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TECTONIC POSITION OF MINGLING DYKES IN ACCRETION-COLLISION SYSTEM OF EARLY CALEDONIDES OF WEST SANGILEN (SOUTH-EAST TUVA, RUSSIA)

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Paleogeodynamics

Abstract: Dykes composed of basic rocks and granite are formed due to interactions between melts in a wide range of conditions, from contrasting compositions and fluid saturation rates to various tectonic settings and processes at different depths. Textures and petrochemical characteristics of the dykes are thus widely variable. This paper is focused on composite dykes observed in the West Sangilen region in South-East Tuva, Russia.

The Sangilen wedge is a fragment of the Early Caledonian orogenic structure of the Tuva-Mongolia Massif which evolved in a succession of geodynamic settings, from collision (transpression, 570–480 Ma) to transform faulting (transtension, 480–430 Ma). Intensive tectonic deformation facilitated massive basic-rock and granite magmatism at various layers of the crust and associated heating and metamorphism of the rocks (510–460 Ma). Basic-rock–granite composite dykes were formed in the above-mentioned period in various tectonic settings that controlled conditions of dyke intrusions and their compositions.

We distinguish two groups of composite dykes observed on two sites, in the area between the Erzin and Naryn rivers and on the right bank of the Erzin river (Strelka and Erzin Sites, respectively) (Fig. 1). The dykes in both groups originated from one and the same basic-rock melt source. However, mingling of the contrasting melts was carried out by different mechanisms as suggested by the proposed intrusion models.

In the area between the Erzin and Naryn rivers (Strelka Site), the host rock of the composite dykes is granite of the Nizhneerzin massif. The mingling dykes are composed of amphibole gabbro and monzogabbro, granosyenite and two-feldspar granite. Contacts between basic and felsic rocks vary from smooth contrasting to complex 'lacerated' flame-shaped, and gradual transition zones are present (Fig. 6).

The dykes were formed at mesoabyssal or abyssal depths, and the subliquidus heat regime was thus maintained for a long time, and even the smallest portions of the basic-rock melt were consolidated through quite a long period of time. As a consequence, indicators of deformation are lacking in the composite dykes, while transition zones and hybridization are present.

On the right bank of the Erzin river (Ersin Site), the dykes cut through migmatite-granite of the Erzin formation in the same-name tectonic zone. Contacts with host rocks are transverse. Melanocratic rocks are represented by small-grained diorite and quartz diorite, and the felsic composite dykes are composed of medium- and small-grained two-feldspar granite and leukogranite. Transition zones, hornfelsing and contact alterations are absent at contacts of all the types (Fig. 8).

The composite dykes of this type intruded and emplaced when the shear zone was subject to extension and fragmentation, which predetermined active intrusion of basic and, possibly, felsic melts through conjugated faults. Crystallization of the melts was rapid, and their potential heat impact on the adjoining rocks was thus excluded, as evidenced by the presence of oxygonal chips of igneous and host metamorphic rocks, vein pegmatoid intrusions, and composite dykes of the reticulate-cuspate texture with the dominant basic-rock component.

The mingling dykes classified in the first group intruded when the Erzin and Kokmolgarga shear zones were formed at the early stage of the tectonic-magmatic evolution of the Sangilen orogen (510–490 Ma). Intrusions of the basic-rock melts were accompanied by the formation of relatively large massifs of the basic composition, i.e. the Erzin and Bayankol gabbro-monzodiorite massifs, as well as by the occurrence of composite dykes that are abundant in the area between the Erzin and Naryn rivers. In the second stage (460–430 Ma), the composite dykes occurred when the orogen was subject to extension along the system of tectonic zones, the Bashkymugur gabbro-monzodiorite massif was emplaced, and fracture-vein structures, including the dykes, were formed.

Key words: mingling, composite dykes, net-veined complexes, shear zone, tectonic and magmatic evolution, Sangilen, South-East Tuva.

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Тектоническая позиция минглинг-даек в аккреционно-коллизионной системе ранних каледонид Западного Сангилена (Юго-Восточная Тува)

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Аннотация: Формирование базит-гранитных комбинированных даек происходит в широком спектре условий и обстановок взаимодействия контрастных по составу расплавов, начиная от специфики состава и флюидонасыщенности расплавов и заканчивая тектоническими обстановками и глубинностью процессов. Все эти факторы отражаются на структурно-текстурных и петрогеохимических характеристиках даек. В настоящей работе данные вопросы рассмотрены на примере комбинированных (минглинг) даек Западного Сангилена (Юго-Восточная Тува).

Сангиленский выступ представляет собой фрагмент раннекаледонской орогенной структуры Тувино-Монгольского массива, тектоническая эволюция которой отражает смену геодинамических обстановок – от коллизионной (режим сжатия, 570–480 млн лет) до сдвиговой (режим растяжения, 480–430 млн лет). Интенсивные тектонические деформации способствовали проявлению масштабного базитового и гранитоидного магматизма на различных уровнях земной коры и связанного с ним теплового прогрева и метаморфизма пород в период 510–460 млн лет. С этим же периодом связано проявление базит-гранитных комбинированных даек, формирование которых происходило в различных тектонических обстановках, контролирующих условия их внедрения и становления.

В статье рассматривается две группы минглинг-даек, изученных в междуречье Эрзина и Нарына и на правобережье р. Эрзин (рис. 1). В обоих случаях их происхождение связано с одним источником базитового расплава. Однако, механизмы смешения контрастных расплавов отвечают различным моделям внедрения.

В междуречье Эрзина и Нарына вмещающими породами комбинированных даек являются гранитоиды Нижнеэрзинского массива. Минглинг-дайки сложены амфиболовыми габбро и монцогаббро, граносиенитами и двуполевошпатовыми гранитами. Контакты между основными и кислыми породами различны и изменяются от ровных и контрастных до пламеневидных и микрофестончатых с образованием зон постепенных переходов (рис. 6).

Формирование даек этого типа происходило на мезоабиссальных либо абиссальных уровнях глубинности, что обеспечило при их становлении сохранность длительного субликвидусного теплового режима и относительно продолжительный период консолидации даже мелких порций базитового расплава. Как следствие, в комбинированных дайках отсутствуют признаки деформаций, но наблюдаются переходные зоны и гибридизация.

Дайки на правобережье р. Эрзин прорывают мигматит-граниты эрзинского комплекса в одноименной тектонической зоне. Контакты с вмещающими породами секущие. Меланократовые породы представлены мелкозернистыми диоритами и кварцевыми диоритами, кислая часть комбинированных даек сложена средне-, мелкозернистыми двуполевошпатовыми гранитами и лейкогранитами. Для всех типов контактов характерно отсутствие зон перехода, ороговикования и контактовых изменений (рис. 8).

Внедрение и становление комбинированных даек данного типа происходило в условиях обстановок растяжения и фрагментации сдвиговой зоны, что обусловило как активное внедрение базитовых и, возможно, кислых расплавов по сопряженным трещинам, так и их быструю кристаллизацию. Наличие остроугольных обломков магматических и вмещающих метаморфических пород, существование жильных пегматоидных образований, сетчато-фестончатый характер минглинг-даек с преобладанием базитовой составляющей прямо указывают на быструю кристаллизацию базитовых расплавов без возможности их последующего теплового воздействия на окружающие породы.

Внедрение первой группы минглинг-даек связывается с заложением Эрзинской и Кокмолгаргинской тектонических зон и отвечает раннему этапу тектономагматической эволюции Сангиленского орогена на рубеже 510–490 млн лет. Данный этап сопровождался как внедрением базитовых расплавов с формированием относительно крупных массивов основного состава (Эрзинский и Баянкольский габбро-монцодиоритовые массивы), так и появлением комбинированных даек, распространенных в междуречье Эрзина и Нарына. Второй этап формирования минглинг-даек связывается с тектономагматической активностью в регионе на рубеже 460–430 млн лет, когда происходило активное растяжение орогенной структуры по системе тектонических зон, внедрение и становление Башкымугурского массива габбро-монцодиоритов и развитие трещинно-жильных образований, в том числе комбинированных даек.

Ключевые слова: минглинг, комбинированные дайки, сетчатые интрузии, тектоническая зона, тектоно-магматическая эволюция, Сангилен, Юго-Восточная Тува.

1. Introduction

In case of interaction between basic-rock magma and granitoid magma, chemical and mechanical processes, i.e. mixing and mingling, take place simultaneously. Resultant structures are called composite / mingling dykes and net-veined complexes.

The problem of mingling has been discussed in many publications, including [*Wiebe, 1973; Gambler, 1979; Marshall, Sparks, 1984; Furman, Spera, 1985; Frost, Mahood, 1987; Cook, 1988; Huppert, Sparks, 1988; Didier, Barbarin, 1991; Litvinovsky et al., 1995; Nardi, de Lima, 2000; Fedorovsky et al., 2003; Perugini, Poli, 2005; Dokukina, Vladimirov, 2005; Sklyarov, Fedorovskii, 2006*], and numerous models have been proposed to describe and clarify the textures and structures of composite dykes.

Dykes can occur in a wide range of conditions predetermining interactions between melts of contrasting compositions. Such conditions include – but not limited to – tectonic processes, crustal depths and structures, duration of melt consolidation, composition and fluid saturation of interacting melts. Mingling dykes of various patterns and textures may be observed in one and the same region due to the presence of shear faults that differ in age and origin and control movements of basic-rock and granitoid melts. In our study, we review composite dykes located in West Sangilen, analyse petrogeochemical compositions at micro- and macroscopic levels and attempt at establishing relationships between the compositions and regional tectonic and magmatic events.

2. Geological setting

West Sangilen, a part of the Sangilen upland, is located at the border of Tuva, Mongolia and Buryatia in the Tuva-Mongolia Massif (hereafter TMM) in the Central Asian folded belt that is traditionally viewed as a collage of island arcs, continental blocks and oceanic crust fragments attached to the Siberian craton during the Neoproterozoic and Paleozoic [*Kovalenko et al., 2004, Kuzmichev et al., 2001*]. TMM is bordered by deep faults, and its structure differs from that of the neighbouring blocks. In its current coordinates, the Sangilen wedge is located in the north-western TMM (Fig. 1). It is bordered from the north-west by the Agardag ofiolite zone that is also viewed as the TMM boundary [*Kuzmichev, 2004*].

The Sangilen wedge is a fragment of the Early Caledonian orogenic structure of TMM which evolved in a succession of geodynamic settings, from collision (transpression, 570–480 Ma) to transform faulting (transtension, 480–430 Ma) [*Vladimirov et al., 2005*]. Intensive shearing facilitated massive basic-rock and granitoid magmatism at various layers of the crust and associated heating and metamorphism of the rocks (510–460 Ma) [*Vladimirov et al., 2005; Egorova et al., 2006; Karmysheva, 2012*].

The current West Sangilen structure includes the Muguro-Chinchilig and Erzin-Naryn metamorphic blocks separated by the Erzin shear zone (Fig. 1). The Muguro-Chinchilig block is mainly composed of a Moren metamorphic complex (medium temperature and high pressure). The Erzin-Naryn block's texture is inhomogeneous as it is composed of a variety of rocks from epidote-amphibolite to granulite facies of metamorphism, such as garnet-biotite, cordierite and spinel-cordierite schists and gneisses. Amphibolite and granulite are related to the Erzin metamorphic complex at the boundaries of the blocks which follow the tectonic boundaries, i.e. the Erzin and Kokmolgarga shear zones (Fig. 1).

