces [7, 23]. According to modern data, the plutonic and volcanic belts of the Russian East are similar in composition and structure to the occurrences of Central Asian plume magmatism [7, 16]. These data allowed to develop a model of Pacific magmatism with the participation of shallow plumes (mantle diapirs) in the areas of the subducted lithosphere breaks, so-called slab window [8, 20-22]. The difference consists in the fact that collisional magmatic and metamorphic formations are developed in the Asian folded belt, and epioceanic sedimentary strata with subduction, collisional, and rift magmatic complexes prevail in the Pacific belt.

Comparison of the granitoid magmatism ranges in the Asian and American segments of the Pacific belt shows that, in contrast to the linear ranges of Canada, the USA, and Peru, in Eastern Russia there is a chain of magma-controlling concentric geostructures (MCCG) concentrated in three granitoid provinces: Novosibirsk-Chukotka (NChP), Yano-Kolyma (YKP) and Sikhote-Alin (SAP) (see Figure). Granitoid massifs tend towards the margins of geostructures, framing their amagmatic cores [2, 10, 15]. An analysis of the MCCG deep structure allows concluding that they are confined to areas of the Earth’s crust of increased thickness composed of dislocated sedimentary complexes with excessive heat flux [4, 19, 23].

The study of gravimetric and seismic data along geotraverses showed a fluctuation in the lithospheric horizons thickness of the Eastern Russia [4-6, 15, 17]. The crust thickness in folded regions is 25-40 km, in the orogenes and crystalline massifs – 35-45 km, in the Cenozoic troughs and on the marginal seas shelf – 20-32 km. The sial's thickness is reduced from the rear zone of the Pacific belt (25-30 km) to the ocean and in the areas of the Cenozoic troughs (10-12 km). The greatest thickness of the granite-metamorphic layer was recorded in Precambrian-Paleozoic geostructures – the Kolyma-Omolonsky and Bureinsky massifs, the Mongolo-Okhotsk belt, and on the Aldan shield. Thickening of sial (up to 35 km) and crust in general (up to 45 km) in the Badzhalo-Yamalinsky granitization area is noted [4-6, 17, 22, 24]. Geoelectric and geothermal models record the lithosphere thickness of 75-100 km in Chukotka and Yakutia and 50-100 km in Primorye and Amur regions. There was revealed the Maya-Selemdzhinsky asthenospheric megadome [5, 6], within which the Bureino-Badzhalsky uplift with a lithosphere thickness of 50 km was identified (figure).

The heat flux density in the Mesozoic dislocated strata of the Eastern Russia is 45-70 mW/m^2, and in the Precambrian massifs it is 20-50 mW/m^2. The heat influx from the mantle is weakening, since the radiogenic component dominates (40-60 %) in the heat flux. The heat flux (70-90 mW/m^2) is more intense in the regional Cenozoic depressions (Sredneamurskaya, Oljoyskaya, Sunlyao), in rifts (Momsko-Laptevsky) and volcanogenic zones (Umlekano-Ogodzhinskaya, Bolshekhinganskaya). The maximum heat flow density value of 100-120 mW/m^2 was recorded in the Okhotsko-Chukotka and East Sikhote-Alin volcanic belts. “Hot” areas are penetrated by deep faults, for example, the trans-regional Tanlu fault passes through the eastern side of Sunliao [5, 16].



Magma-controlling concentric geostructures of the Eastern Russia

1 – Precambrian-Paleozoic cratons, shields, and betwixt mountains; 2 – the structure of pre-Cretaceous consolidation; 3 – Verkhoyanides; 4 – Himalayaides (according to [18]); 5 – boundaries of concentric geostructures and their numbers: I – Chaunskaya, II – Polousnaya, III – Verkhne-Yanskaya, IV – Verkhne-Indigirskaya, V – Verkhne-Kolymskaya, VI – Okhotskaya, VII – Yuzhno-Verkhoyanskaya, VIII – Bureino-Badzhalskaya, IX – Bira-Khinganskaya, X – Primorskaya, XI – Khankaiskaya [10]; 6 – boundaries of tectonic regions (a)

