GEODYNAMICS & TECTONOPHYSICS

PUBLISHED BY THE INSTITUTE OF THE EARTH'S CRUST
SIBERIAN BRANCH OF RUSSIAN ACADEMY OF SCIENCES

2019 VOLUME 10 ISSUE 1 PAGES 79–99

ISSN 2078-502X

https://doi.org/10.5800/GT-2019-10-1-0405

Paleogeodynamics

A REVIEW OF EARLY PERMIAN (300–270 MA) MAGMATISM IN EASTERN KAZAKHSTAN AND IMPLICATIONS FOR PLATE TECTONICS AND PLUME INTERPLAY

S. V. Khromykh[1, 2], P. D. Kotler[1, 2], A. E. Izokh[1, 2], N. N. Kruk[1]

[1] *V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of RAS, Novosibirsk, Russia*
[2] *Novosibirsk State University, Novosibirsk, Russia*

Abstract: The history of the Central Asian Orogenic Belt (CAOB) was marked by several major events of magmatism which produced large volumes of volcanic and intrusive (mafic-ultramafic and granitic) rocks within a relatively short time span (30–40 Ma) over a vast area. The magmatic activity postdated the orogenic stages of accretionary-collisional belts in Central Asia and likely resulted from the impact of mantle plumes that formed Large Igneous Provinces (LIPs). The formation of the Tarim–South Mongolia LIP at 300–270 Ma is the best known among the major Permian events of basaltic and granitic magmatism. Early Permian igneous rocks (volcanic, subvolcanic and intrusive suites that vary from ultramafic to felsic compositions) of the same age range (300 to 270 Ma) have been recently found also in Eastern Kazakhstan, within the late Paleozoic Altai collisional system. The compositions and ages of the rocks suggest that the Eastern Kazakhstan magmatism was the northward expansion of the Tarim LIP. The spread of the Tarim LIP was apparently facilitated by lithospheric extension after the Siberia-Kazakhstan collision. The extension led to rheological weakening of the lithosphere whereby deep mantle melts could penetrate to shallower depths. The early Permian history of Eastern Kazakhstan was controlled by the interplay of plate tectonic and plume processes: plate-tectonic accretion and collision formed the structural framework, and the Tarim mantle plume was a heat source maintaining voluminous magma generation.

Key words: Central Asian Orogenic Belt; post-orogenic magmatism; Tarim mantle plume; mantle-crust interaction

RESEARCH ARTICLE

Received: September 12, 2018
Revised: December 14, 2018
Accepted: January 12, 2019

For citation: *Khromykh S.V., Kotler P.D., Izokh A.E., Kruk N.N.*, 2019. A review of Early Permian (300–270 Ma) magmatism in Eastern Kazakhstan and implications for plate tectonics and plume interplay. *Geodynamics & Tectonophysics* 10 (1), 79–99. doi:10.5800/GT-2019-10-1-0405.

РАННЕПЕРМСКИЙ (300–270 МЛН ЛЕТ) МАГМАТИЗМ ВОСТОЧНОГО КАЗАХСТАНА КАК РЕЗУЛЬТАТ СОЧЕТАНИЯ ПЛЕЙТ- И ПЛЮМ-ТЕКТОНИЧЕСКИХ ФАКТОРОВ

С. В. Хромых[1, 2], П. Д. Котлер[1, 2], А. Э. Изох[1, 2], Н. Н. Крук[1]

[1] *Институт геологии и минералогии им. В.С. Соболева СО РАН, Новосибирск, Россия*
[2] *Новосибирский национальный исследовательский государственный университет, Новосибирск, Россия*

Аннотация: В истории развития крупнейшего Центрально-Азиатского складчатого пояса (ЦАСП) выявлены несколько периодов крупномасштабной эндогенной активности, характеризующихся проявлениями значительных объемов вулканических и интрузивных (как базитовых, так и гранитоидных) пород на обширных территориях в сравнительно короткие временные интервалы (30–40 млн лет). Эти вспышки магматической активности обычно происходят после завершения аккреционно-коллизионных процессов в складчатых системах и рассматриваются как результат воздействия мантийных плюмов на литосферу – крупные изверженные провинции. Одним из ярких примеров является Тарим-Южномонгольская крупная изверженная провинция (300–270 млн лет назад), характеризующаяся широким развитием базитового и гранитоидного магматизма в западной части ЦАСП. Исследования последних лет показали, что в Восточном Казахстане, в пределах Алтайской коллизионной системы герцинид, широко распространены как базитовые, так и гранитоидные комплексы раннепермского возраста (300–270 млн лет). В приведенном кратком обзоре показано, что особенности состава и условия формирования этих магматических ассоциаций позволяют рассматривать их как результат северо-западного распространения влияния Таримской крупной изверженной провинции. Распространение этого термического возмущения в литосфере, по-видимому, стало возможным благодаря постороогеническому растяжению после коллизии Сибирского и Казахстанского континентов. Реологическое ослабление литосферы позволило глубинным расплавам проникать в литосферную мантию, образовав крупные очаги базитовых магм. Таким образом, современный геологический облик и металлогеническая специфика территории Восточного Казахстана является результатом плейт-тектонических процессов посторогенического растяжения на фоне повышенного термического градиента в мантии, вызванного активностью Таримского мантийного плюма.

Ключевые слова: Центрально-Азиатский складчатый пояс; посторогенный магматизм; Таримский плюм; мантийно-коровое взаимодействие

1. INTRODUCTION

The Central Asian Orogenic Belt (CAOB) is the largest accretionary structure in the Earth's history, also known as Altaids [*Şengör et al., 1993*], formed by closure of the Paleoasian Ocean. The Altaid tectonic collage includes numerous terranes of different origin amalgamated by multiple accretionary and collisional events in tectonic settings changing from compression to extension and shear [*Şengör et al., 1993; Dobretsov, 2003; Windley et al., 2007; Levashova et al., 2009; Xiao et al., 2010; Xiao, Santosh, 2014*]. Its history included several major events of magmatism which produced significant volumes of volcanic and intrusive (mafic-ultramafic and granitic) rocks in a relatively short time span (30–40 Ma) over a large area. The magmatic activity postdated the orogenic stages in the evolution of accretionary-collision systems. From the viewpoints of plate tectonics, the post-orogenic magmatism is caused by post-orogenic lithospheric extension as a result of its delamination [*Xiao et al., 2008; Xiao, Santosh, 2014; Konopelko et al., 2018*] or results from active transtensional strike-slip tectonics accompanied by upwelling of the asthenosphere [*Seltmann et al., 2011; Wang et al., 2014*] or breaking of subducted oceanic plate (slab break-off) [*Konopelko et al., 2017*]. The alternative viewpoint for large-scale magmatism in accretionary-collision systems is the impact of mantle plumes. The plume activity leading to the formation of Large Igneous Provinces (LIPs) [*Ernst et al., 2005; Bryan, Ernst, 2008; Ernst, 2014*] can account for a number of Paleozoic magmatic events in CAOB: (1) early Paleozoic, with a late Cambrian – early Ordovician LIP in the Altai, Sayan and Western Mongolia regions [*Izokh et al., 2010; Dobretsov, 2011; Vladimirov et al., 2013*]; (2) middle Paleozoic, with a Devonian LIP in the Minusa basin and the Vilyui rift in East Siberia [*Vorontsov et al., 2013; Kiselev et al., 2014*]; and (3) late Paleozoic, with Permian LIPs in Central Asia. Large-scale mafic and granitoid magmatism in Permian time produced the

Tarim–South Mongolia LIP at 300–270 Ma [*Zhang et al., 2010; Wei et al., 2014; Xu et al., 2014; Yu et al., 2017*]; the Barguzin LIP at 330–280 Ma [*Kuzmin, Yarmolyuk, 2014; Yarmolyuk et al., 2014*]; and the Khangai LIP at 270–245 Ma [*Yarmolyuk et al., 2014*] (Fig. 1).