The time periods when magmatism occurred in the Muguro-Chinchilig and Erzin-Naryn blocks are different. The Erzin-Naryn block includes the Bayankol gabbro-monzodiorite-granodiorite-granite, Nizhneerzin gabbro-monzodiorite-granosyenite-granite, Teskhem granosyenite-granite, and Ukhadag granosyenite-granite massifs (490±10 Ma). The Erzin shear zone includes the Nizhneulor granite massif (475±5 Ma) and the Matut gneiss-granite massif (510–490 Ma, according to the geological data). Mingling dykes composed of basic rocks and granite (i.e. the subject of our study) are observed in migmatite-granite of the Erzin complex

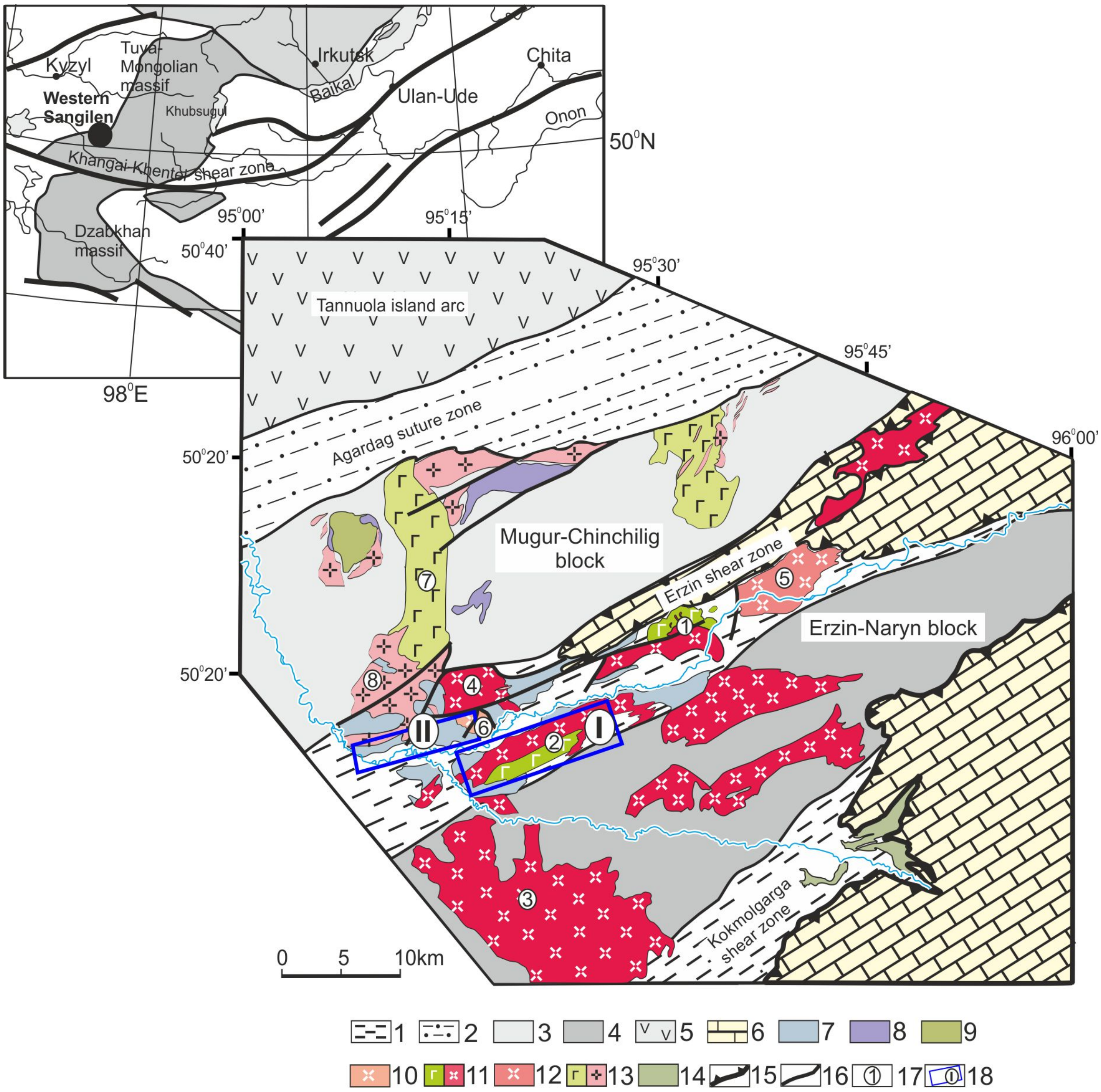

Fig. 1. The structural-tectonic scheme of West Sangilen (South-East Tuva, Russia). The inset shows the West Sangilen position at the southern margin of the Siberian craton (according to [*Kuzmichev, 2004*]).

1 – Erzin and Kokmolgarga shear zones (Є$_{1-2}$); *2* – Agardag ophiolitic belt (V-Є$_1$); *3* – Moren metamorphic complex (R$_3$); *4* – Nizhneerzin metamorphic complex (R$_3$); *5* – Tannuola island arc (V-Є$_1$); *6* – carbonate-terrigenous cover of the Tuva-Mongolia microcontinent (V$_1$); *7* – Erzin granulitic migmatite-granite complex (Є$_3$-O$_1$); *8* – Aktovrak dunite-harzburgite complex (V); *9* – Pravotarlashkin anortosite-gabbronorite complex (Є$_1$); *10* – Matut gneiss-granite massif (O$_1$); *11* – Bayankol gabbro-monzodiorite-granosyenite (granodiorite)-granite-leukogranite series (O$_1$); *12* – Nizhneulor granite massif (O$_1$); *13* – Bashkymugur gabbro-monzodiorite-granite-leukogranite series (O$_{1-2}$); *14* – gabbroids of the Kokmolgarga massif; *15* – nappe boundaries; *16* – faults; *17* – intrusive massifs: 1 – Bayankol gabbro-monzodiorite-granodiorite-granite, 2 – Nizhneerzin gabbro-monzodiorite-granosyenite-granite, 3 – Teskhem granosyenite-granite, 4 – Ukhadag granosyenite-granite, 5 – Nizhneulor granite, 6 – Matut gneiss-granite, 7 – Bashkymugur gabbro-monzodiorite, 8 – Baidag granite-leukogranite; *18* (I and II) – Strelka and Erzin Sites, respectively, where mingling dykes were studied in detail.

Рис. 1. Структурно-вещественная схема Западного Сангилена (Юго-Восточная Тува). На врезке – положение Западного Сангилена в структурах южного обрамления Сибирской платформы по [*Kuzmichev, 2004*].

1 – Эрзинская и Кокмолгаргинская тектонические зоны (Є$_{1-2}$); *2* – Агардагский офиолитовый пояс (V-Є$_1$); *3* – моренский метаморфический комплекс (R$_3$); *4* – нижнеэрзинский метаморфический комплекс (R$_3$); *5* – Таннуольская островная дуга (V-Є$_1$); *6* – карбонатно-терригенный чехол Тувино-Монгольского микроконтинента (V$_1$); *7* – эрзинский гранулитовый мигматит-гранитный комплекс (Є$_3$-O$_1$); *8* – актовракский дунит-гарцбургитовый комплекс (V); *9* – правотарлашкинский анортозит-габбронoритовый комплекс (Є$_1$); *10* – Матутский гнейсогранитный массив (O$_1$); *11* – баянкольская габбро-монцодиорит-граносиенит (гранодиорит)-гранит-лейкогранитная серия (O$_1$); *12* – Нижнеулорский гранитный массив (O$_1$); *13* – башкымугурская габбро-монцодиорит-гранит-лейкогранитная серия (O$_{1-2}$); *14* – габброиды Кокмолгаргинского массива; *15* –границы покровов; *16* – разломы; *17* – интрузивные массивы: 1 – Баянкольский габбро-монцодиорит-гранодиорит-гранитный, 2 – Нижнеэрзинский габбро-монцодиорит-граносиенит-гранитный, 3 – Тесхемский граносиенит-гранитный, 4 – Ухадагский граносиенит-гранитный, 5 – Нижнеулорский гранитный, 6 – Матутский гнейсогранитный, 7 – Башкымугурский габбро-монцодиоритовый, 8 – Байдагский – гранит-лейкогранитный; *18* – участки детального исследования минглинг-даек: I – участок «Стрелка»; II – участок «Эрзинский».

and granosyenite-granite of the Nizhneerzin massif. Results of the isotope geochoronology suggest that the dykes are not younger than 462.5 Ma as shown by the following data: 471.2±1.9 Ma – Ar/Ar, amphibole from basic rocks; 462.5±1.0 Ma – Ar/Ar, biotite from basic rocks [*Vladimirov et al., 2005*], and 467±21 Ma – Rb/Sr, rocks in gross [*Petrova, 2001*].

The Muguro-Chingilig metamorphic block contains younger igneous rocks (460±10 Ma). The Bashkymugur gabbro-monzodiorite and Baidag granite-leukogranite (alaskaite) massifs are of the same age.

In our study, we focus on mingling dykes composed of basic rocks and granite which are observed on Strelka and Erzin Sites, i.e. in the area between the Erzin and Naryn rivers and on the right bank of the Erzin river, respectively (Fig. 1).

3. Composite dyke structure and texture

In the area between the Erzin and Naryn rivers, the host rock of the composite dykes is granite of the Nizhneerzin massif. Visible segments of the dykes are traceable for several tens to hundreds meters, and their depth varies from 0.15 to 3.5 m (Fig. 2 and 3). It is not always possible to clearly define the positions of the endo- and exocontact zones, and the contacts with the host rocks are not clarified. Separate nodules of basic rocks penetrating into the host matrix can be observed in the marginal exocontact zones of the composite dykes (Fig 2, II). Typically, a large basic-rock body is either surrounded by a leucocratic rim or cut by a system of granite veins (Fig. 2, III and 3, IV). It is noteworthy that contacts of the granite veins are almost always flame-shaped and never linear (Fig. 2, III and 3, IV).

Basic-rock bodies of patchy shapes with flame-shaped contacts are cut by veins of large-grained granites (Fig. 3, II). In some cases, basic rocks in the granitoid matrix compose tree-shaped elongated bodies with elements of viscous boudinage and separate nodules (Fig. 3, I). However, such cases are not numerous, and composite dykes containing irregularly distributed fragments of basic rocks are dominating (Fig. 3, II and 3, III).

On Strelka Site, two generations of composite dykes are distinguished: (1) early sub-horizontal dykes composed by basic rocks, strongly boudinaged and cut by granite, and (2) later subvertical dykes composed by basic rocks, which cut the dykes of the first generation, have chill zones and are cut by aplite that cuts both the dykes and the host granite [*Izokh et al., 2004; Vasyukova et al., 2008*].

On Erzin Site, the dykes cut through migmatite-granite of the Erzin formation in the same-name shear zone. Clusters of composite dykes form linear zones which strike is similar to that of the Erzin shear zone. Depth of some dykes vary from 0.5 to 2.5 m. Contacts with host rocks are transverse (Fig. 4 and 5). In the leucogranitic component of the mingling dykes, oxygonal xenoliths of the host rocks (which maintain their original structure) are combined with separate angulated inclusions of diorite (Fig. 4, I). A contact acid rim is lacking around the dykes. Pegmatoid inclusions are common at the boundary between granites and host rocks and inside conjugated fractures (Fig. 4, II). The texture of such dykes is complex, reticulate-cuspate or patchy (see Fig. 5, I–III). Transition zones, hornfelsing and contact alterations are absent at contacts of all the types.

4. Composition of basic rocks and granites of mingling dykes

In the area between the Erzin and Naryn rivers (Strelka Site), the basic-rock component of the composite dykes is variable in composition from amphibole gabbro to monzogabbro and amphibole monzogabbro with gabbro and porphiric-like structures: Hbl (45–60 %), Kfs (20–35 %), Pl (10–15 %), Bt (5 %), and Qtz (>5 %). Accessory minerals are fine-grained sphene and apatite. Coarse-grained amphibole rims and plagioclase are absent in the contact zones.