The lithosphere of Eastern Russia is complicated by the Indochina-Chukotka gravity anomaly as a step of the north-north-east strike. The anomaly magnitude is 50-100 mGal, the lateral gradient is 1-2 mGal/km. On the surface, the anomaly is marked by submeridional sutures, formed during the interaction of the Pacific and Asian continental plates [2]. In plane view, the Indochina-Chukotka anomaly stretches for thousands of kilometers and spreads up to 150 km in latitude, and its roots are traced in the upper mantle [5, 17]. Numerous MCCG are strung on the arcwise axis of the gravity anomaly. In the north of the region, the anomaly is associated with the Okhotsko-Chukotka volcanic-plutonic belt. In the South of the Amur region, Yu.F.Malyshev [6] identified the Khingano-Okhotsky element of this anomaly at depths of 34-42 km. It goes around the Bureinsky massif from the East and includes the gravity minimums of the Bureino-Badzhalskaya and Bira-Khinganaya MCCG (figure).

The Indochina-Chukotka anomaly divides the East of Russia into the Continental and Transitional Regions. The Continental region is characterized by negative gravity anomalies against the background of increased (40-42 km) thickness of the earth's crust. The most contrasting anomalies

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are confined to the Okhotsky and Khankaisky shields and to the Verkhoyansk belt, where they correspond to Polousnaya, Verkhne-Yanskaya, Verkhne-Indigirskaya, Okhotskaya and Yuzshno-Verkhoyanskaya, as well as Verkhne-Kolymskaya and Khankaiskaya MCCG. In the Transitional region, a positive gravity field is observed, including the Primorskaya and Chaunskaya MCCG. The Primorskaya anomaly region is characterized by a complex Moho relief and a reduced crust thickness of 28-36 km [15, 24]. In the southern part of the region, Moho deepens towards the North China platform up to 38-40 km. In the adjacent territory of China, the gravity anomaly is known as the Dahingan-Taihangskaya step [23, 25]. As in the East of Russia, it divides the lithosphere into western and eastern regions of different thicknesses [2, 17, 22].

The concentric geostructures of the Russian East are the epicenters of magmatic diapirs. The driving force of geodynamic processes and granitoid magmatism was mantle heat fluxes in reduced zones of the lithospheric slab [8, 20-22]. The distribution of asthenospheric windows along the strike of the Pacific mobile belt determines the location of the MCCG and the magnitude of granitoid magmatism in the provinces of the Russian East of: Sikhote-Alinskaya, Yano-Kolymskaya and Novosibirsk-Chukotka [1, 4, 6, 10, 17, 22, 23]. The deep structure of the MCCG was revealed using the materials of the State Geological Map and a complex of geological and geophysical data along geotraverses. It has been found that the Okhotsko-Chukotka, Umlekano-Ogodzhinsky, Bolshekhingansky, and East Sikhote-Alin magmatic belts differ in the differentiated relief of the mantle roof [4, 5, 17]. The most important fact is that MCCGs are the epicenters of gravity minimums, the chain of which marks the transregional leucocratization zone of the earth's crust with a width of more than 1000 km. The composition of this zone includes the Far Eastern belt of Li-F granites [1].

Due to mantle diapirism, the regional gravity field of 0-80 mGal is complicated by local negative anomalies of 80-160 mGal, which correspond to the deep regions of the density deficit and granitization. A geological and geophysical interpretation of this phenomenon can be found in the publications of A.I.Khanchuk, E.N.Lishnevsky, Yu.F.Malyshev, Yu.A.Pavlov, L.I.Bryansky, N.P.Romanovsky, A.S.Egorov, Yu.Ya.Vashchilov, V.A.Bormotov, A.N.Didenko, K.Li, F.Pirajno, W.Lin and others [4-6, 8, 9, 12-15, 23, 25]. Numerous asthenospheric protrusions have been identified on geotraverses [4-6]. Geophysical modeling of the orogenic belts of the East of Russia shows signs of Meso-Cenozoic granitization of the lithosphere.

