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GEOLOGICAL AND GEOCHEMICAL ASPECTS OF THE ROCK GRANITIZATION PROCESS

(1 Fig., 3 Tabs.)

Abstract: The authors define the term „granitization". Six stages of granitoids formation are identified: I = re-crystallization of rocks under the conditions of metamorphic amphibolite facies; II – coarsering and metasomatic changes in the rocks, with a possibility of metasomatic granitoids being generated; III and IV – anatexis, partial (III) and complete (IV) melting of enclosed rocks; V – overall homogenization of large masses of the melt palingenesis; VI – injection of homogenized magma, subsequent crystallization of which gives rise to intrusive granitoids. Granitization proper comprises II-V stages. Homogenization of large masses is a most intensive manifestation of anatexis.

Metasomatic granitoids are characterized by the following features: 1 – inheritance of the schistosity of the enclosing rocks; 2 – "ghost" banding; 3 – association with tectonically weakened zones; 4 – leucocratic composition; 5 – low concentration of accessory minerals; 6 – existence of gradual and sharp contacts with enclosing rocks, but with no quenching zone at the contact; 7 – occurrence in the environment of deeply metamorphozed rocks; presence of blastic deformation structures. Anatectic granitoids are characterized by: 1 – the presence of mineral alignment; 2 – veins of aplite and pegmatite; 3 – xenoliths of the enclosing rocks; 4 – no quenching zone at the contact; 5 – partial tracing of metamorphic rocks' structure in granitoids; 6 – a possible orientation of biotite. Granitization involves a rather intensive re-distribution of chemical elements and their isotopes. During the stage of transforming the rocks under granitization into granite-gneisses there is observed a dramatic change in the concentration of elements. Granitization is accompanied by the enrichment in alkali metals, depletion in alkali-earth elements and those of the iron group, accumulation of Sn, Zr, Y, F and in some places Be and Nb. In a number of cases the re-distribution of elements results in their local concentration and the formation of a mineral deposit.

An increase in volume of the rocks under granitization results in the generation of dome-like structures which are recognized as concentric brachy form occurrences of 20 to 30 km across. The central part of the domes is composed of the most intensively granitized rocks, i. e. anatectic granites, which are interrupted in places by intrusive granites.

The originally sedimentary and volcanogenic material is transformed into metamorphic rocks, later subjected to granitization. This process results in steady growth of the upper crust.

Key words: granitization, metasomatic granitoids, anatectic granitoids, geochemistry.

Granitization involves a number of geochemical processes (grain coarsering, metasomatism and anatexis)with the result that various rocks undergo changes in composition and fabric and eventually turn into granites. Granitization is significantly easier if the rocks' chemical composition resembles that of granite.

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Table 1

Sequence of events in the process of rocks granitization and granitoids distinctive properties

Stage (GRANITIZATION)		Occurrence condition	Form	Orientations of biotite	Contacts	Enclosing rocks	Other signs
VI Intrusions of palingenetic melt into upper structural stages (upper crust) ↑	Magmatic (intrusive) granites to 20–30 %	Allochthonous	Intrusive bodies of varying forms	Doesn't exist	Intrusive, sharp. Quenching, hornfelsation of enclosing rocks. Possibly skarns	Variable	Granite texture
V Overall homogenization of the melt – palingenesis ↑	Palingenetic granites				Indistinct		Abundance of exocontact varieties
IV Complete melting – diatexis; III Local melting – metatexis (mobilizate + restite) ↑	Anatectic granites 60–80 %	Parautochthonous or autochthonos	Largest bodies, usually heterogeneous	Exists	Usually conform, gradual	Metamorphic and granitized rocks of amphibolitic facies	Ghost textures, abundance of pegmatites and migmatites
II Blastesis ↑ / Metasomatism ↑	Metasomatic granites to 10–15 %	Autochthonous	Relatively small massifs, associated with fault zones	Always oriented	Conform, gradual (rarely sharp, secant). No quenching	Metamorphic rocks of amphibolic facies	Relicts of substituted rocks. Banding. Blastic structures
I Re-crystallization ↑ ↑ ↑	Gneisses and other rocks of amphibolite facies metamorphism						
Metamorphic rocks							

Granitization processes give rise to metasomatic granites and anatectic granite melts; when crystallizing, these latter form anatectic, including palingenetic (i. e. with 100 % degree of melting), granites and intrusive granites. The following stages are identified in the process of granitoid formation (see Tab. 1):

Stage I: recrystallization of rocks. This stage is responsible for the emergence of gneisses and other rocks pertaining to the amphibolite facies of metamorphism. It precedes granitization and is classified as a metamorphic phenomenon.