The felsic dykes are composed of coarse-grained granosyenite: Kfs (40–65 %), Qtz (20–25 %), Pl (10–15 %), and Bt+Hbl (3–5 %), and two-feldspar granite: Kfs (35–40 %), Qtz (25–35 %), Pl (15–20 %), and Bt+Hbl (up to 3 %). Accessory minerals are sphene and ortite. Rocks vary from evenly grained to glomeroporphyric. Porphyric inclusions contain large aggregates of K-Na feldspar and, rarely, quartz. Small veins and fractures in the basic rocks are filled with the most coarsely grained rocks.

Contacts of basic and acid rocks are variable in shapes, from smooth to contrasting (Fig. 6, I), flame-shaped to micro-cuspate, with zones of transition from granites to basic rocks (Fig. 6, II–V). In microsections, changes in the composition and grain size of the rocks are clearly evidenced by 'bay-shaped' contours. The inner structure is changed near the contact from the side of basic rocks due to the occurrence of poikilitic grains of quartz with inclusions of idiomorphic small crystals of biotite and amphibole. Patchy aggregates with flame-shaped contacts, which are quite common, may be cut by acidic veins.

In the contact zone, basic rocks vary from gabbrodiotite to amphibole monzogabbro. Transitions from one rock to another are abrupt and clearly detected at the meso- and micro-levels. In several microsections and rock slices, amphibole gabbro and monzogabbro are rimmed by coarse-grained amphibole (see Fig. 6, III).

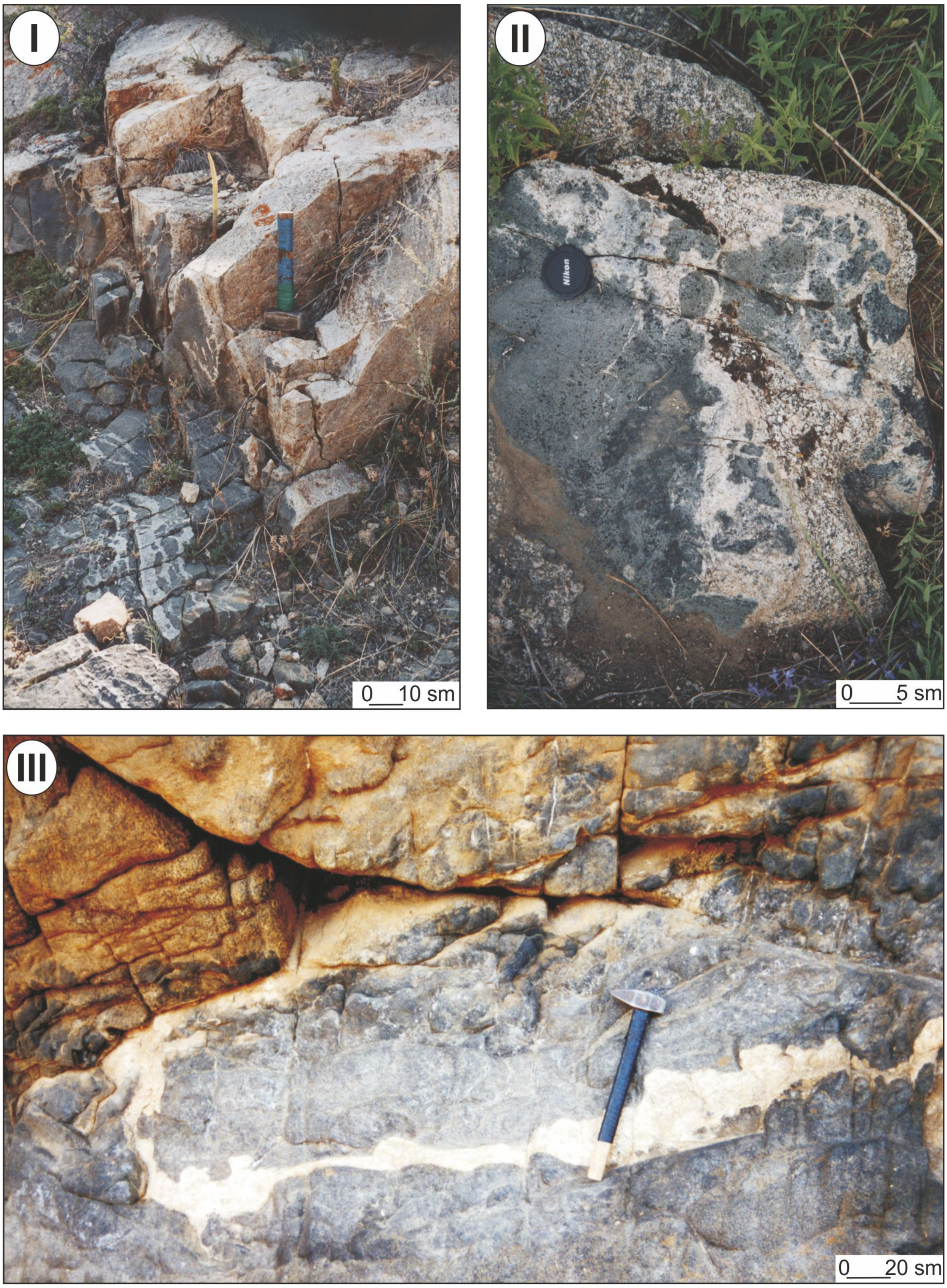

Fig. 2. Contacts between mingling dykes and host granite of the Nizhneerzin massif in the area between the Erzin and Naryn rivers (Strelka Site).

I – linear composite dyke composed of basic rocks and leucogranites in host parautochthonous granite; II – flame-shaped contact between basic rocks and host mega-porphyric granosyenite and basic-rock nodules in granite; III – cuspate sinuous contacts of the granite vein that cuts basic rocks in the interior zone of the mingling dyke.

Рис. 2. Контакты минглинг-даек с вмещающими гранитоидами Нижнеэрзинского массива в междуречье Эрзина и Нарына (участок «Стрелка»).

I – линейная комбинированная дайка, сложенная базитами и лейкогранитами, в параавтохтонных гранитах; II – пламеневидный контакт базитов с вмещающими крупнопорфировыми граносиенитами с формированием в гранитоидах нодулей основного состава; III – фестончатые, извилистые контакты гранитной жилы, пересекающей базиты, во внутренней зоне минглинг-дайки.

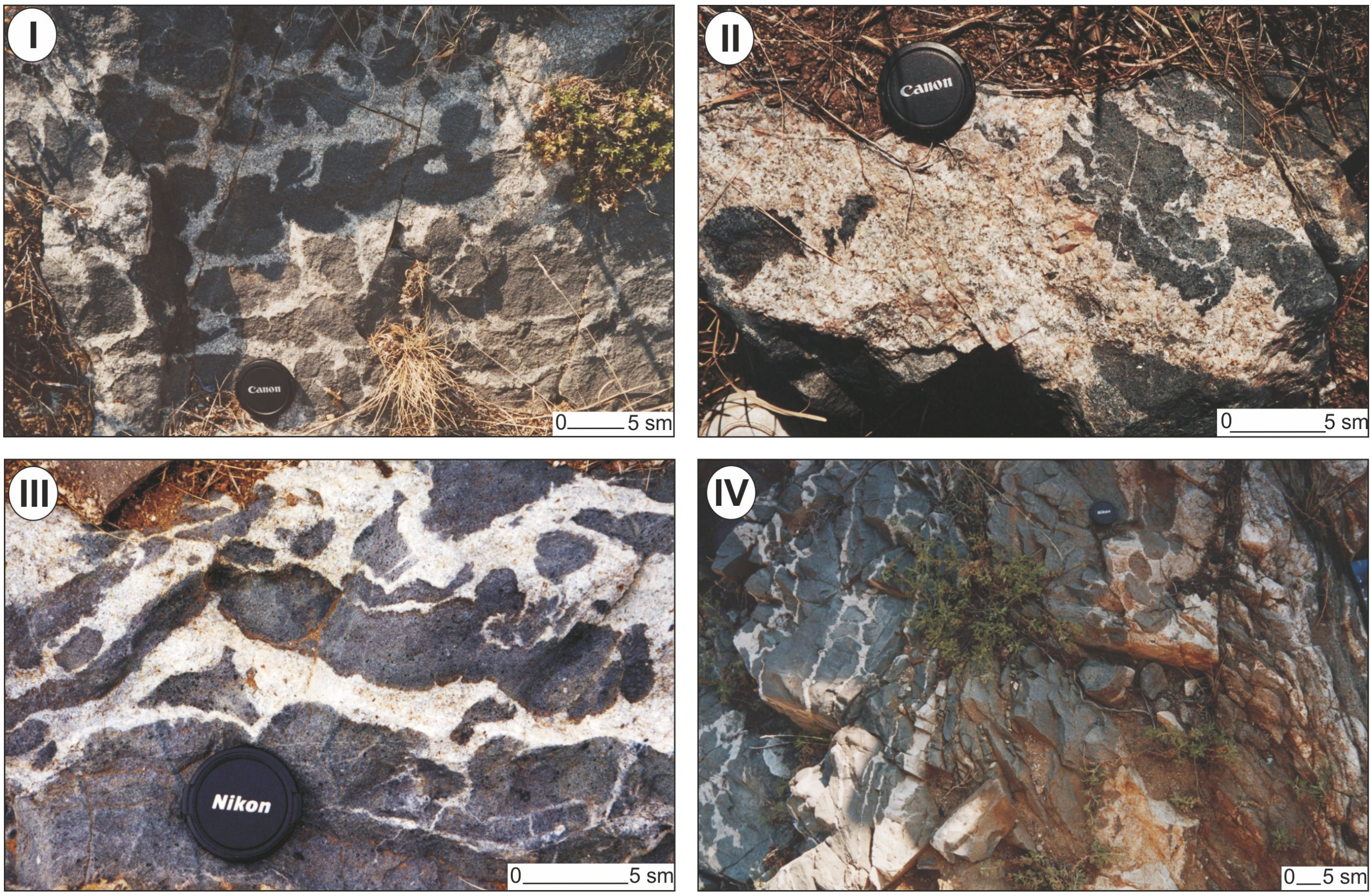

Fig. 3. The interior structure of mingling dykes in the area between Erzin and Naryn rivers (Strelka Site).

I – tree-shaped, reticulate-cuspate and nodule structure of basic rocks in the felsic matrix; II – patchy basic-rock bodies with flame-shaped contacts and thin leukogranite veins in the porphyric granosyenite matrix; III – reticulate-nodule texture of the composite dyke; IV – reticulate-cuspate inner texture of the composite dyke with the dominant basic-rock component.

Рис. 3. Внутренняя структура минглинг-даек в междуречье Эрзина и Нарына (участок «Стрелка»).

I – дендроидная, сетчато-фестончатая и нодульная структура обособлений базитов, заключенных в матрикс кислого состава; II – кляксообразные тела базитов с пламеневидными контактами и маломощными жилами лейкогранитов в матриксе порфировидных граносиенитов; III – сетчато-нодульная структура комбинированной дайки; IV – сетчато-фестончатая внутренняя структура комбинированной дайки с доминированием базитовой составляющей.

Contact zones may differ in width, and their patterns may be complex. The contact zones contain small nodules of basic rocks, fine-grained transitional rocks with evenly scattered melanocratic minerals and porphyric inclusions of K-Na feldspar, medium-grained transitional rocks with unevenly scattered melanocratic and leucocratic minerals, and sporadic coarse-grained aggregates of biotite and hornblende in granosyenite.