One of the largest areas of granitization in the East of Russia is the May-Selemdzhinskaya mantle-crust structure with an area of about 580,000 km^2, which covers the outskirts of the Siberian platform, Jiamusi-Bureinsky massif and adjacent folded belts [5]. This lithospheric megastructure includes the Bureino-Badzhalsky, Bira-Khingansky, and Primorsky MCCG. Fluctuations in the thickness of the lithosphere range from 80-90 km to 150-170 km on an adjacent platform, while the thickness of the earth's crust ranges from 35-40 to 42-46 km. Oscillations of other MCCG parameters are also observed: the temperature on the Moho surface varies from 600-900 to 300-400 °C; the velocity of P-waves in the base of lithosphere ranges from 8.05-8.12 to 8.20-8.25 km/s [6, 11]. The Maya-Selemdzhinskaya MCCG group is bordered by a chain of negative gravity anomalies with the size ranging from 100 to 250 km, which record the location of the mantle diapirs of the Amur region (figure). MCCGs of the Russian East are characterized by an increase in the Moho's surface temperature (at an average of 700 °C), a decrease in velocity at the bottom of the lithosphere (8.16 km/s), density of a substance (up to 2.62 g/cm^3), a decrease in the thickness of the lithosphere (90 km) and Earth's crust (Table 1). Responsible for the MCCG's formation are ascending plumes [7].

The Nizhne-Amurskaya and Centralno-Aldanskaya MCCGs correspond to gold ore regions and are characterized by a decrease in the Moho temperature (on average 350 °C), an increase in speed (8.24 km/s), and the lithosphere thickening (140 km) [6]. They are formed under the influence of descending plumes [7]. The most contrasting is the Bureino-Badzhalskaya MCCG , divided into Dussealin-Yamalskaya and Komsomolsko-Badzhalskaya structures. The gravity minimum amplitude is –30-60 mGal [4-6, 12, 13, 15]. Primorskaya and Bira-Khinganskaya MCCGs are charac-

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terized by moderate amplitudes of anomalies (Table 1). Primorskaya MCCG is divided into smaller structures containing granitoid plutons [15]. The Sikhote-Alin heat flux has a density of 55 mW/m^2 [6], which brings the MCCG closer to the Cenozoic rifts. The predominance of radiogenic heat (0.57) over mantle indicates a weakening of mantle heating.

Table 1

Geophysical characteristics of magma-controlling concentric geostructures in the East of Russia (according to [5, 6, 14, 17])

Concentric geostructure	Thickness, km		ρ, g/cm^3		V_p, km/s	Moho, °C	q, mW/m^2	Δg, mGal
	E	L	E	M				
Dussealin-Yamalinskaya	38-40	< 100	–	3.20-3.30	8.0-8.05	800-900	–	–60
Komsomolsko-Badzhalskaya	34-38	60-90	2.62	3.25	8.12	500-800	55-90	–30
Bira-Khinganskaya	34-36	110-150	2.67	3.30-3.35	8.17	300-400	74	–40
Primorskaya	34-38	90-100	–	3.25	–	500-600	55	–25
Nizhne-Amurskaya	32-34	100-120	2.90	3.20-3.30	8.35	300-400	51	+20
Centralno-Aldanskaya	44-45	150-160	2.70	3.18	8.23	300-400	38-42	–5

Note. ρ – density of the layer; E – earth's crust, L – lithosphere, M – mantle; V_p – velocity of P-waves in the lithosphere; Moho – temperature on the surface of Moho; q – heat flux density; Δg – a value of the gravity minimum.

Discussion of the results. Mantle diapirs and their epicenters in the form of MCCGs are an integral part of the tectonosphere of the Russian East. Their study requires the use of geophysical data on the lithospheric structure [9, 13, 20-22]. On the example of the Yano-Kolymskaya granitoid province, delamination of the lithosphere in the Late Mesozoic is revealed, caused by its partial melting under the mantle-nuclear heat fluxes. The developed poly-astenospheric model of the deep structure of the North-East of Russia shows a decrease in the lithospheric thickness from 170 in the Elginsky region to 50-70 km on the coast of the Sea of Okhotsk and the Bering Sea. Deformation and heating of the lithosphere caused its tectonic stratification [8] and large-scale granite formation [14, 21]. The hypothesis of the poly-asthenosphere is confirmed by direct observations: a five-layer structure of the lithosphere has been determined [13].

The vertical stratification of the lithosphere is combined with lateral gradients of thickness and density, the most important of which are mantle diapirs – dome-shaped structures at the asthenosphere-lithosphere boundary. The density of the earth's crust over diapirs is reduced due to granitization of the crustal matter under the influence of deep heat and fluid flows. On the day surface, diapirs are reflected as MCCGs. For example, the formation of the Bureino-Badzhalsky, Bira-Khingansky and Primorsky MCCGs (see Figure) is associated with the interaction of the Sikhote-Alinsky, Central Asian and Aldan-Stanovoy geoblocks and the rise of super-heated matter to the surface. The connection between the Amur region plumes and the Pacific superplume is not excluded [6, 7].