Stage II: plastic deformation, metasomatic reformation of rocks. The stage comprises enrichment and depletion in elements. Metasomatic granites are likely to emerge.

Stages III and IV: anatexis, with partial (III) and complete (IV) melting of enclosing rocks.

Stage V: palingenesis, with overall homogenization of the melt.

Stages III to V result in melts which, when crystallized, give rise to anatectic and palingenetic granites which are autochthonous or parautochthonous.

Stage VI: injection of palingenetic granite magma into the upper crust; when crystallized, this magma gives birth to genuine magmatic (intrusive) granites. This stage is not assigned to granitization, but rather is descriptive of the magmatic process proper. Granitization proper evolves only through stages II to V, that is, blastesis (plastic deformation), metasomatic changes and anatexis, with palingenesis regarded as an extreme case of anatexis.

Many aspects of granitization have been discussed in detail in a number of publications by scientists from the U.S.S.R and other countries Korzhinsky (1959, 1968 and other), Sobolev et al. (1967), Zharikov – Gavrikova (1987), Read (1955), Platen (1967), Pitcher (1967), Mehnert (1968), Roubault – de la Roch (1972), Taylor – McLennan (1985).

Granitization takes place under the PT-conditions of amphibolite facies regional metamorphism. It starts with the development of microcline porphyroblasts in crystalline schists and gneisses. These porphyroblasts formed from fluids rich in water and alkalies, which are capable of travelling considerable distances. Metasomatic changes of greater intensity are revealed in the spreading feldspars formation occurring in rocks of different composition and genesis. Metasomatic processes involving enrichment in some elements and depletion in others, lead to the formation of augen gneisses, granite-gneisses and pegmatites; at a certain level of intensity they might give rise to granitoides. Metasomatic granitoids are remarkable in that they are rich in feldspars and poor in coloured minerals, chiefly in biotite, which is always oriented parallel to the schistosity of the enclosing rocks. Metasomatic granitoids can be identified by:

1 – relict schistosity of the enclosing rocks mimicked by parallel biotite orientation in the granites;

2 – relict ghost banding similar to that of enclosing rocks;

3 – association with zones tectonically weakened (blastomylonites, augen gneisses);

4 – leucocratic composition manifested by the partial or complete absence of coloured components (biotite content is as low as 1 to 5 %), and a considerable amount of feldspar as compared with magmatic granitoids. The rocks are usually fine-grained;

5 – accessory minerals, which are the most common in granites (apatite, magnetite, zircon, etc.), are at a minimum;

6 – contact zones which are both gradual and clear-cut; no quenching is recognized at the contact with enclosing rocks;

7 – occurrence in the environment of deeply metamorphized rocks;

8 – existence of blastic structures.

Metasomatic granitoids are rather similar to granite-gneisses with the only difference being their more leucocratic composition and granite-like habit. Metasomatic granites constitute only 10 to 20 % by volume of all granite rocks. It should be noted that metasomatic granites have not been through a magmatic stage.

Anatexis and palingenesis are regarded as key processes in the formation of the Earth's crust. The first phase of anatexis involves local melting of rocks and is termed metatexis (Mehnert, 1968). The lowest melting temperature leucocratic (quartz-feldspathic) material of metamorphic rocks, i. e. mobilizate, is first to melt. After the mobilization removal, the remaining part of the rock restite is enriched in elements of the iron group (Fe, Mg, etc.). Metatexis gives rise to various migmatites, granite-gneisses (granitized gneisses) and pegmatites. Local melting of rocks seems to be associated, in the first place, with the re-distribution of elements in the course of granitization (Milovsky-Mathveeva, 1970).

The last phase of anatexis consists of complete melting of the rock, termed diatexis (Mehnert, 1968). Anatectic granites are generated during this stage. These granites are autochthonous (not transported) or parautochthonous (transported a little) (Read, 1955). Raguin (1976) has suggested that these granites should be termed stratimorphic, i. e. granites with the inherited texture of enclosing rocks. The same granites are commonly referred to as synkinematic ones.