The transitional zones are composed of amphibole (10–60 %), biotite (10 %), K-Na feldspar (15–40 %), plagioclase (5–10 %) and quartz (>5 %) (Fig. 7). K-Na feldspar can form poikilite structures containing inclusions of fine-grained prismatic crystals of amphibole and biotite. Recrystallization of individual grains of quartz and plagioclase is typical of the marginal parts. Besides, a high content of sphene is noted in the transition zones, and sphene grains (up to 1 mm) are larger than those in monzogabbro and granosyenite.

Composite dykes on the right bank of the Erzin river (*Erzin Site*). Melanocratic rocks are represented by fine-grained diorite and quartz diorite: Amf (45–50 %), Pl (40–45 %), Qtz (10–15 %), and Bt (5 %). The rock texture is gabbro-ophite and porphyric. Porphyric inclusions are agglomerates of amphibole with a cribrose texture.

Felsic dykes are composed of medium- and fine-grained two-feldspar granite and leucogranite: Kfs (25–30 %), Pl (20–40 %), Otz (25–40 %), and Bt (1–3 %). The granite and porphyric textures are evenly grained. Porphyric inclusions are composed of K-Na feldspar. Deformation twins are observed in plagioclase grains.

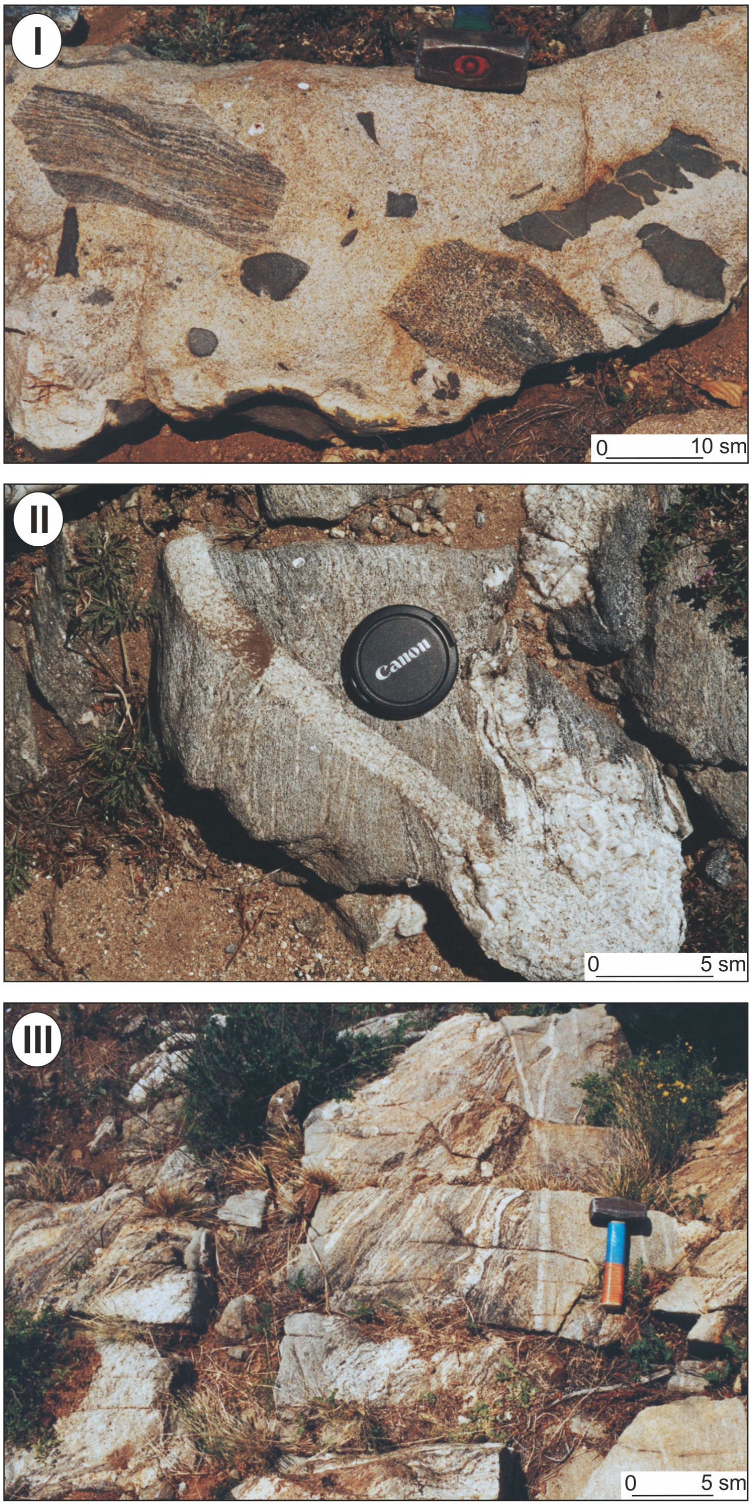

Fig. 4. The morphology of mingling dykes in migmatite of the Erzin metamorphic complex on the right bank of Erzin river (Erzin Site).

I – combination of oxygonal xenolithes of host rocks and angular diorite inclusions in leukogranite of mingling dykes; II – migmatite of the Erzin complex which is cut by leukogranite of composite dykes with pegmatoid inclusion in the contact zone of extension; III – transverse 'cold' contacts between granite in mingling dykes and host garnet-biotite-cordierite schist.

Рис. 4. Морфология минглинг-даек в мигматитах эрзинского метаморфического комплекса на правобережье р. Эрзин («Эрзинский» участок).

I – сочетание остроугольных ксенолитов вмещающих пород и угловатых обособлений диоритов в лейкогранитовой составляющей минглинг-даек; II – мигматиты эрзинского комплекса, прорванные лейкогранитами комбинированных даек с пегматоидным обособлением в приконтактовой зоне растяжения; III – секущие «холодные» контакты гранитоидов минглинг-даек с вмещающими гранат-биотит-кордиеритовыми сланцами.

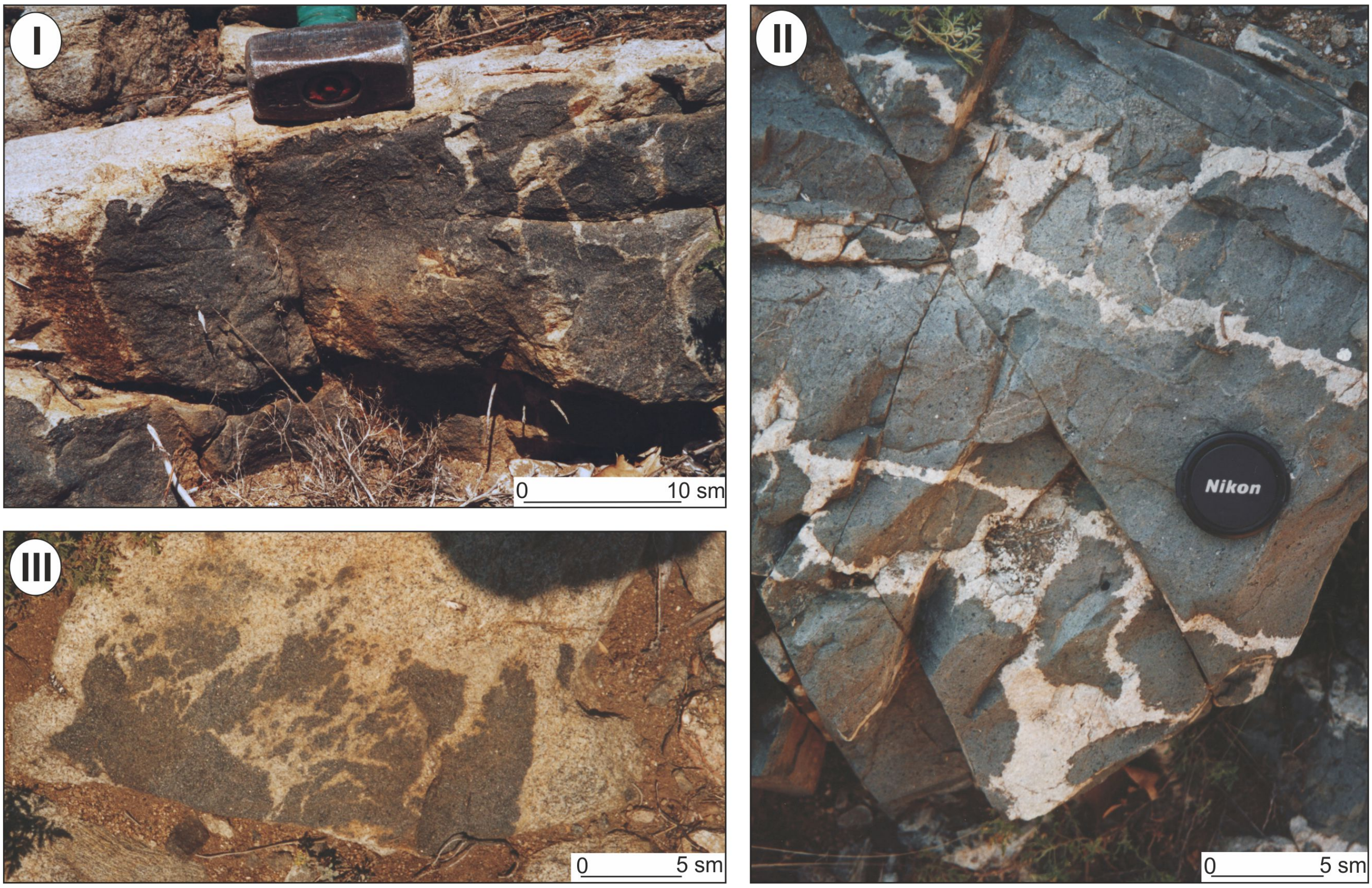

Fig. 5. The inner textute of mingling dykes on the right bank of the Erzin river (Erzin Site).

I-II – reticulate-cuspate contacts between granite and diorite in composite dykes with dominatant basic-rock component; III – complex patchy morphology of the mingling dyke.

Рис. 5. Внутренняя структура минглинг-даек на правобережье р. Эрзин («Эрзинский» участок).

I-II – сетчато-фестончатый контакт гранитов и диоритов в комбинированных дайках с резким преобладанием базитовой составляющей; III – сложнопятнистая морфология минглинг-дайки.

The diorite-granite contact is marked by smooth contours without any transitional zone as clearly evidenced by grain sizes and compositions of the rocks in the microsections and rock slices (Fig. 8). In the endocontact of diorites, observed are glomero-clusters of leust-biotite and a poikilite structure composed by quartz aggregates with inclusions of fine-grained idiomorphic crystals of biotite and amphibole (Fig. 8, II). In the contact zone, granites are characterized by porphyric inclusions of quartz and xenomorphic 'blurred' fine-grained aggregates of quartz, plagioclase and K-Na feldspar. Boundaries between the minerals are indistinct and patchy. Round-shaped porphyric grains of quartz are attenuated by cloud in crossed polars of a microscope.

The smooth contrasting contacts without any indicators of shifting of the original composition give evidence of the rapid crystallization of the basic-rock and granite melts, and the 'gradual' transition zones observed at the macro- and micro-levels may suggest that the lowest-melt-point minerals of granite and diorite were subject to recrystallization, or elements (K, Na, Ca, and Ti) were exchanged by diffusion between the rocks of contrasting compositions, or the rocks have not consolidated yet.