The Tarim – South Mongolia Province is the largest area of diverse late Paleozoic magmatism in Central Asia, with voluminous continental flood basalts and other volcanic rocks found within the Tarim continental block [*Yu et al., 2011; Li et al., 2014, 2017*]. As confirmed by recent studies, the Tarim LIP spreads over the regions of South Mongolia [*Kozlovsky et al., 2015*], Chinese Altai [*Zhang et al., 2014*], North-Western Xinjiang [*Pirajno et al., 2011; Gao et al., 2014*], and Tien Shan [*Seltmann et al., 2011*], as well as into Eastern Kazakhstan.

2. LATE PALEOZOIC ALTAI ACCRETIONARY-COLLISIONAL SYSTEM

Eastern Kazakhstan is part of the Altai collisional system in the western Central Asian Orogenic Belt. The system formed in late Paleozoic as a result of an oblique collision of Siberia with the Kazakhstan composite terrane [*Vladimirov et al., 2003, 2008; Xiao et al., 2010*]. In Devonian through early Carboniferous time, the paleocontinents of Siberia and Kazakhstan were separated by the Ob'-Zaisan oceanic basin (a fragment of the western Paleoasian Ocean) with subduction involving continental blocks (Rudny-Altai and Zharma-Saur terranes) on its margins. Remnant oceanic crust and subduction-related sedimentary and volcanic rocks can be found as numerous fault blocks within the Central part of Altai collisional system [*Safonova et al., 2012, 2018*]. Collisional crust thickening and orogeny show up in the presence of late Carboniferous continental molasse with basal conglomerates in several intermontane basins (Fig. 2). The post-orogenic (latest Carboniferous – earliest Permian) tectonic activity occurred mainly as strike-slip motions [*Buslov, 2011*].

The igneous rocks of Eastern Kazakhstan, including various ultramafic to felsic volcanic, subvolcanic and intrusive suites, were studied in detail in the 1970s [*Shcherba et al., 1976, 1998; Ermolov et al., 1977, 1983; Lopatnikov et al., 1982*]. Variations in their forms and compositions allow suggesting their origin at different evolution stages, from the early Carboniferous to the Triassic. The studies of magmatism in Eastern Kazakhstan remained suspended in the 1990s – 2000s, until we resumed the work in 2005 at a more advanced level. Since then, a wealth of data has been obtained on the compositions and ages of igneous rocks in the region, which bracket the magmatic activity between 300 and 270 Ma, or within the early Permian (Fig. 2). The results from some units have been reported in recent publications [*Khromykh et al., 2011, 2013, 2014, 2016, 2017a, 2017b, 2018*]. In this paper, we present a brief overview of the obtained data with implications for post-collisional processes in the region.

3. VOLCANIC BASINS AND STRUCTURES (297–290 MA)

There are several volcanic basins filled with subalkaline basalts, basaltic andesites and andesites in the central part of the studied region (Fig. 2) and some basins filled with dacites and rhyolites in the southeastern areas. Some basins contain also small subvolcanic bodies of andesite and dacite porphyries.

Mafic volcanic rocks contain relatively high alkalis (Na_2O+K_2O from 3.2 to 9.2 wt. %), potassium (K_2O up to 4.9 wt. %), alumina (Al_2O_3 from 14 to 23 wt. %), phosphorus (P_2O_5 up to 1 wt. %) and titanium (TiO_2 up to 1.5 wt. %), as well as Ba, Zr and LREE (Fig. 3, *a*–*d*). Trachydacites from the Daubai and Tyureshoke basins have LA-ICP-MS U-Pb zircon ages of 297±1 Ma and 290±4 Ma, respectively (Fig 3, *e*–*f*). Felsic volcanics in some basins coexist with subvolcanic garnet dacites and clinopyroxene andesites derived from magmas that were generated in the lower crust at ~10 kbar and 1000 to 1200 °C by partial melting of the crustal substrate under the effect of hot mantle melts [*Khromykh et al., 2011*].

4. SUBALKALINE GABBRO AND PICRITES (293–280 MA)

There are about fifty small intrusions that consist of gabbro, or gabbro and picrites (Fig. 4) and belong to the (1) Argimbai plagiosyenite-gabbro (older) and (2) Maksut gabbro-picrite (younger) complexes. The Argimbai gabbro was dated at 293±2 Ma by the SHRIMP-II U-Pb method on zircons. The Maksut gabbro and picrites have an Ar-Ar age of 280±3 Ma on biotite (3 samples from 3 different intrusions) and amphibole (1 sample from the Maksut intrusion) [*Khromykh et al., 2013*].

Both the Argimbai gabbroic rocks and the Maksut picrites have high contents of alkalis (5.2 to 7.8 wt. % and 2 to 5 wt. % Na_2O+K_2O in the two complexes, respectively), relatively high potassium (up to 2.8 wt. % and 1.3 wt. % K_2O, respectively) and phosphorus (to 0.8 wt. % and 0.3 wt. % P_2O_5, respectively). The Argimbai gabbro typically contain up to 1000 ppm LREE and Ba, 980 ppm Sr, 350 ppm Zr, and 25 ppm Rb. The concentrations of trace and rare-earth elements in the Maksut picrodolerite and picrite are lower than in the Argimbai gabbro but higher than in ultramafic rocks (up to 280 ppm Ba, 830 ppm Sr, 110 ppm Zr, and 8 ppm Rb) (Fig. 5). Mineralization in the two complexes [*Mekhonoshin et al., 2017*] consists of Ti (Argimbai

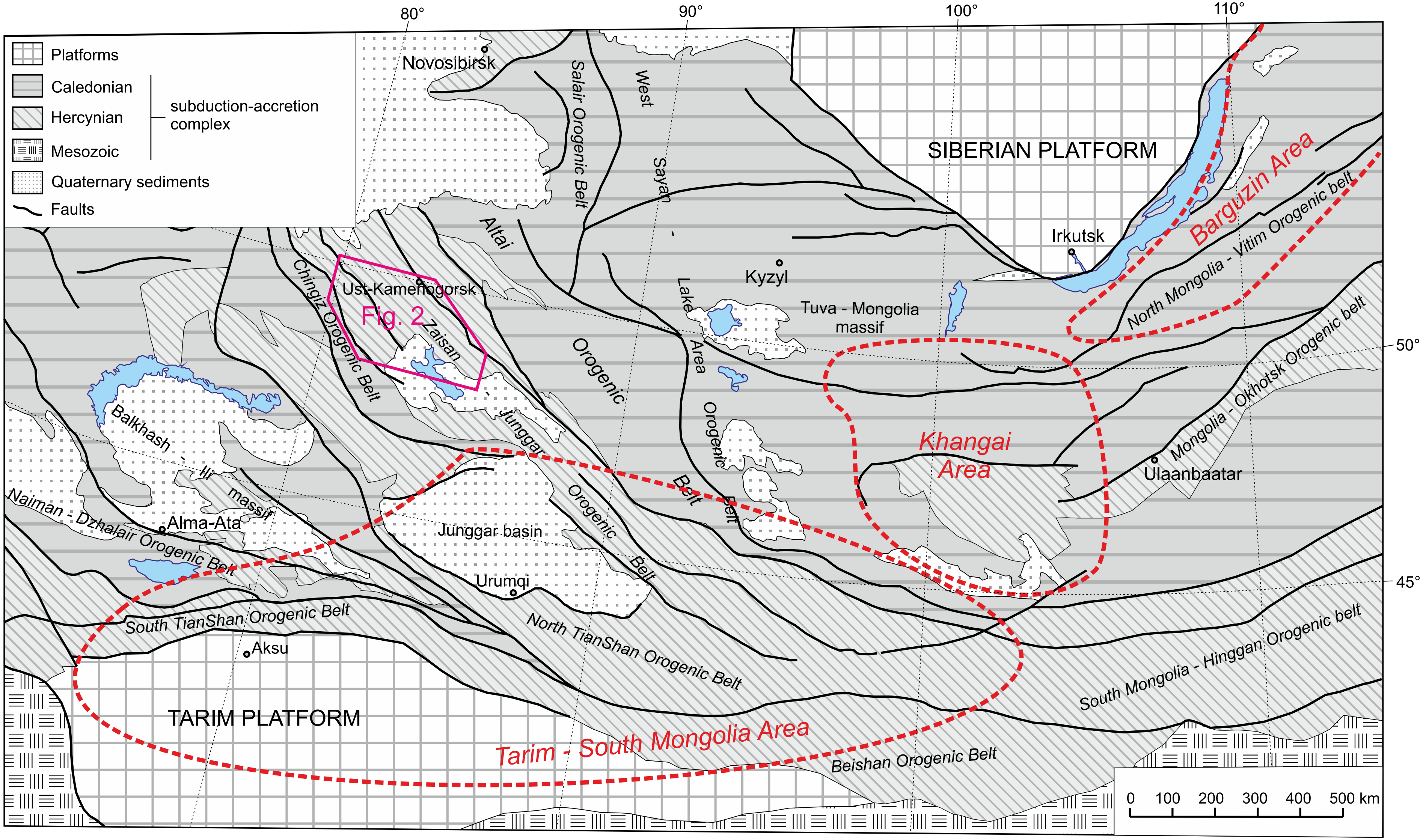

Fig. 1. Simplified tectonics of the Central Asian Orogenic Belt (after [*Windley et al., 2007; Levashova et al., 2009; Xiao et al., 2010*]) and location of Permian Large Igneous Provinces (after [*Yarmolyuk et al., 2014*]).