The cause of mantle diapirism is the formation of asthenospheric windows upon the break of the lithospheric slab [8, 20-22]. Granitoid magma chambers appear under the influence of basic melts and fluid flows penetrating into the upper horizons of the earth's crust. Large geoblocks with a diameter of hundreds of kilometers and a thickness of up to 10-20 km are leucocratic and close to granitoids composition. Granitoid cryptobatolites (Chaunsky, Badzhalsky, Bikino-Malinovsky, etc.) are located in such sialitic blocks that meet two main conditions of ore genesis:

• there is a significant accumulation of water, fluorine, and other volatile components capable of concentrating and moving ore substance;

• the concentration of ore components by femic minerals with high isomorphic capacity is sharply reduced.

Due to the inextricable genetic link between granitization of the earth's crust and mantle diapirs, the MCCG contours determine the boundaries of ore-bearing leucogranite complexes and ore regions [10]. With the differentiation of leucocratic granites, Li-F ore-bearing granites may oc-

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cur [1]. Li-F granites and the largest rare-metal-tungsten-tin deposits in the region are controlled by the MCCG (Table 2).

Table 2

Ore-bearing granites and rare-metal-tungsten-tin deposits in the concentric geostructures of the Russian East

Geostructures, Li-F granites intrusions, and W-Sn deposits			Li-F granites stock coordinates	
Geostructure	Li-F granites stock	Deposit	Latitude	Longitude
Chaunskaya	[Iultinsky]	Iultin	67°51'25"N	178°44'54"W
Chaunskaya	Kulyuveemsky	Pyrkakayskoye	69°43'49"N	171°55'24"E
Polousnaya	Odinoky	Odinokoe	69°45'36"N	141°59'40"E
Polousnaya	Polarny	Polarnoe	69°40'59"N	141°39'40"E
Verkhne-Yanskaya	Kestersky	Kesterskoe	67°15'51"N	134°12'24"E
Verkhne-Yanskaya	Verhneburgaliysky	Burgaliyskoe	65°39'59"N	139°24'19"E
Verhneindigirskaya	Sphinx	Sphinx	65°20'28"N	144°36'35"E
Verkhne-Kolymskaya	[Nevsky]	Nevskoe	62°15'27"N	155°28'34"E
Verkhne-Kolymskaya	[Butugychagsky]	Butugychag	61°19'26"N	149°13 '02"E
Okhotskaya	Nyutskie stocks	–	60°35'33"N	144°49'09"E
Bureino-Badzhalskaya	Dozhdlivy	Pravourmiyskoe	50°24'14"N	134°05'17"E
Primorskaya	Tigriny	Tigrinoe	46°11'14"N	135°50'33"E
Khankaiskaya	Voznesensky	Voznesenskoe	44°09'58"N	132°11 '30"E

Note. In square brackets – cjncealed intrusions.

The data presented in the table allow us to conclude that mantle diapirs serve as the cores of granitoid ore-magmatic systems and the most productive ore clusters and regions. The distribution of ore regions in concentric geostructures with areas of negative gravity anomalies is the most important metallogenic pattern in the East of Russia, which reflects the relationship of ore content with the deep structure of the earth's crust.

Conclusions. 1. In the East of Russia, there is a chain of magma-controlling concentric geostructures concentrated in three granitoid provinces: Novosibirsk-Chukotka, Yano-Kolymskaya, and Sikhote-Alinskaya.

2. The driving force of geodynamic processes and granitoid magmatism of the East of Russia was mantle heat fluxes in the reduced zones of the lithospheric slab. The distribution of asthenospheric windows along the strike of the Pacific mobile belt determines the location and scale of granitoid magmatism.

3. Mantle diapirs of the East of Russia serve as the cores of granitoid ore-magmatic systems. The location of the most important ore regions of the Eastern Russia in concentric geostructures surrounded by annuli of negative gravity anomalies is the most important regional metallogenic pattern reflecting the correlation between ore content and deep structure of the earth's crust.

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