5. Petro- and geochemical characteristics of composite dykes

In the area between the Erzin and Naryn rivers (*Strelka Site*), granites are represented by midalkaline peraluminous (A/CNK=0.94–1.14) granosyenites and two-feldspar granites (Fig. 9). Average contents of petrogenic elements are given in Table 1. Rare-earth-element (REE) scatter diagrams and spider diagrams show that granite and granosyenite are characterised by negative slopes of the spectrum and high contents

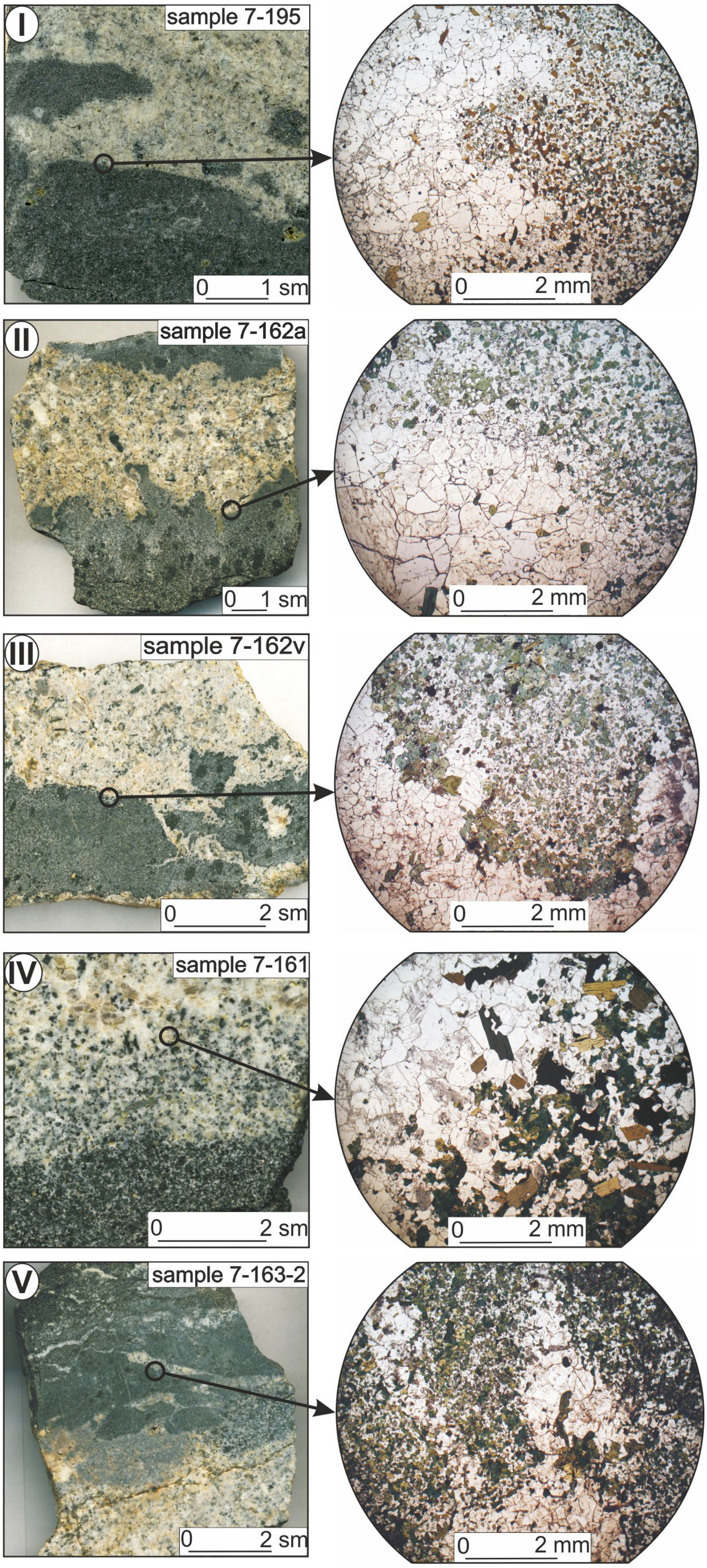

Fig. 6. Microtextures of contacts between basic rocks and granite in composite dykes in the area between the Erzin and Naryn rivers (Strelka Site). Left – rock slice texture; right – fragment in the corresponding transparent microsection (translucent light).

I – smooth contrasting contact between basic rocks and granite in the rock plate; in the microsection, it is sinuous; II – smooth flame-shaped contact between basic rocks and granite in the rock slice; a small transition zone is noted in the microsection; III – complex 'lacerated' flame-shaped contact between basic rocks and granite; it is clearly visible in both the rock slice and the microsection that the basic rocks become more melanocratic towards the contact; IV – gradual assimilation of the gabbro vein in granite; granosyenite and rocks in the transition zone are clearly distinguished in the microsection; V – complex contact between basic rocks and granite; the transition zone is composed of coarse- to fine-grained rocks with small nodules of basic rocks and contains; fractures are filled with rocks of the transitional composition and granite.

Рис. 6. Микроструктурная характеристика контактов и взаимоотношений базитов и гранитоидов в комбинированных дайках междуречья Эрзина и Нарына (участок «Стрелка»). Ряд слева – структурно-текстурная характеристика в пластинке, ряд справа – соответствующий фрагмент структуры в прозрачном петрографическом шлифе (проходящий свет).

I – контрастный ровный контакт базитов и гранитоидов в пластинке на микроуровне образует «заливообразный» контур; II – пламеневидный контакт базитов с гранитоидами в пластинке характеризуется ровной границей между базитами и гранитоидами с узкой переходной зоной; III – сложный «рваный», пламеневидный контакт базитов и гранитоидов. В шлифе и пластинке отчетливо видно увеличение меланократовости базитов в приближении к контакту; IV – постепенная ассимиляция габброидной жилы в гранитоидах. На микроуровне отчетливо различаются граносиениты и породы переходной зоны; V – сложный контакт базитов и гранитоидов с образованием переходной зоны, сложенной породами разной зернистости, мелкими нодульными агрегатами базитов и трещинами, заполненными породой переходного состава и гранитоидами.

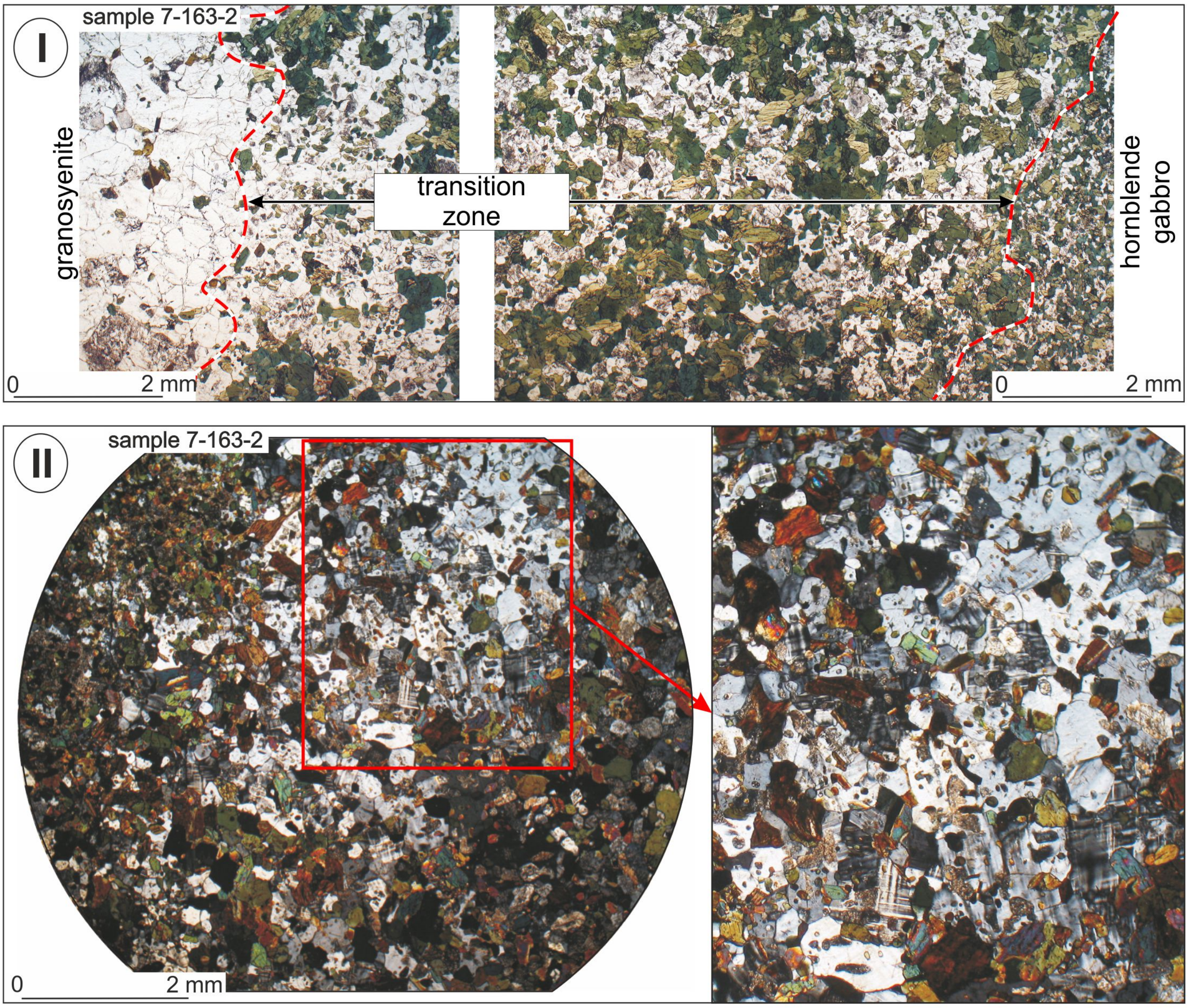

Fig. 7. Petrography of rocks in the zone of transition from basic rocks to granites in mingling dikes in the area between Erzin and Naryn rivers (Strelka Site).

I – transition zone at the contact between granosyenite and hornblende gabbro (translucent-light photos); II – poikilitic texture of potassium feldspar in the transition zone (crossed-nicols photos).

Рис. 7. Петрографический состав пород переходной зоны между базитами и гранитоидами в комбинированных дайках междуречья рек Эрзин и Нарын (участок «Стрелка»).

I – строение переходной зоны в контакте граносиенитов и роговообманковых габбро (снимки сделаны в проходящем свете); II – пойкилитовая структура калиевого полевого шпата в породах переходной зоны (снимки сделаны в скрещенных николях).

of REE. Light REE dominate over heavy REE: (La/Yb)n=8.37–16.04. A negative Eu anomaly is poorly expressed (Eu/Eu*=0.56–0.64). Multi-element spectra show negative slopes, large-ion lithophile elements (LILE) enrichment, and sharp minimums of Nb, Ti and Sr, as well as maximums of Zr and Hf (Table 2, and Fig. 10).

The REE scatter in gabbroids composing the mingling dykes on Strelka Site (see Table 1) is characterized by a sloping negative spectrum with a weak positive Eu anomaly (Eu/Eu*=1.15). The content of REE is high, and light REE dominate over heavy REE: (La/Yb)n=5.87–6.77. Multi-element spectra show LILE enrichment, sharp minimums of Nb and Sr, and insignificant values of Ti (Table 2, and Fig. 10).