Рис. 1. Упрощенная тектоническая схема Центрально-Азиатского складчатого пояса (по [*Windley et al., 2007; Levashova et al., 2009; Xiao et al., 2010*]) и пермских крупных изверженных провинций (по [*Yarmolyuk et al., 2014*]).

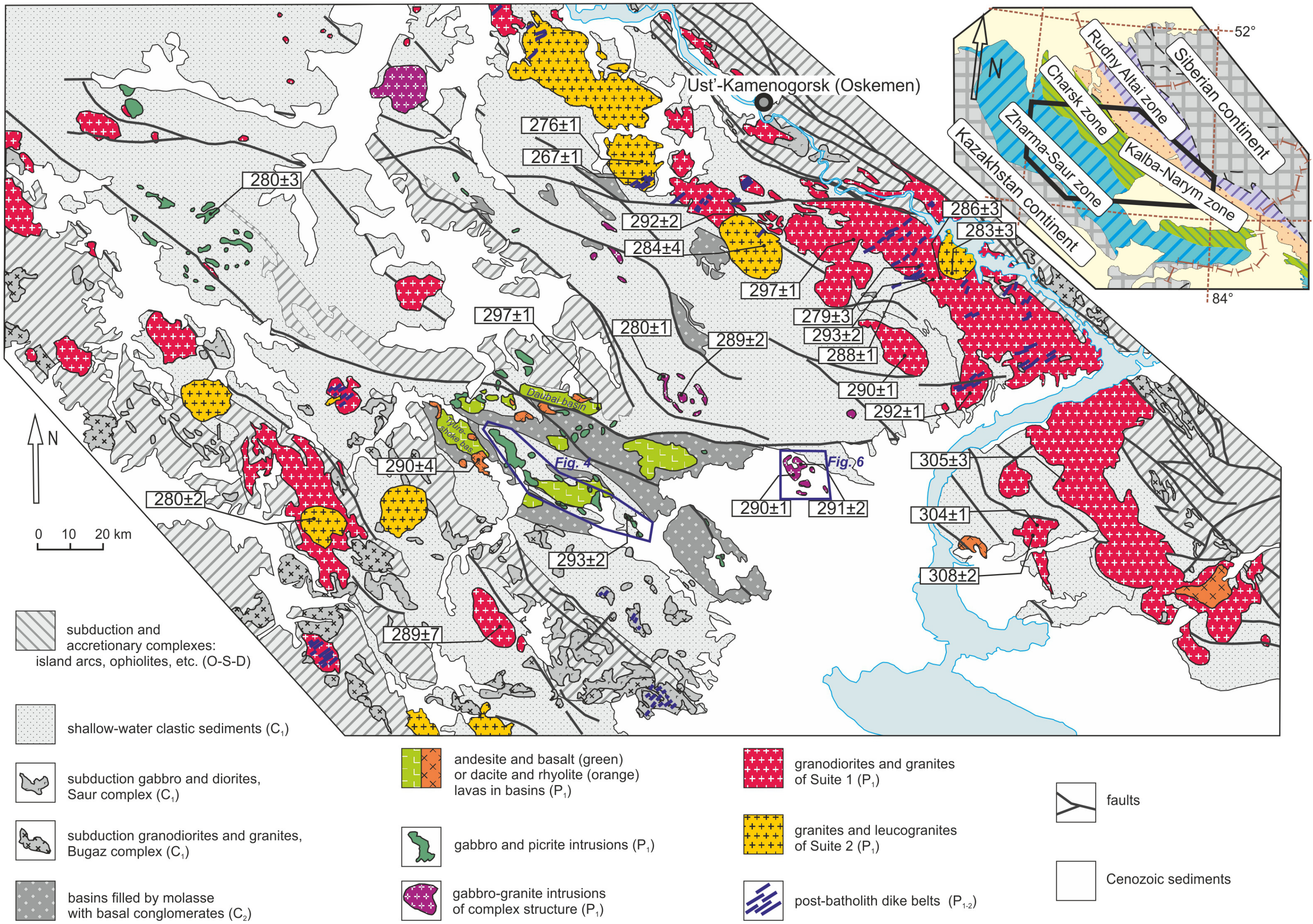

Fig 2. Sketch map of the central part of Altai collisional system (Eastern Kazakhstan), after [*Khromykh et al., 2017b*]. Subduction-accretion-collision complexes are in gray shades; post-orogenic magmatic complexes are coloured.

Рис. 2. Расположение посторогенных магматических комплексов (выделены цветом) на схеме геологического строения центральной части Алтайской коллизионной системы (Восточный Казахстан), по [*Khromykh et al., 2017b*]. Предшествующие геологические комплексы аккреционно-коллизионной стадии показаны серым фоном.