Anatectic granites can be identified on the basis of the following criteria:

1 – the presence of both metamorphic and typically granite textures, this latter is essential; the rocks are medium-grained and of varying grain size;

2 – abundance of vein granite bodies, that is, aplites, pegmatites, etc. (in the initial anatexis);

3 – the absence of quenching, apophyses or interveined granite streaks in the contact zone;

4 – xenoliths, feature a texture orientation which is similar to or identical with that of the enclosing metamorphic rocks;

5 – outlines of the textures of metamorphic seqeuences (contacts of the fold) extends in part into the granitoids;

6 – a possible relict banding and orientation in biotite.

Metasomatic granites rather resemble granitized (feldspathized) gneisses and granite--gneisses, while anatectic granites are much more like genuine granites. Typical of the former type are blastic structures, of the latter type, granite textures. The abundance of migmatites and pegmatites in the fringes of granitoid massifs testify to their anatectic origin.

Anatectic granites do not always exhibit biotite orientation and banding, it is often difficult to tell them from intrusive granites by eye. Granites of this type are palingenetic and emerge as a result of melting involving appreciable masses of enclosing rocks, while the melted material itself is largely homogenized (does not show any orientation). Palingenetic granites, however, are not intruded granites. They feature gradual contacts with anatectic granites and usually occur within the latter, forming central parts of dome structures. Endocontacts (margin parts) reveal widely varying palingenetic granites. Anatectic granites (palingenetic ones included) constitute less than 60–80 % of the total amount of granitoids.

Genuine intrusive granites are only those which have crystallized from granite magma intruded into rocks of the upper crust. They feature magmatic texture and intrusive contacts. Magmatic granitoids constitute no more than 20 to 30 % of all granitoids. Magmatic granites are always allochthonous and are not associated with the enclosing rocks. When they occur in the cores of granite-gneiss domes they show intrusive contacts with the enclosing granitoids.

Magmatic intrusive granites have a granite-gneiss base or a migmatitic one, in the entrails of which the granite magma originated. Magmatic granites are always younger in age than associated anatectic and metasomatic granites and granite-gneisses.

Table 2

Calculation of the elements budget in the granitization of Mugodzhary rocks

Type of analysis	Oxides, elements	Plagiogneisses (I) → Granite-gneisses (II)						Amphibolites (I) → Granitized amphibolites (II)					
		Content, weight %		Number of atoms per 10 000 Å^3		Enrichment-depletion per 10 000 Å^3		Content, weight %		Number of atoms per 10 000 Å^3		Enrichment-depletion per 10 000 Å^3	
						Difference						Difference	
		I	II	I	II	Absolute	In % to I	I	II	I	II	Absolute	In % to I
Silicate		n = 14	n = 15					n = 18	n = 17				
	SiO_2	65.43	74.90	178.49	197.48	+18.99	+11	49.90	63.18	144.06	169.74	+25.68	+18
	TiO_2	0.82	0.25	1.67	0.50	−1.17	−70	1.5	0.60	3.26	1.21	−2.05	−62
	Al_2O_3	15.28	12.85	48.93	39.93	−3.00	−6	14.63	15.30	49.78	48.40	−1.38	−3
	Fe_2O_3	1.91	1.16	3.90	2.30	−1.6	−41	4.44	1.97	9.65	2.98	−6.67	−69
	FeO	3.80	1.03	8.63	2.27	−6.36	−74	8.13	3.46	19.62	7.77	−11.85	−60
	MnO	0.12	0.06	0.28	0.13	−0.15	−54	0.20	0.14	0.49	0.32	−0.17	−35
	MgO	2.10	0.61	8.50	2.40	−6.10	−72	6.72	2.53	28.90	10.13	−18.77	−65
	CaO	2.28	1.35	6.64	3.81	−2.83	−43	9.12	4.45	28.21	12.80	−15.41	−55
	P_2O_5	–	–	–	–	–	–	0.22	0.13	0.54	0.30	−0.24	−44
	F	0.34	0.15	6.16	2.64	−3.52	−57	0.27	0,06	5.19	1.07	−4.12	−79
Flame photometry		n = 11	n = 9					n = 11	n = 9				
	Na	3.53	3.98	25.06	27.42	+2.36	+9	3.34	3.63	25.20	25.49	+0.29	+1
	K	2.93	3.43	12.23	13.90	+1.67	+14	2.92	3.31	12.96	13.70	+0.74	+6
	Li	0.006	0.005	0.14	0.11	−0.03	−21	0.005	0.004	0.12	0.09	−0.03	−25
	Rb	0.008	0.007	0.02	0.02	0.00	–	0.008	0.005	0.02	0.01	−0.01	−50
Spectrum		n = 20	n = 44					n = 62	n = 10				
	Cr	0.048	0.004	0.15	0.01	−0.14	−93	0.015	0.006	0.05	0.02	−0.03	−60
	Ni	0.006	0.0004	0.02	0.00	−0.02	−100	0.007	0.002	0.02	0.01	−0.01	−50
	Co	0.004	0.0003	0.01	0.00	−0.01	−100	0.006	0.0008	0.02	0.00	−0.02	−100
	V	0.041	0.003	0.13	0.01	−0.12	−92	0.015	0.006	0.05	0.02	−0.03	−60
	Si	0.013	0.004	0.03	0.01	−0.02	−66	0.024	0.004	0.07	0.01	−0.06	−85
	Zr	0.016	0.076	0.03	0.13	+0.10	+33	0.006	0.011	0.01	0.02	+0.01	+100
	Σ_+					+23.12	+8					+26.69	+8
	Σ_-					−25.08	−8					−60.83	−19
	Σ			301.02	293.06	−1.96	0			328.22	294.69	−34.14	−11