On the right bank of the Erzin river (*Erzin Site*), the salic mingling dykes are composed of normal- and medium-alcaline, high- and medium-potassium, peraluminous (A/CNK=0.97–1.20) granite and leucogranite (see Table 1 and Fig. 9). According to the REE

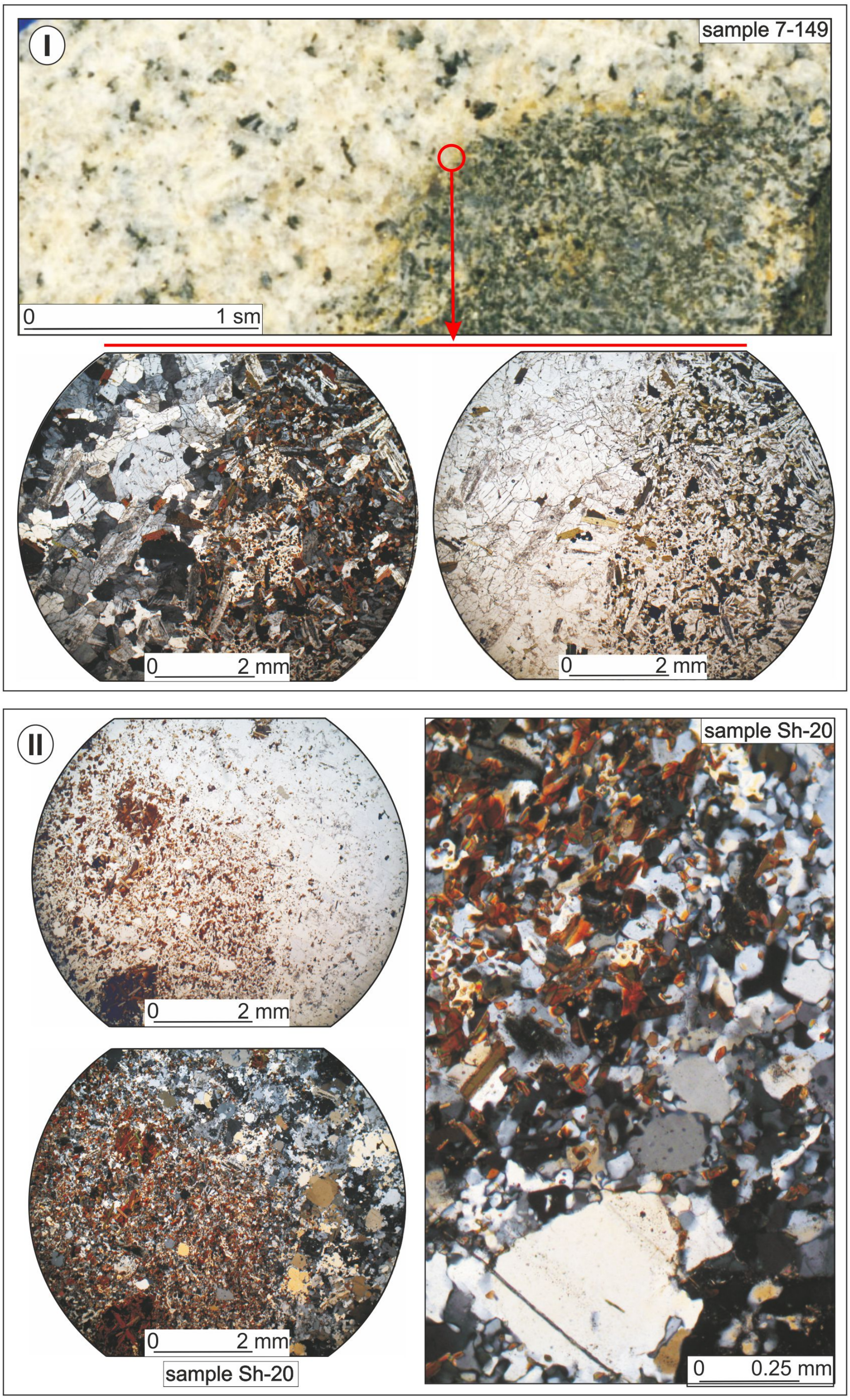

Fig. 8. Typical contacts and relations between basic rocks and granite in mingling dykes on the right bank of the Erzin river (Erzin Site).

I – smooth contact between basic rocks and granite; a poikilitic structure is observed in diorite (translucent-light and crossed-nicols photos); II – biotite glomero-clusters; a poikilitic structure and porphyric-quarts inclusions at the contact between diorite and leukogranite.

Рис. 8. Характерные контакты и взаимоотношения базитов и гранитоидов в минглинг-дайках на правобережье р. Эрзин («Эрзинский» участок).

I – ровный контакт базитов и гранитоидов; в шлифе со стороны диоритов наблюдается пойкилитовая структура (фотографии шлифов сделаны в проходящем свете и скрещенных николях); II – гломероскопления биотита. Пойкилитовая структура и порфировидные вкрапленники кварца в контакте диоритов и лейкогранитов.

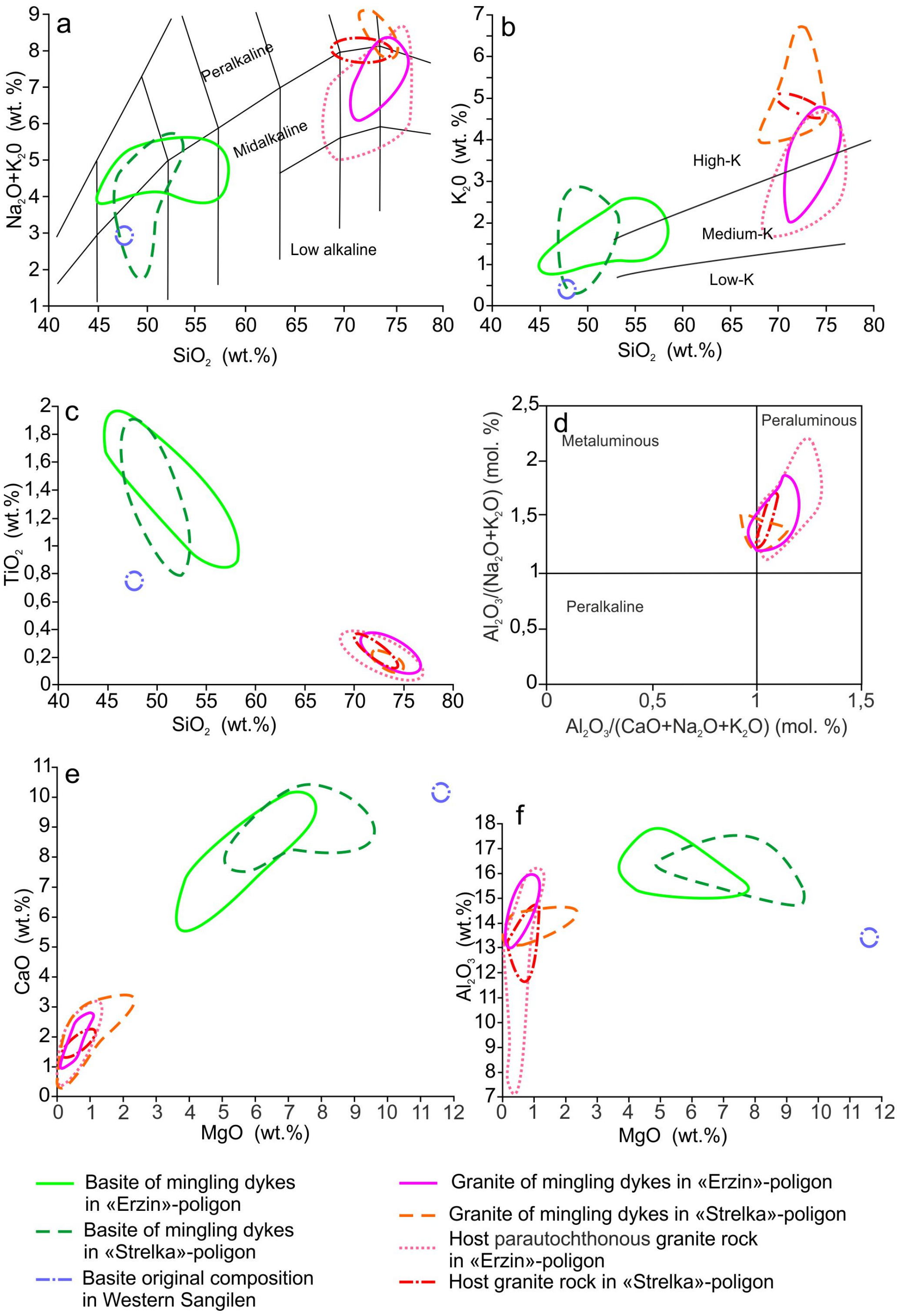

Fig. 9. Petrochemical diagrams. Comparison of compositions of the original basic rocks and host granite of the Nizhneerzin massif, and parautochtonous granite of the Erzin migmatite-granite complex and rocks in composite dykes.

Fig. 9a and b – classification boundaries according to [*Petrographic Code*.., *2009*] and [*Le Maitre et al*., *1989*], respectively. Fig. 9c – Harker's diagram SiO_2–TiO_2. Fig. 9d – Shand's diagram [*Maniar, Piccoli*, *1989*]. Fig. 9e and f – binary diagrams MgO–CaO и MgO–Al_2O_3, respectively.

Рис. 9. Петрохимические графики сравнения состава исходного базитового расплава и вмещающих гранитоидов Нижнеэрзинского массива и параавтохтонных гранитов эрзинского мигматит-гранитного комплекса с составами комбинированных даек.

Рис. 9a – классификационные границы [*Petrographic Code*.., *2009*]; рис. 9b – классификационные границы [*Le Maitre et al*., *1989*]; рис. 9c – диаграмма Харкера SiO_2–TiO_2; рис. 9d – диаграмма Шенда [*Maniar, Piccoli*, *1989*]; рис. 9e–f – бинарные диаграммы MgO–CaO и MgO–Al_2O_3.

T a b l e 1. **Content of petrogenic oxides (wt %) in mingling dykes of West Sangilen**

Т а б л и ц а 1. **Содержание петрогенных оксидов (мас. %) в минглинг-дайках Западного Сангилена**

Component	Rocks of mingling dykes on Strelka Site		Rocks of mingling dykes on Erzin Site		Source melt
	Mafic dykes (n=27)	Salic dykes (n=8)	Mafic dykes (n=21)	Salic dykes (n=12)	
SiO_2	47.45 – 52.9	62.76 – 74.52	45.48 – 57.76	66.31 – 76.01	47.84
	49.22	71.56	53.57	73.13	
TiO_2	0.79 – 1.89	0.12 – 0.93	0.88 – 1.93	0.13 – 0.78	0.75
	1.4	0.38	1.30	0.28	
Al_2O_3	14.86 – 17.09	13.21 – 14.43	15.40 – 17.61	13.19 – 15.86	13.42
	16.24	13.37	16.57	14.10	
Fe_2O_3*	7.69 – 12.79	1.27 – 7.35	8.07 – 12.38	1.36 – 4.34	11.52*
	10.96	2.96	9.80	2.50	
MnO	0.11 – 0.18	<0.01 – 0.09	0.12 – 0.23	<0.01 – 0.12	-
	0.17	0.03	0.17	0.05	
MgO	5.09 – 9.40	0.14 – 2.26	3.84 – 7.66	0.19 – 1.00	11.62
	7.73	0.64	4.92	0.50	
CaO	7.59 – 10.29	1.13 – 3.24	5.61 – 10.00	1.21 – 2.63	10.16
	9.22	1.61	7.46	1.74	
Na_2O	1.41 – 3.75	2.23 – 3.64	2.28 – 3.73	2.89 – 4.64	2.51
	2.52	3.14	2.91	3.50	
K_2O	0.41 – 2.66	3.40 – 6.65	0.88 – 2.46	1.59 – 4.65	0.41
	1.15	4.92	1.80	3.71	
P_2O_5	0.16 – 0.66	<0.01 – 0.32	0.27 – 0.58	0.04 – 0.25	-
	0.32	08.11	0.39	0.10	
Alum slate index	-	0.94 – 1.14	-	0.97 – 1.20	
		1.03		1.09	

N o t e. Above the line – variations of contents of petrogenic components; under the line – average content; n – number of samples; Fe_2O_3* – total content of Fe in Fe_2O_3; the Fe content in the source melt is given in FeO; the alum slate index is $Al_2O_3/(CaO+K_2O+Na_2O)$ (mol. %) [*Maniar, Piccoli*, *1989*]. Contents of petrogenic elements were analysed by the 'wet' chemical method (Assayer N.N. Ukhova, IEC SB RAS, Irkutsk) and the X-ray fluorescence analysis method using SRM-25 installation (Assayer A.D. Kireev, V.S. Sobolev IGM SB RAS, Novosibirsk).