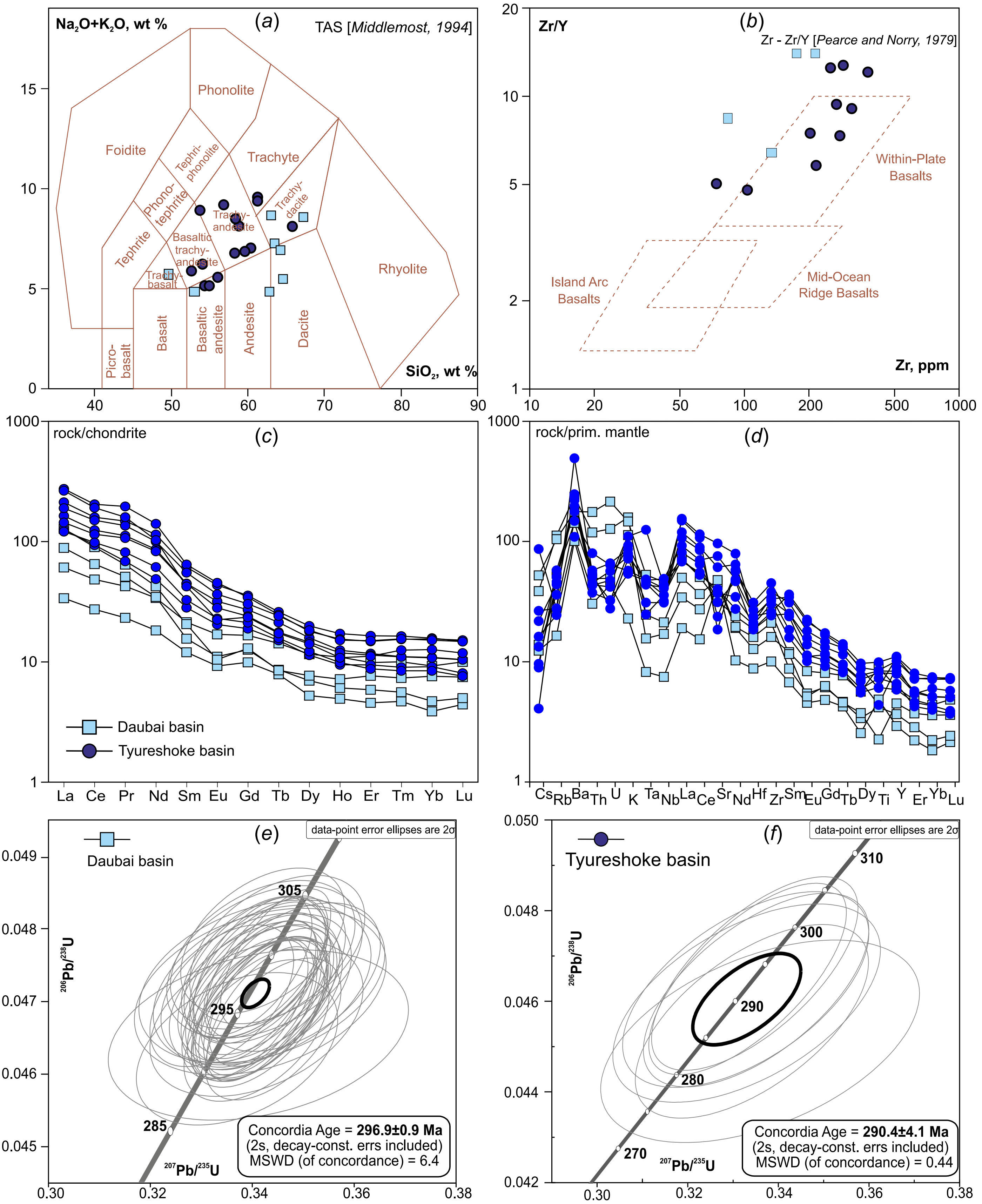

Fig. 3. Basalts and andesites from volcanic basins in the TAS (*a*) and Zr-Zr/Y (*b*) diagrams; REE (*c*) and trace-element (*d*) compositions of volcanic rocks; U-Pb ages of andesite from the Daubai basin (*e*) and dacite from the Tyureshoke basin (*f*).

Рис. 3. Составы базальтов и андезитов из вулканических прогибов на классификационных диаграммах TAS (*a*) и Zr-Zr/Y (*b*); спектры распределения РЗЭ (*c*) и мультиэлементные спектры (*d*) для вулканических пород; U-Pb диаграммы с конкордией для цирконов из андезитов Даубайского прогиба (*e*) и из дацитов Тюрешокинского прогиба (*f*).

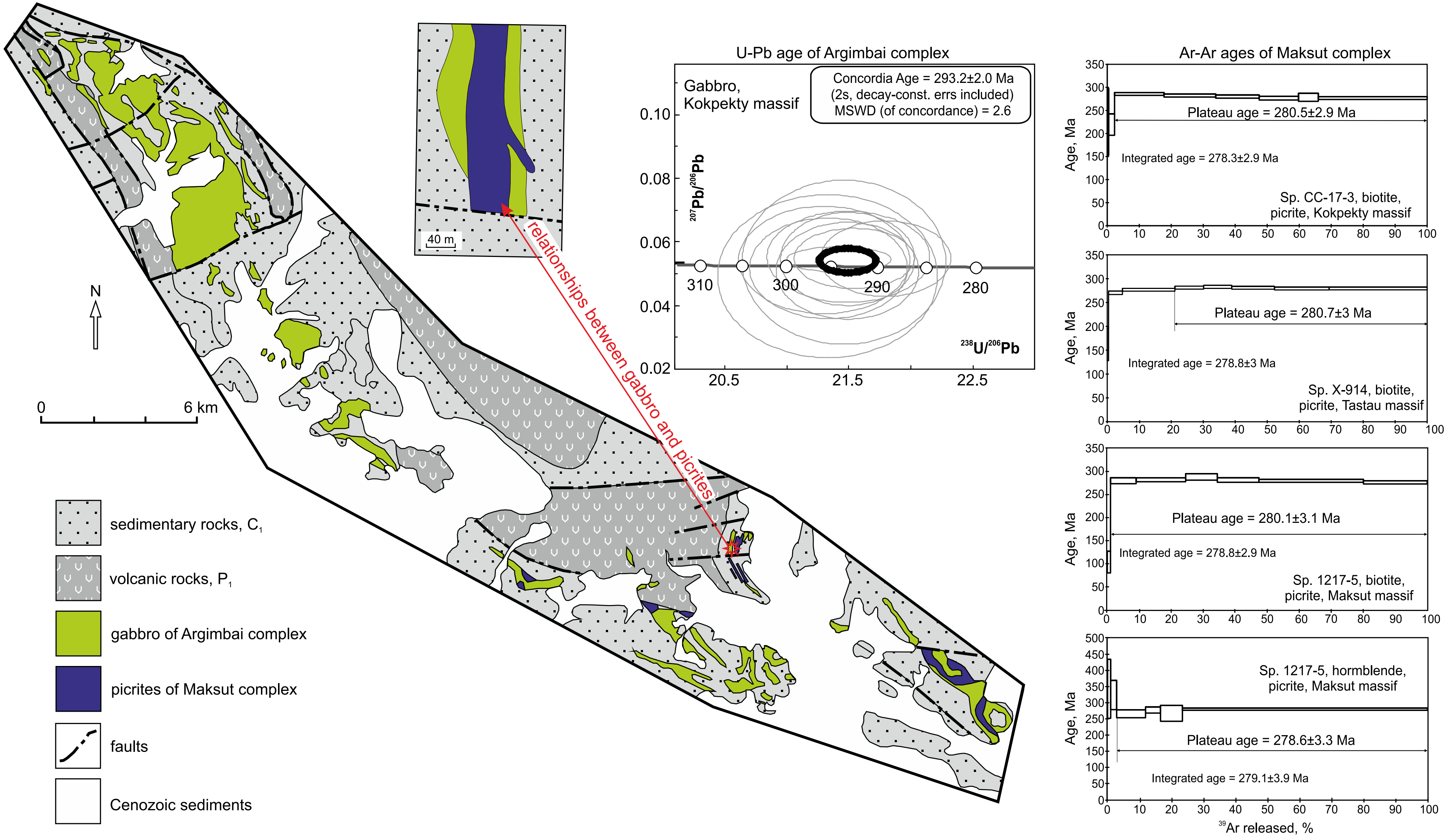

Fig. 4. Simplified geology of the Argimbai intrusive area [*Khromykh et al., 2013*], and ages of gabbro and picrites of the Argimbai and Maksut complexes.

Рис. 4. Схема геологического строения Аргимбайского интрузивного пояса [*Khromykh et al., 2013*] и результаты определения возраста для габбро и пикритов аргимбайского и максутского комплексов.