Density $\delta_I = 2.71$ $\sigma_{II} = 2.63$ $\delta_I = 2.88$ $\sigma_{II} = 2.68$

So, in the course of granitization (evolving from gneisses to granite-gneisses, metasomatic, anatectic and magmatic granitoids) relicts of the enclosing rocks, banding, schistosity and blastic textures disappear. The interrelation and sequence of events in the process of rock granitization are shown in Tab. 1.

The successive granitization of rocks results in the redistribution of chemical elements and their isotopes. Study of this phenomenon has been undertaken in Pribaikalie, Ukrainian shield, Western Kazakhstan (Mugodzhary), the Yenisei chain of hills, Priladozhie, etc. (Milovsky–Mathveeva, 1970 and others). Tab. 2 provides calculation of the element budget following the atomic-volumetric method applied to the case of Western Kazakhstan (Mugodzhary).

Petrographic and petrochemical analysis of the rocks testifies to the fact that the composition and structure of rocks under granitization change dramatically when transforming into granite-gneisses (Fig. 1.). Fig. 1a shows parental rocks composed mainly of biotite schists and gneisses (pelitic rocks); Fig. 1b represents amphibolites.

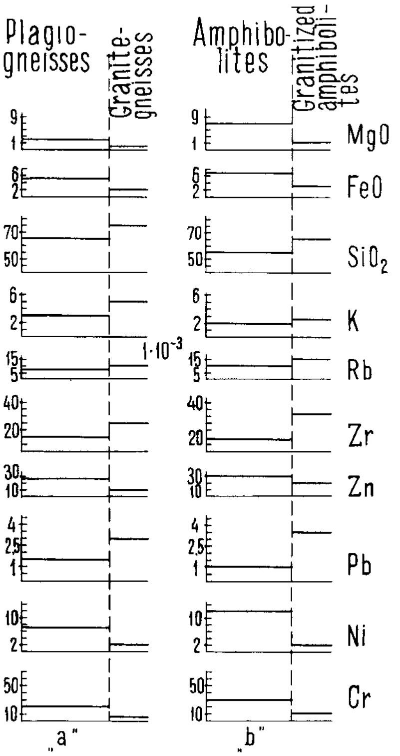

Fig. 1. Distribution of oxides and chemical elements (wt. %) in the rocks at different leves of granitization.
a – parental rocks of pelites and psammites;
b – parental rocks of amphibolites.

In both cases there is observed a clear-cut jump in the concentration of chemical elements (the broken line), with granite-gneisses and parental metamorphic rocks and initial stages of their granitization to the left.