П р и м е ч а н и е. Над чертой – вариации содержаний петрогенных компонентов, под чертой – среднее содержание; n – число проб; Fe_2O_3* – суммарное железо в форме Fe_2O_3, для исходного расплава содержание железа указано в форме FeO; индекс глиноземистости – $Al_2O_3/(CaO+K_2O+Na_2O)$ (мол. %) [*Maniar, Piccoli*, *1989*]. Анализ содержания петрогенных элементов выполнен методом «мокрой» химии (аналитик – Н.Н. Ухова, ИЗК СО РАН, г. Иркутск) и методом РФА на установке СРМ-25 (аналитик – А.Д. Киреев, ИГМ им. В.С. Соболева СО РАН, г. Новосибирск).

scatter diagrams, granite is characterized by a sharp domination of light REE over heavy REE: $(La/Yb)_n$= =7.42–13.10. A Eu anomaly is absent (Eu/Eu*=0.96–1.06). Multi-element spectra show negative slopes, LILE enrichment, and low contents of HFSE. Sharp minimums are noted for Ti and Nb (Table 2, and Fig. 10).

The melanocratic composite dykes located on Erzin Site are composed of diorite and quartz diorite (see Table 1, and Fig. 9). The REE scatter shows a sloping negative spectrum and a high content of REE (381 g/t), and a Eu anomaly is absent (Eu/Eu*=0.94–1.17). There is an insignificant domination of light REE over heavy REE: $(La/Yb)_n$=4.62–7.99. In spider diagrams, minimums are noted for Ti and Nb (Table 2, and Fig. 10).

6. Correlation between compositions of composite dykes and igneous complexes of West Sangilen

In West Sangilen, the largest basic-rock massifs are Bashkymugur, Erzin and Bayankol (490–460 Ma) that are composed of gabbro-monzodiorite originating from source magmas of similar compositions, as suggested by results of mineralogical, petrographical and petrochemical studies of the basic rocks [*Shelepaev, 2006*].

Т a b l e 2. **Contents of petrogenic elements (wt %), rare and rare-earth elements (g/t) in representative samples of basic rocks and granite from mingling dykes of West Sangilen**

Т а б л и ц а 2. **Содержания петрогенных элементов (мас. %), редких и редкоземельных элементов (г/т) в представительных пробах базитов и гранитов из минглинг-даек Западного Сангилена**

Component	Rocks of mingling dykes on Strelka Site					Rocks of mingling dykes on Erzin Site					
	Mafic dykes		Salic dykes			Mafic dykes				Salic dykes	
	7-158-2	7-192-3	7-159	7-160	7-163-2	7-149-3	7-153-1	7-153-2	BC-402	7-149	7-150
SiO_2	52.24	51.25	73.24	62.76	72.30	57.11	45.48	46.05	48.45	73.35	66.31
TiO_2	0.79	1.23	0.20	0.93	0.22	1.12	1.64	1.93	1.83	0.18	0.78
Al_2O_3	15.91	16.36	14.01	14.43	13.21	16.00	15.40	15.68	16.69	14.01	15.86
Fe_2O_3*	7.69	9.82	1.54	7.37	1.77	8.07	12.17	12.38	11.41	2.05	4.34
MnO	0.11	0.18	0.01	0.06	0.01	0.12	0.15	0.16	0.17	0.03	0.11
MgO	6.24	5.66	0.22	2.26	0.55	3.84	7.66	7.05	6.05	0.38	1.00
CaO	9.44	7.59	1.35	3.24	1.19	5.61	9.36	10.00	8.41	1.71	2.63
Na_2O	3.37	3.69	3.64	3.55	2.23	3.17	2.87	3.06	3.73	3.75	4.64
K_2O	1.53	1.75	4.96	3.40	6.65	2.27	1.05	0.88	1.39	4.08	3.63
P_2O_5	0.17	0.32	0.05	0.32	0.05	0.33	0.27	0.27	0.42	0.07	0.25
Loss on ignition (LOI)	2.12	2.09	0.38	1.47	0.66	2.22	1.81	1.84	1.67	0.22	0.71
Total	**100.24**	**99.63**	**99.83**	**99.96**	**98.96**	**99.57**	**99.58**	**99.87**	**99.80**	**99.98**	**100.20**
Rb	47	50	117	111	145	61	19.1	11.6	28	70	77
Sr	657	497	179	263	506	525	439	459	619	308	438
Y	18.5	27	32	51	13.1	30	24	25	31	10	44
Zr	72	130	115	331	76	170	133	142	137	161	432
Nb	4.5	7.1	8.2	7.9	8.0	9.9	13.3	12.8	6.5	4.9	17.0
Cs	0.29	0.79	1.87	1.36	1.10	0.32	1.11	0.54	0.25	1.44	1.54
Ba	156	369	901	1029	1141	601	173	181	505	1077	1262
La	15.9	19.2	35	46	27	31	13.3	13.8	26	24	43
Ce	35	43	67	93	45	63	29	31	57	41	91
Pr	4.9	6.2	7.8	13.8	4.9	8.6	4.3	4.5	8.5	5.0	12.8
Nd	19.8	25	27	55	16.1	32	17.9	19.5	34	16.2	48
Sm	4.0	4.9	4.7	11.5	2.5	5.9	4.2	4.5	6.6	2.4	9.6
Eu	1.46	1.90	0.84	2.3	0.50	1.85	1.59	1.67	2.6	0.71	3.2
Gd	3.6	5.1	4.3	11.1	2.3	5.9	4.5	4.9	6.9	1.99	8.5
Tb	0.53	0.75	0.73	1.61	0.35	0.86	0.67	0.73	0.92	0.30	0.86
Dy	2.8	4.3	4.2	8.4	2.0	4.6	3.9	4.1	5.2	1.38	6.6
Ho	0.54	0.83	0.89	1.61	0.40	0.91	0.78	0.81	0.97	0.28	1.34
Er	1.59	2.3	2.8	4.5	1.15	2.6	2.1	2.2	2.8	0.92	3.9
Tm	0.24	0.35	0.46	0.62	0.18	0.40	0.30	0.32	0.41	0.18	0.62
Yb	1.59	2.2	2.8	3.6	1.15	2.6	1.94	1.99	2.5	1.21	3.9
Lu	0.24	0.35	0.42	0.51	0.18	0.40	0.28	0.30	0.37	0.19	0.59
Hf	2.2	3.2	3.9	8.4	2.5	4.5	3.3	3.5	3.2	4.2	9.5
Ta	0.38	0.43	0.92	0.38	0.80	0.73	0.78	0.78	0.32	0.43	1.10
Th	2.8	3.0	19.5	3.0	16.4	7.9	1.08	1.17	1.17	7.6	9.0
U	1.37	1.32	2.7	0.78	0.83	3.4	0.36	0.33	0.63	0.99	3.6

N o t e. Fe_2O_3* – total Fe in Fe_2O_3. Contents of petrogenic elements (wt %) were analysed by the 'wet' chemical method (Assayer N.N. Ukhova, IEC SB RAS, Irkutsk). Contents of rare elements (g/t) were analysed by the ICP-MS method (Assayer I.V. Nikolaeva, V.S. Sobolev IGM SB RAS, Novosibirsk).

П р и м е ч а н и е. Fe_2O_3* – суммарное железо в форме Fe_2O_3. Анализ содержания петрогенных элементов выполнен методом «мокрой» химии (аналитик – Н.Н. Ухова, ИЗК СО РАН, г. Иркутск), содержание компонентов приведено в мас. %. Анализы редких элементов выполнены методом ICP-MS (аналитик И.В. Николаева, ИГМ им. В.С. Соболева СО РАН, г. Новосибирск), содержание компонентов приведено в г/т.

It is assumed that the source magma corresponds by its composition to olivine basalt or olivine gabbronorite [*Egorova, 2005*] (see Table 1 and Fig. 9).

The mingling dykes located on Erzin and Strelka Sites have similar compositions of the basic rocks which differ from the source magma composition by contents of TiO2 and MgO. An insignificant difference is noted between contents of alkalies in the source melt and in the basic rocks from the dykes. The REE scatter diagrams and the spider diagrams (see Fig. 10) show similar spectra and similar absolute values. Minimums are noted for Nb, Th, Hf, and Ti.

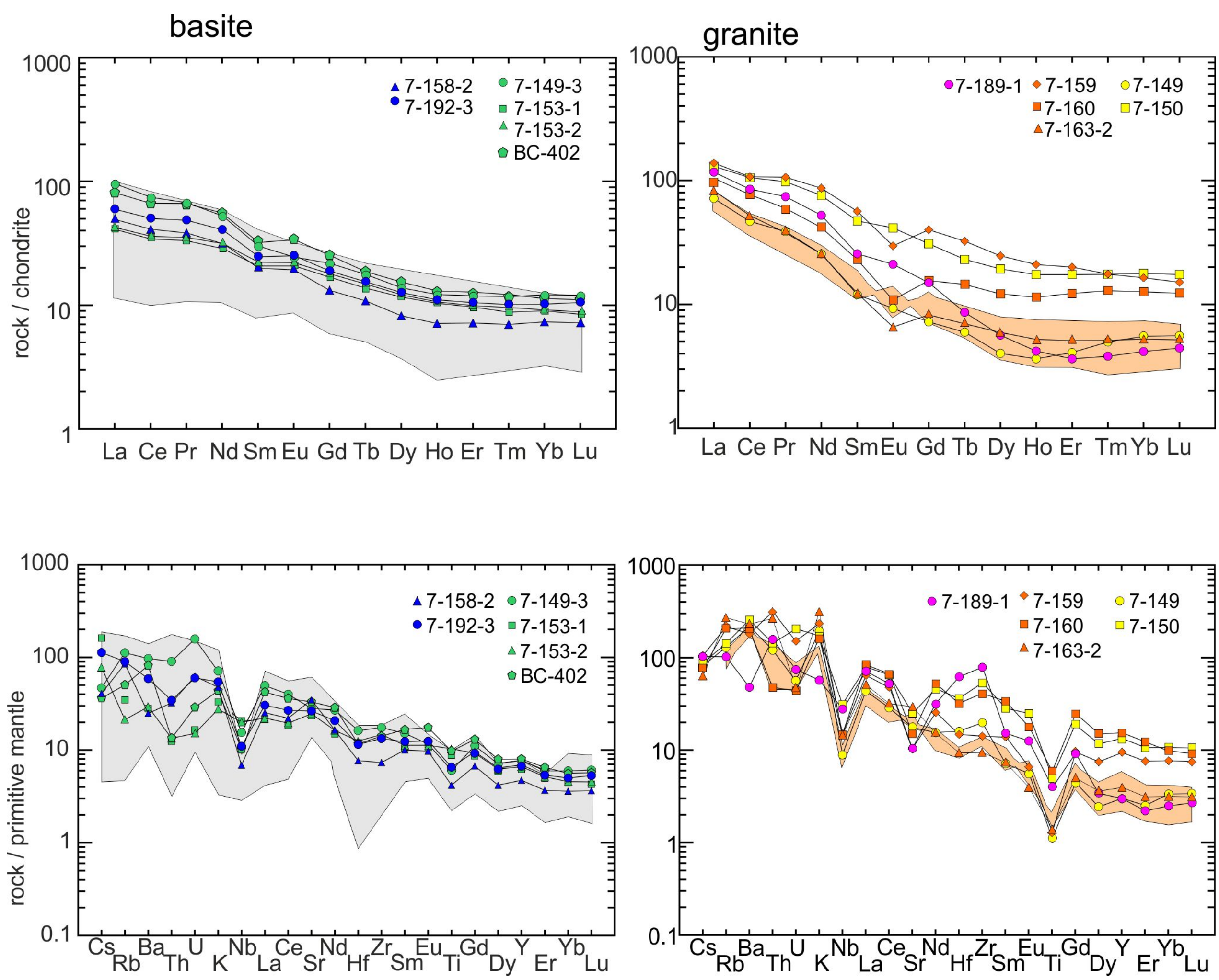

Fig. 10. REE scatter diagrams and spider diagrams for basic rocks and granite from mingling dykes and magmatic complexes of West Sangilen.