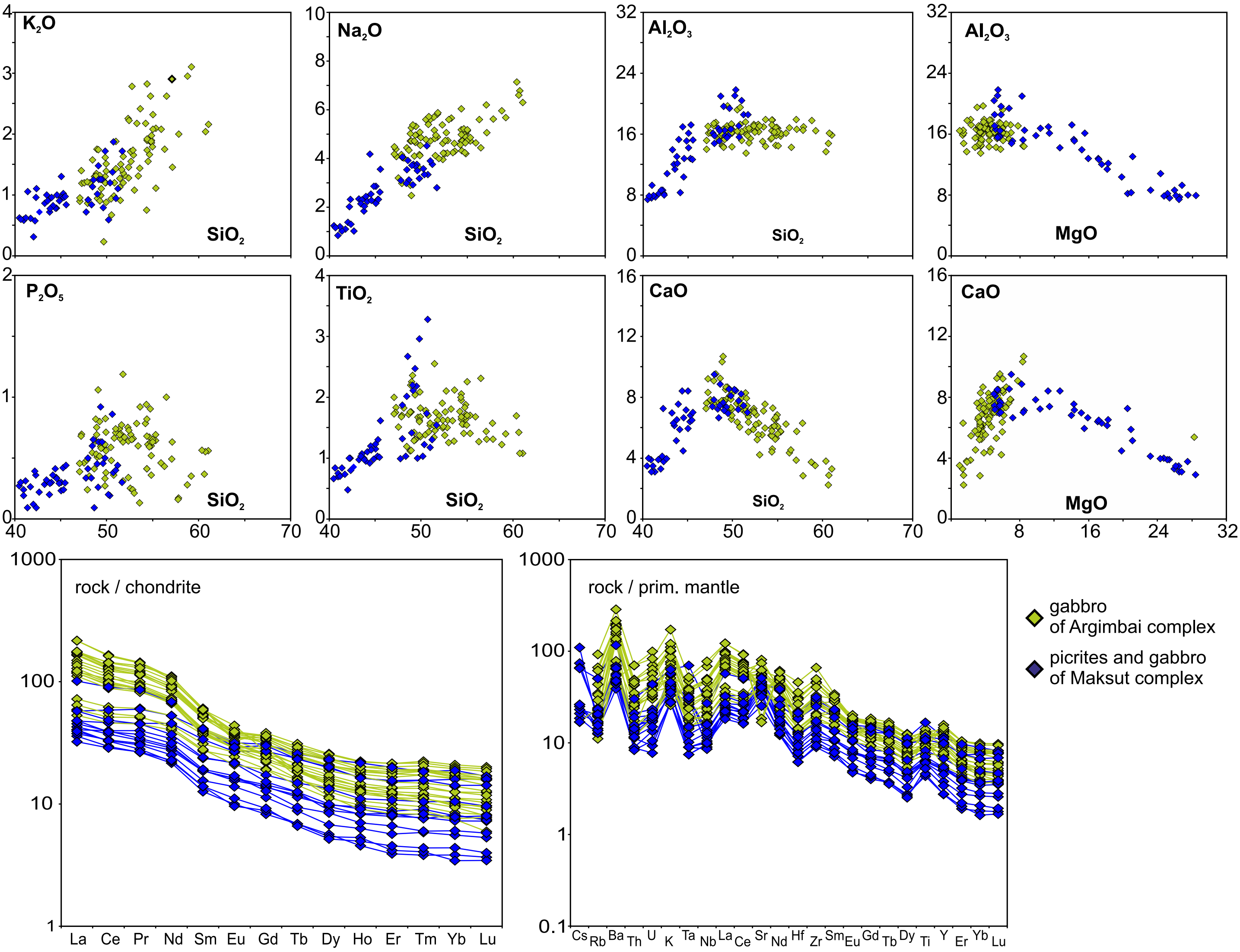

Fig. 5. Compositions of the Argimbai gabbro and the Maksut picrites and gabbro.

Рис. 5. Составы габбро аргимбайского комплекса, габбро и пикритов максутского комплекса.

gabbro) and Cu-Ni sulfides and precious metals (Maksut picrites). The intrusions similar in composition, age and mineralization are manifested in the south-eastern extension of these complexes, in Chinese Altai (Kalatongke) and East Tianshan (Huangshan-Jing and others) [*Polyakov et al., 2008; Pirajno et al., 2011*].

5. COMPLEX GABBRO-GRANITE INTRUSIONS (290–280 MA)

Some gabbro-granite intrusions (Preobrazhenka, Tastau and Delbegetei) that occur among metasedimentary and metavolcanic rocks in the central part of Eastern Kazakhstan have a complex structure. They are as large as 100 to 300 km^2 and isometric in plan view. The best documented Preobrazhenka intrusion (Fig. 6) comprises both mafic and granitic lithologies: (i) dolerite (Ol+OPx+CPx+Pl+Bt), biotite gabbro (Pl+CPx+Bt±Amp), and monzodiorite (Pl+Amp+Bt±CPx) and (ii) Qtz monzonite (Pl+Kfs+OPx+Amp+Bt+Qtz), granosyenite (Pl+Kfs+Qtz+Amp+Bt), granite (Qtz+Pl+Kfs+Bt+Amp) and leucogranite (Qtz+Pl+Kfs±Bt±Grt) lithologies, respectively. The rocks of the two groups formed separately by differentiation of mafic and granitic parent magmas, which intruded synchronously, as evidenced by the presence of mingling structures (Fig. 6, *b–d*) [*Khromykh et al., 2017a, 2018*]. The Preobrazhenka intrusion was dated at 290±2 Ma (LA-ICP-MS zircon U-Pb, Qtz monzonite) and 290±1 Ma (LA-ICP-MS zircon U-Pb, granite) (Fig. 6, *e–f*). The Tastau granodiorites and granosyenites have LA-ICP-MS zircon U-Pb ages of 289±2 and 280±1 Ma, respectively [*Khromykh et al., 2018*].

The Preobrazhenka mafic and granitic rocks have independent composition trends in binary diagrams

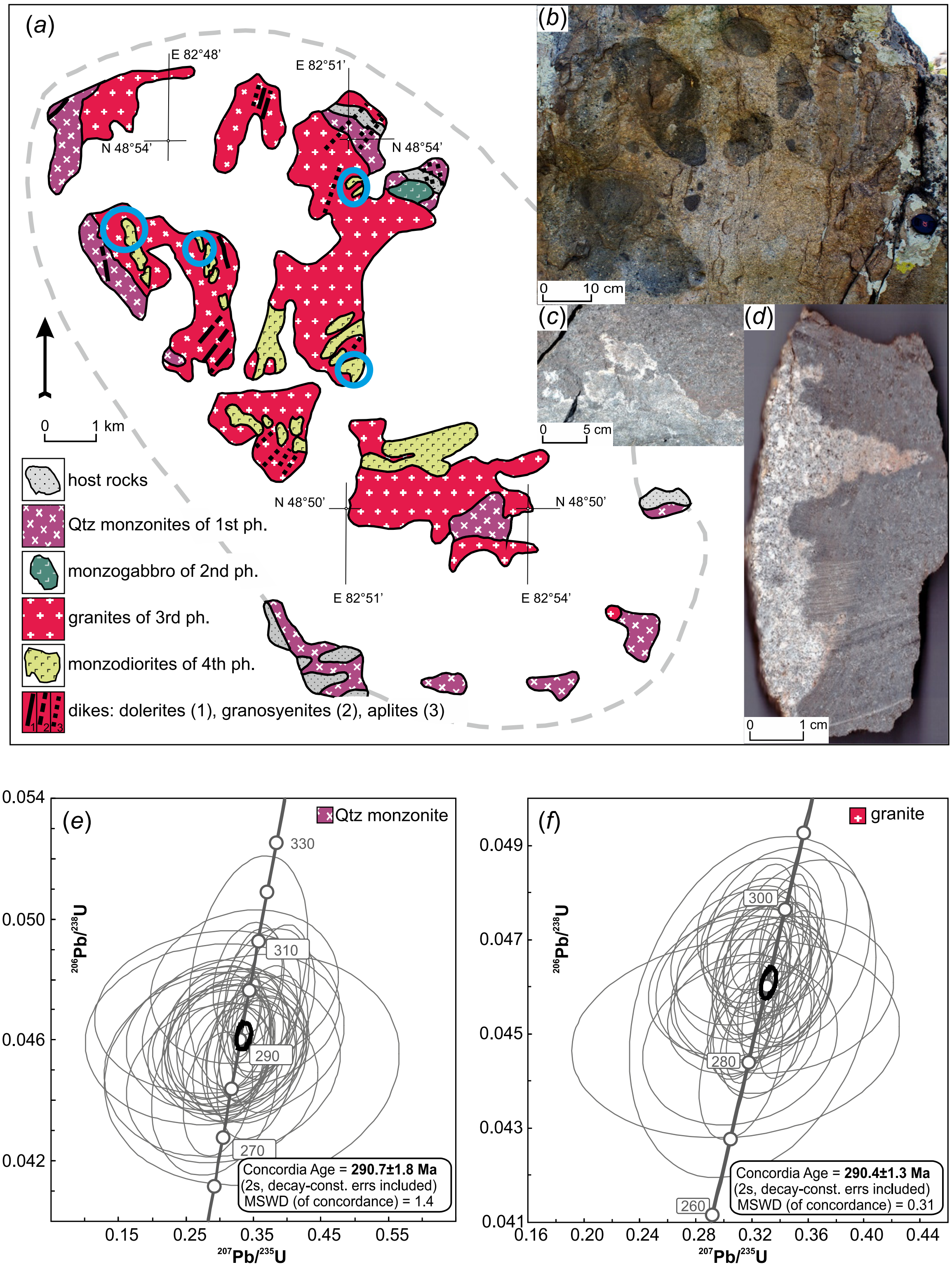

Fig. 6. (*a*) – simplified geology of the Preobrazhenka gabbro-granite intrusion [*Khromykh et al., 2017a, 2018*]. Blue circles mark mingling relations between granosyenite (phase 3) and monzodiorite (phase 4). (*b–d*) – photographs illustrating relationships between igneous rocks: monzodiorite (dark gray) and porphyritic granosyenite (light gray) nodules in granite of phase 3 (*b*); contact of monzodiorite and porphyritic granosyenite in an outcrop photo (*c*) and in the photo of a sample (*d*); U-Pb ages of Qtz monzonite of phase 1 (*e*) and granite of phase 3 (*f*).