Generalized data on the chemical budget of rocks undergoing granitization in various regions suggest the following phenomena: 1 – enrichment in Si in all types of rocks (quartzite

Table 3

Depletion in elements during granitization from 1 km^3 of non-granitized rocks, in 10^3tons

Element	Priladozhie		Mugodzhary		Yenisey chain of hills	Ukrainian massif
	1	2	1	2	1	1
iron	98 150	151 300	73 860	170 000		
copper	130	240	237	600	78	160
zinc	420	500			190	270

(1 – from gneisses to granite – gneisses, 2 – from amphibolites to granitized amphibolites)

excluded) throughout various regions (10–18 %); Al-content remains largely unchanged; 2– enrichment in alkali metals, especially K (10–90 %) and Rb. The K is derived from sedimentary rocks of the Earth's crust; the budget of Na and Li varies from province to province; 3 – depletion in alkali-earth elements Ca and Mg (20–60 %); 4 – depletion in elements of the iron group: Fe, Mn, Ti (40–70 %), Cr, V, Ni, Co (60–90 %), as well as P (about 40 %); 5 – depletion in chalcophile elements Cu (50–80 %); 6 – depletion in H_2O (60–80 %); 7 – accumulation of Sn, Zr, Y and in some cases Be and Nb; 8 – the accumulation of fluorine which is enriched in the younger granites.

In regions of regional metamorphism and ultrametamorphism all types of metamorphic rocks are subject to granitization: metamorphozed psammitic rocks (metasandstones and quartzites), metamorphozed pelitic rocks (schists and plagiogneisses), metamorphozed rocks of a basic composition (amphibolites) and other rocks. However, no matter what their composition was before granitization, all the rocks are close to granite in composition after granitization.

According to degree of granitization, metamorphozed psammite rocks can be arranged in the following series: metasandstone-leptite – granite-gneiss – granite. Rocks of this series originally constitued the arkose suite, which is rather typical of late Precambrian. During the process of granitization, mineral composition and textural-structural features of the rocks gradually change, as well as the morphology and composition of certain rock-building and accessory minerals. Plagioclase becomes enriched with an albite component, potassium feldspar acquires the perthite structure, facets of zircon get closer to perfection.

It is quite probable that the appropriate structural conditions and type of environment might affect the element migration pattern so that the elements would be concentrated locally and anomalously, forming a deposit. Calculation of element depletion in the process of granitization made for a number of regions of the U.S.S.R is given in Tab 3. In other cases structural conditions and the type of environment might favour a long-distance migration of elements, possibly out of the entire source region.

Water released during progressive metamorphism may become the transporting agent for the elements (Ryabchikov, 1975 and other publications). In the process of progressive metamorphism rocks are melted under fluid-present conditions.

Granitization of rocks leads to the formation of typical geological formations, i. e. dome-like structures (the rocks subject to granitization show an increase in volume). In the Southern Urals and Mugodzhary dome-like structures (or domes) are encountered as almost circular brachyformations normally extending 15–20 km (and more) in width. The domes emerged in the course of granitization involving rocks of the Yuzhnomugodzharsky and Taldyksky series. The generated granitoids are autochthonous. In the structure of the domes there are traces of horizontally closed folds made up by Precambrian metamorphic sequences, with the most ancient rocks being localized in the central parts. The centres of domes are composed of the most granitized rocks, i. e. anatectic granites, which are in places cut by intrusive granites.

Moving from the centre to the margins of the domes anatectic granites are gradually replaced by granite-gneisses and finally by gneisses and schists. This gradual change from anatectic granites through a transition zone of granite-gneisses, migmatites, pegmatites and vein bodies up to typical gneisses, takes up a distance of several hundreds of meters to 3–5 km.

As might be expected, schistosity in gneisses, granite-gneisses and anatectic granites is much the same, with the schistosity parallel with the domes' outline, dipping outwards from the dome. The formation of dome structures is depended on the geological environment, particularly the composition and structure of rocks undergoing granitization, the number and nature of faultes, etc. It is difficult to account for all the variety of factors, however, dome structures encountered in different regions are rather similar.

Analyses of granitization taking place in fold structures (as for example in the Milysaisky massif of Mugodzhary) attest to the fact that most granitized rocks always occur in the closed part of a fold. This is explained by the following phenomenon: when the substratum is gradually melting, the most easily-melted leucocrastic material moves into the area of lowest pressure, that is into the hinge of a fold. Numerous observational data fit readily into this concept.

The geological data reveal that granitized rock strata are not very thick, ranging from 3 to 5 km. Deep under these strata the underlying metamorphic and magmatic rocks become increasingly more basic in composition, from whence it may be inferred that granites are characteristic of the chemically more differentiated upper part of the Earth's crust (the upper crust).

Granitization is an irreversible differentiation process of the Earth's crust. Originally sedimentary, pelitic and psammitic material, as well as volcanogenic rocks convert into various metamorphic rocks and finally into granites. Granites become increasingly more widespread throgh the geological history of the Earth's crust, with their composition aquiring greater diversity with time.

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