Basic rocks: 7-158-2, 7-192-3 – Strelka Site; 7-149-3, 7-153-1, 7-153-2, and BC-402 – Erzin Site; area in grey – olivine gabbronorite of the Bashkymugur massif [*Egorova*, *2005*]. Granite: 7-189-1 – host granite on Strelka Site; 7-159, 7-160, and 7-163-2 – Strelka Site; 7-149, and 7-150 – Erzin Site; area in orange – host parautochtonous granite on Erzin Site [*Karmysheva*, *2012*]. The REE contents are normalized to CI contents in chondrite [*Boynton*, *1983*]. In the spider diagrams, normalization is done to CI contents in the primitive mantle [*Taylor*, *McLennan*, *1985*].

Рис. 10. Спектры распределения РЗЭ и спайдер-диаграммы для базитов и гранитов минглинг-даек и магматических комплексов Западного Сангилена.

Базиты: 7-158-2, 7-192-3 – участок «Стрелка»; 7-149-3, 7-153-1, 7-153-2, BC-402 – участок «Эрзинский»; серое поле – оливиновый габбронорит Башкымугурского массива [*Egorova*, *2005*]. Граниты: 7-189-1 – вмещающие гранитоиды на участке «Стрелка»; 7-159, 7-160, 7-163-2 – участок «Стрелка»; 7-149, 7-150 – участок «Эрзинский»; оранжевое поле – параавтохтонные вмещающие граниты на участке «Эрзинский» [*Karmysheva*, *2012*]. Содержания РЗЭ нормированы по содержанию в хондрите CI [*Boynton*, *1983*]. На спайдер-диаграммах содержания нормированы к таковым в примитивной мантии [*Taylor, McLennan*, *1985*].

Considering the similarity of the petrochemical composition of the basic rocks from the mingling dykes and the composition of the source basic rocks, it can be suggested that the mafic dykes originated from the same upper mantle or intruded from the same magma chamber as the large gabbro-monzodiorite massifs of West Sangilen. Figure 9 shows an insignificant difference between compositions of the basic rocks of the mingling dykes located on the different sites. The composition of the basic rocks from the dykes on Strelka Site are closer to the composition of the source basic-rock melt, while the basic rocks from the dykes on Erzin Site are more felsic, which may suggest hybridization with either host rocks or granite of the dykes proper.

In samples from the different sites, compositions of granite from the mingling dykes are practically similar, with insignificantly different contents of potassium.

The Nizhneerzin massif (486+10 Ma – Rb-Sr) [*Petrova, 2001*]; 491.6+9.5 Ma – U-Pb [*Kozakov et al., 1999*]) is composed of porphyric granosyenite (see Fig. 9). Lines in the REE scatter diagrams and the multielement spectra of granite from the mingling dykes on Strelka Site and the host porphyric granite from the Nizhneerzin massif are practically coincident. Minimums are noted for Nb, Sr, and Ti. A noticeable difference is the lacking Eu minimum in granite from the Nizhneerzin massif, while the Eu minimum is expressed in granite of the composite dykes, and the Zr maximum is evident in the host rocks (see Fig. 10).

On Erzin Site, parautochthonous granite of the Erzin complex (which is the host rock for the composite dykes) is represented by peraluminous, medium-fine-grained, poorly foliated, garnet-containing biotite granite [*Karmysheva, 2012*]. In the REE scatter diagrams and the spider diagrams, the spectra of the host granite and granite from the mingling dykes are coincident, and typical minimums for Nb and Ti and maximums for K and Zr are noted (see Fig. 10).

7. Discussion of results

Based on the available geological data, the composite/mingling dykes of West Sangilen are classified into two types. Their textures are studied at the macro- and micro-levels, and the petrochemical characteristics are subject to comparative analyses. Results of our studies give grounds to conclude that specific features of the mingling dykes are predetermined by geological settings of their formation, depths and duration of tectonic and magmatic processes.

Composite dykes in the area between the Erzin and Naryn (*Strelka Site*). By its texture, granite from the mingling dykes located on Strelka Site does not differ much from the host porphyric granite from the Nizhneerzin massif containing the rocks that are either not deformed or show rare traces of flow in the fine-grained rock samples. In felsic composite dykes, traces of deformation are absent, while indicators of recrystallization of K-Na feldspar, plagioclase, quartz and biotite are present.

The model proposed in [*Huppert, Sparks, 1988*] can provide an explanation of the similarity between the petrochemical compositions of granite from the Nizhneerzin massif and granite from the mingling dykes [*Vasyukova et al., 2008*]. According to the above-mentioned model, the host granite is partially melted due to the intrusion of the basic rocks which leads to mechanical mixing of the melts contrasting in composition and rheologial properties. Consequently, the chemical composition is inherited, and specific mingling textures and structures, such as reticulate-cuspate structures and round-shaped basic-rock bodies cut by thin veins of granite, are formed. Using the model, it is possible to explain specific petrogeochemical properties of the composite dykes and the local reomorphism of granite in the Nizhneerzin massif, which took place when the basic rocks intruded into granite. However, the model fails to explain the tectonic position of the composite dykes on Strelka Site.

The intrusion of granite of the Nizhneerzin massif took place at the post-collisional stage of the orogen's evolution in conditions when the compression regime was replaced by the extension regime (480–490 Ma) [*Vladimirov et al., 2005*]. As of the time of the Nizhneerzin massif emplacement, the crust was locally disturbed and thinned due to developing extension of the Erzin metamorphic block along the Erzin and Kokmolgarga shear faults, and the basic-rock melts were uplifted and intruded into the extension zones.

As of the time of the basic-rock intrusions, granite of the Nizhneerzin massif was only partially consolidated, as evidenced by structures and textures of the composite dykes, such as non-linear 'patchy' outlets of the mingling dykes in the massif's body, their vague contacts with the host granite, lacking indicators of deformation, the presence of zones with mixed basic rocks and granite, and diffusional smoothing of the compositions in high-temperature conditions.

The absence of active penetrating tectonic deformation is also evidenced by the similar petrochemical compositions and similar scatter of LILE and HFSE in the host granite and granite of the mingling dykes, i.e. melting and recrystallization of the source granite took place practically in a closed system.

It is most likely that the dykes were formed at mesoabyssal or abyssal depths, and the subliquidus heat regime was thus maintained for a long time, and even the smallest portions of the basic-rock melt were consolidated through quite a long period of time. Indicators of deformation are thus absent in the composite dykes, and transition zones and hybridization are observed.

The composite dykes on the right bank of the Erzin river (*Erzin Site*) were formed in the period of active extension of the Sangilen fragment of the orogen which took place along the systems of shear zones (460–430 Ma) [*Vladimirov et al., 2005*] and was accompanied by the intrusion of the Bashkymugur gabbro-monzodiorite massif (464.6±5.7 Ma – U-Pb [*Kozakov et al., 1999*], 465±1.2 Ma – Ar-Ar [*Izokh et al., 2001*], 464±5 Ma – Rb-Sr [*Petrova, 2001*]). In the same period, the Erzin shear zone was active; later on, its integrity was disturbed by fractures, faults and veins, and it was fragmented [*Vladimirov et al., 2005*]. The occurrence of conjugated fault systems facilitated the formation of local extension zones, provided favourable conditions for intrusions of felsic melts and basic-rock melts and predetermined positions of the composite dykes.

Our assumption that the dykes intruded and emplaced in conditions of the tectonically active zone is supported by many indicators, including positions of the composite dykes in the Erzin shear zone, abrupt transversal contacts with the host rocks, pegmatoids in the decompression zones, the presence of oxygon xenoliths in the composite dykes etc. Besides, due to low temperatures, the main melts were efficiently chilled and consolidated, as evidenced by textures of the mingling dykes which show contrasting contacts with both the host rocks and between the basic rocks and granite, lacking zones of hybridization, the presence of chill zones and indicators of recrystallization of the minerals.

The observed difference between the basic rocks in the first group of mingling dykes from the source composition of the basic rocks in West Sangilen may suggest potential contamination and/or differentiation of the mafic melt during its assent to the upper crustal layers.

Our model showing the intrusion of the melts of contrasting compositions on Erzin Site in the same-name shear zone takes into account the structural and textural characteristics of the rocks, positions of fine-grained granites (mainly in the marginal parts of the mingling dykes), melting of granites (evidenced by the thin rock samples), and petrochemical compositions of the rock samples.

The composite dykes of this type intruded and emplaced when the shear zone was subject to extension and fragmentation, which predetermined active intrusion of basic and, possibly, felsic melts through conjugated faults and rapid crystallization of the melts. Crystallization of the melts was rapid, and their potential heat impact on the adjoining rocks was thus excluded, as evidenced by the presence of oxygonal chips of igneous and host metamorphic rocks, vein pegmatoid intrusions, and composite dykes of the reticulate-cuspate texture with the dominating basic rock component.

8. Main conclusions

Two groups of mingling dykes are distinguished in the Sangilen upland. The dykes in both groups originated from one and the same basic melt source. However, mingling of the contrasting melts was carried out by different mechanisms as suggested by two intrusion models.

In the first model, the basic-rock melts intrude into the non-consolidated granite melt and mix with it. In the second model, the felsic melt occurs due to heating by the mafic magmas, the melts are mechanically mixed, and mingling is controlled by tectonic processes, specifically extension and faulting.

According to the first model, the mingling dykes are related to the emplacement of the Erzin and Kokmolgarga shear zones at the early stage when the compression regime was replaced by the extension regime in the Sangilen fragment of the orogen (510–490 Ma). Intrusions of the basic-rock melts were accompanied by the formation of relatively large massifs of the basic composition, i.e. the Erzin and Bayankol gabbro-monzodiorite massifs, as well as by the occurrence of composite dykes that are abundant in the area between the Erzin and Naryn rivers.

The second stage (460–430 Ma) of the formation of composite dykes took place when the orogenic structure was subject to extension along the system of shear zones, and the Bashkymugur gabbro-monzodiorite massif was intruded and emplaced, and fracture-vein structures (including the composite dykes) were formed.

Isotope geochonological dating of the regional tectonic and magmatic events have yielded the ages that support the above conclusions.

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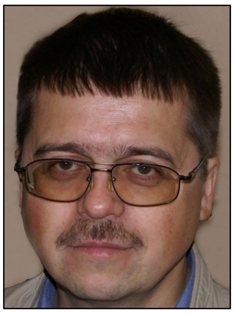

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