Рис. 6. (*a*) – схема геологического строения Преображенского габбро-гранитного массива [*Khromykh et al., 2017a, 2018*]. Голубыми кружками отмечены места проявления минглинг-взаимоотношений между граносиенитами 3-й фазы и монцодиоритами 4-й фазы. (*b–d*) – фотографии, иллюстрирующие взаимоотношения магматических пород: нодули монцодиоритов (темно-серые) и порфировидных граносиенитов (светло-серые) в гранитах 3-й фазы (*b*); контакт монцодиоритов и порфировидных граносиенитов в обнажении (*c*) и на срезе образца (*d*); U-Pb диаграммы с конкордией для цирконов из кварцевых монцонитов 1-й фазы (*e*) и из гранитов 3-й фазы (*f*).

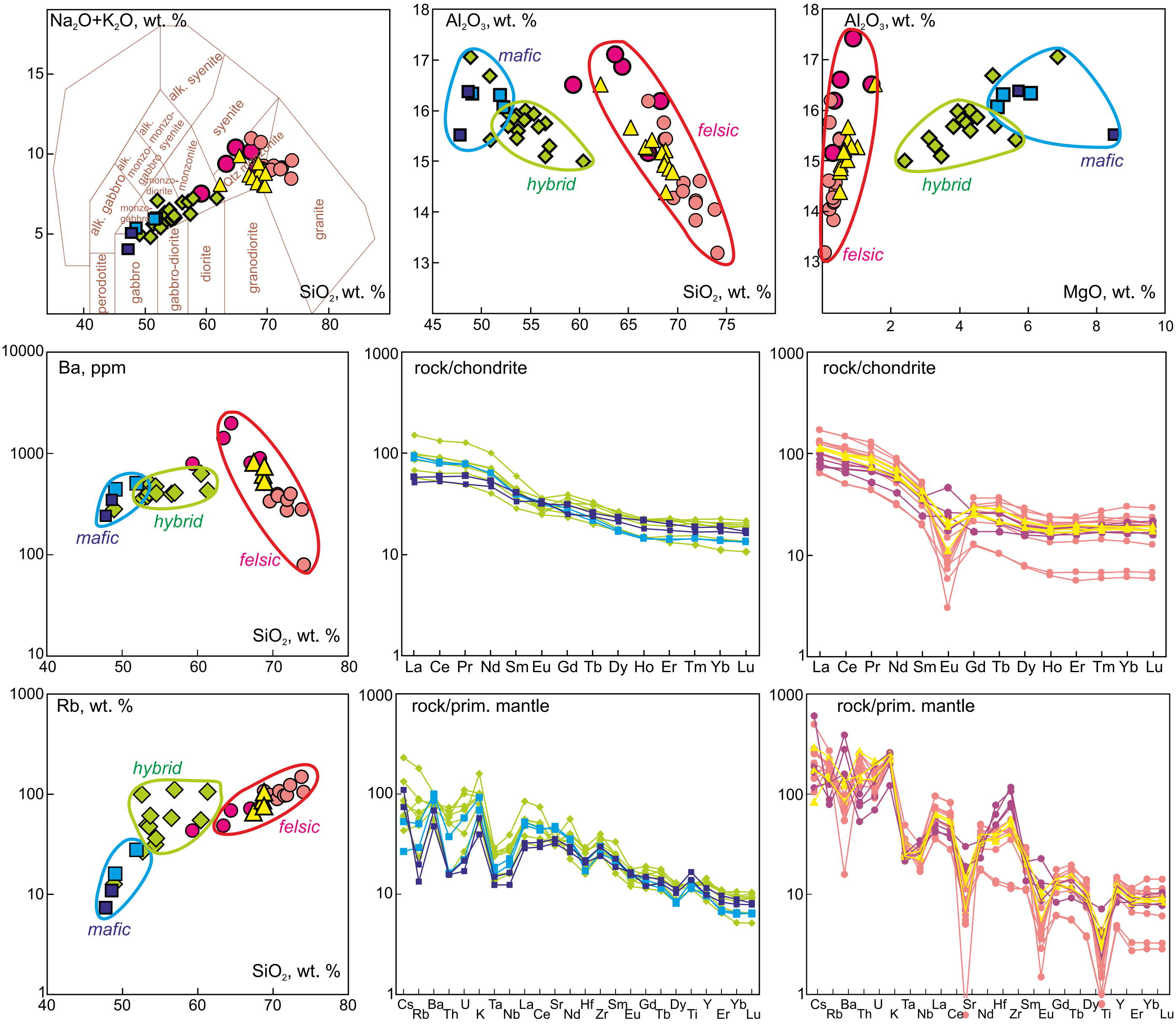

Fig. 7. Composition of the mafic (dolerite and gabbro), felsic (Qtz monzonite, granosyenite and granite) and hybrid (monzodiorite) rocks from the Preobrazhenka intrusion.

Рис. 7. Состав базитовых (долериты и габбро), кислых (Кв монцониты, граносиениты и граниты) и гибридных (монцодиориты) пород из Преображенского массива.

(Fig. 7) and show distinct dissimilarity in the contents of Al_2O_3, MgO, CaO and Rb, Ba, Zr, La, and Eu. Mafic subalkaline rocks have high alkali contents, with K_2O up to 2 wt. % in gabbro and 2.5 wt. % in diorite, LREE higher than HREE, and relatively high Ba, K, Ti, Zr, and Sr. Granitic rocks are likewise rather rich in alkalis (3 to 6 wt. % K_2O); the contents of Al_2O_3, FeO, TiO_2, MgO, CaO, Ba, Sr, and Eu decrease progressively from monzonite to granite and leucogranite.

The detailed petrological studies of the Preobrazhenka rocks showed that mafic lithologies were derived from trachybasaltic magma by fractionation and contamination with crustal anatectic melts, while the granitic lithologies result from melting of the lower or middle crust under a thermal impact of hot mafic magma. The origin of the intrusion was explained [*Khromykh et al., 2018*] in the context of interaction between mafic magma and granitic anatectic melts at different depths. This interaction led to reciprocal contamination of the mafic and felsic magmas and formation of Qtz-bearing monzogabbro and Qtz monzonite at the lower-crust level, but mingling structures formed at the middle-crust level where chemical mixing was minor; in the upper crust, mafic magmas did not interact with granitic material and formed a few dikes only.

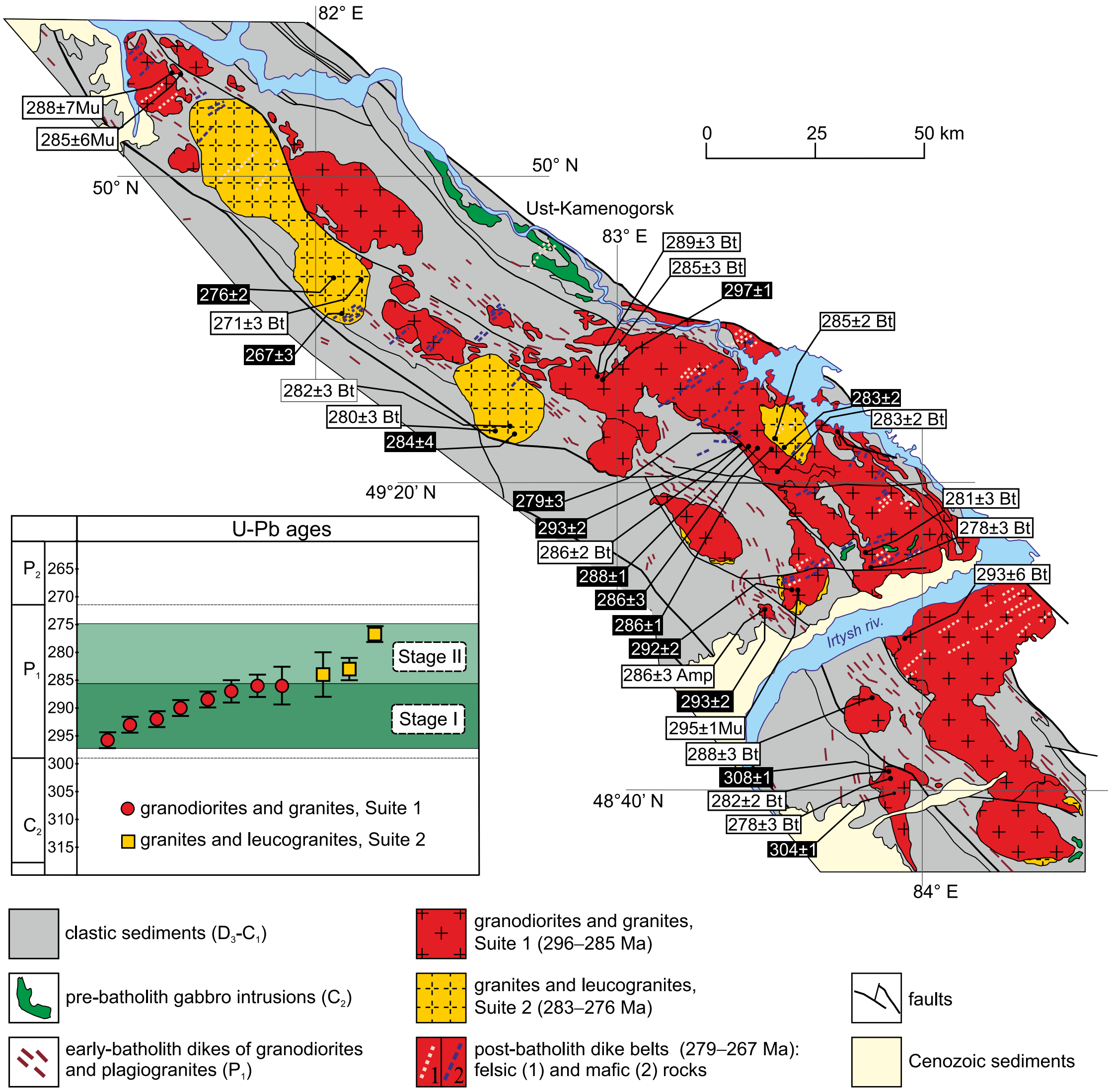

Fig. 8. Simplified geology of the Kalba-Narym batholith, and the results of U-Pb (black squares) and Ar-Ar (white squares) isotopic dating [*Kotler et al., 2015; Khromykh et al., 2016*]. Inset shows the U-Pb ages of granitic samples of suites 1 and 2.

Рис. 8. Упрощенная схема строения Калба-Нарымского батолита и результаты изотопного датирования, выполненного U-Pb (черные прямоугольники) и Ar-Ar (белые прямоугольники) методами [*Kotler et al., 2015; Khromykh et al., 2016*]. На врезке – распределение U-Pb возрастов для образцов гранитов из 1-й и 2-й ассоциаций.

6. LARGE GRANITOID BATHOLITHS (295–275 MA)

Remelting of the clastic metasedimentary and metamorphic rocks led to the formation of two large granitoid batholiths in Eastern Kazakhstan: Zharma in the west, and Kalba-Narym in the east (see Fig. 2). The Kalba-Narym batholith extends from NW to SE within the Kalba-Narym turbidite terrane. According to a classical interpretation [*Lopatnikov et al., 1982; Shcherba et al., 1998*], it would be of collisional origin and would form during an orogenic stage, while the respective plutonic event would last 50–60 myr from the C_3-P_1 boundary to the P_2-T_1 boundary. However, new petrological and geochronological data [*Kotler et al., 2015; Khromykh et al., 2016*] show (Fig. 8) a shorter duration (20–25 myr, i.e. from 300–295 to 280–275 Ma, P_1) and post-orogenic origin of the plutonism. The Kalba-Narym batholith consists of (1) an S-type granodiorite-granite suite making up most of the batholith volume, which emplaced in two phases at 296–288 Ma and 286–285 Ma, and (2) an A-type leucogranite-granite suite occurring as several large independent intrusions (283–276 Ma).

Suite 1 granodiorites and granites vary in SiO_2 from 64 to 75 wt. %, and all elements except K_2O decrease with increasing silica contents (Fig. 9), which is common to S-type granites. The leucogranite-granite suite (2) shows a narrower SiO_2 range of 73–76 wt. % and enrichment in Fe, REE, and HFSE (Ta, Nb, Zr, Hf) with silica increase (Fig. 9), as well as elevated contents of F and Li, which is closer to A-type granite compositions.

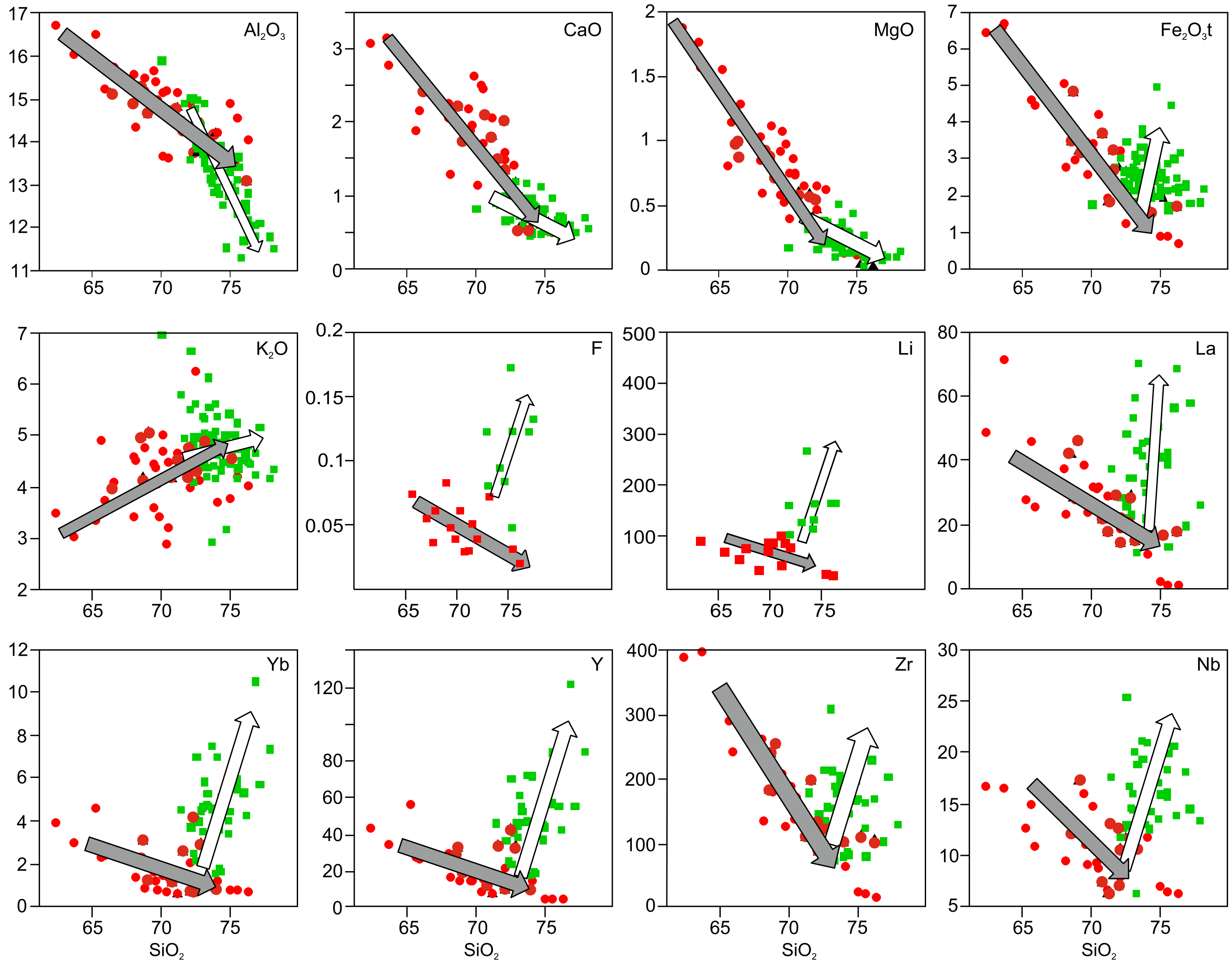

Fig. 9. Composition of granodiorite-granite (red circles, grey arrows) and granite-leucogranite (green squares, white arrows) suites from the Kalba-Narym batholith in the binary diagrams.

Рис. 9. Состав пород гранодиорит-гранитной (красные кружки, серые стрелки) и гранит-лейкогранитной (зеленые квадратики, белые стрелки) ассоциаций Калба-Нарымского батолита на бинарных диаграммах.

Suite 2 granites and leucogranites form large independent intrusions, and there is a small gap between suite 1 and suite 2. We suggest the origin of Suite 2 in a separate melting pulse. The sources and conditions of granitic magma generation for the two suites were inferred from their mineralogy and chemistry, with reference to the compositions of the sedimentary and metamorphic rocks in the region, as well as to the experimental data on melting of crust protoliths. The rocks of suite 1 (similar to S-type granites) formed by partial melting of mixed metapelitic and metabasaltic substrates. The leucogranites and granites of suite 2 (similar to A-type granites) originated by melting of metapelitic crust, with participation of juvenile fluids enriched in HSFE and REE which interacted with the metamorphic material during melting.

7. RARE-METAL GRANITE DIKES AND PEGMATITES (290–285 MA)

Granitic pegmatites in the Kalba-Narym zone bear extensive rare-metal mineralization (Ta, Nb, Li, Be, Sn, W etc.). They occur as veins in granitic rocks of phase 1 of the granodiorite-granite suite. Their relative chronology is confirmed by $^{40}Ar/^{39}Ar$ isotopic dating: the ages obtained for 12 mica samples from pegmatites range from 292 to 285 Ma [*Kotler et al., 2014*]. Rare-metal pegmatites are similar to ongonite and rare-metal granite-porphyry that form two dike swarms near Ust-Kamenogorsk city (Fig. 10). The larger Chechek dike swarm comprises about 15 dikes, 2 to 5 m thick and hundreds of meters long [*Sokolova et al., 2016*]. The age of the dikes was determined as

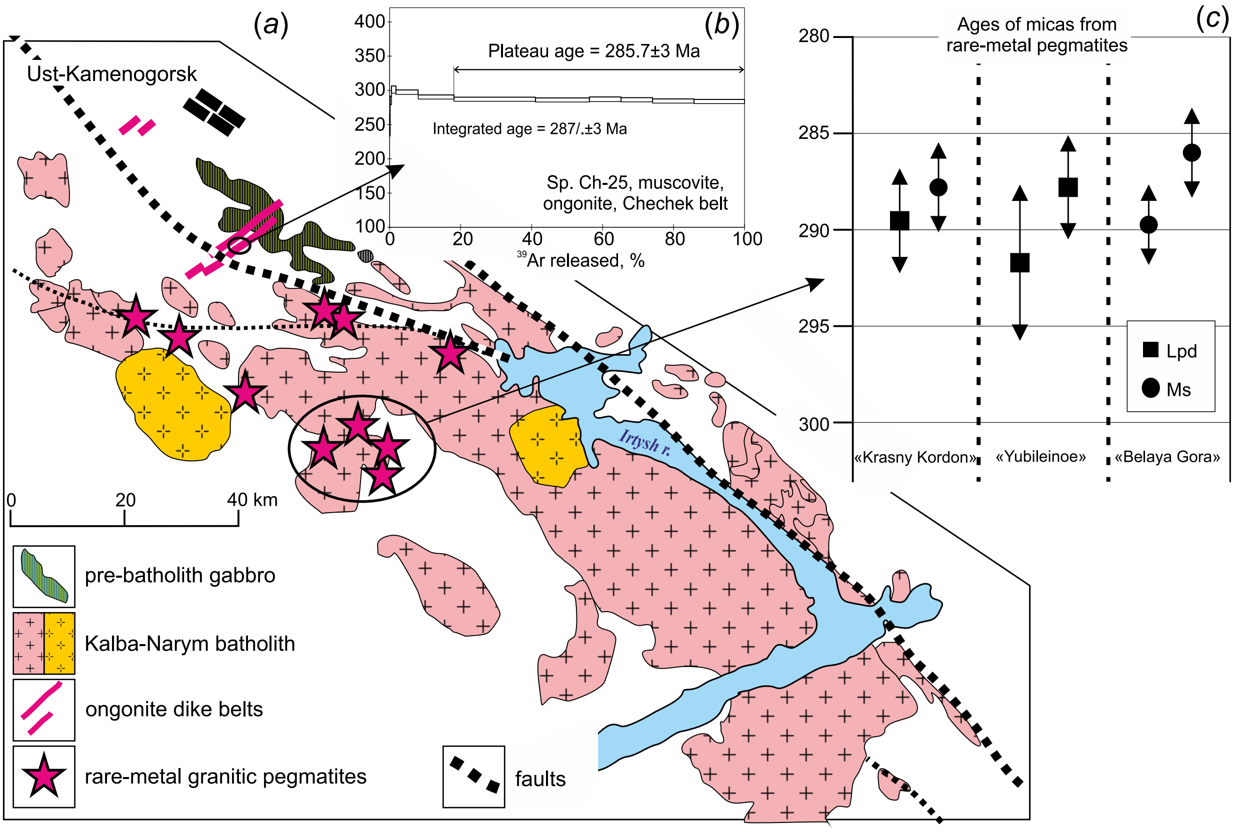

Fig. 10. (*a*) – map of rare-metal mineralization in the Kalba-Narym zone, after [*Sokolova et al., 2016*]; (*b*) – Ar-Ar age of ongonite from the Chechek dike belt [*Khromykh et al., 2014*]; (*c*) – Ar-Ar ages of muscovite and lepidolite from the rare metal pegmatite deposits [*Kotler et al., 2014*].

Рис. 10. (*а*) – схема распространения редкометалльной минерализации в Калба-Нарымской зоне, по [*Sokolova et al., 2016*]; (*b*) – Ar-Ar возрастной спектр для мусковита из онгонита из Чечекского дайкового пояса [*Khromykh et al., 2014*]; (*c*) – результаты определения возраста Ar-Ar методом для мусковита и лепидолита из редкометалльных пегматитовых месторождений [*Kotler et al., 2014*].

286±3 Ma by Ar-Ar dating of liquidus muscovite phenocrysts from a thick ongonite dike [*Khromykh et al., 2014*]. The dike rocks have high concentrations of LILE and F, like Li-F granites, and split into three composition groups with relatively high, high, and ultra-high contents of rare metals: (1) up to 1000 ppm Li+Rb+Cs, 0.45 wt. % F, and 40–100 ppm ΣREE; (2) up to 2500 ppm Li+Rb+Cs, 1.4 wt. % F, 0.35 wt. % P_2O_5, and 3–15 ppm ΣREE; and (3) up to 4000 ppm Li+Rb+Cs and 110–180 ppm ΣREE (Fig. 11). The concentrations of 'typical granitic' rare metals (Sn, Nb, Ta) in dikes are much higher than in granites (15–100 times more Sn, 1.5–2 times more Nb, and 2–12 times more Ta).

The mineralogy and chemistry of the dike rocks [*Sokolova et al., 2016*] suggests their origin from granitic melts that were enriched in rare metals. This makes them closer to rare-metal granite pegmatites of the Kalba-Narym batholith. We assume that magmas rich in rare metals formed in the granite chambers of the Kalba-Narym batholith. However, their local occurrence indicates that their generation involved inputs of F, P_2O_5, rare metals, as well as other specific components with juvenile fluids, besides intra-chamber differentiation. This formation mechanism of the rare metal magmas is similar to that for suite 2 granites and leucogranites in the Kalba-Narym batholith.

8. MAFIC DIKE SWARMS (280–270 MA)

The juvenile fluids that contributed to the formation of rare metal granitic magmas may come from a subcrustal mafic reservoir (magmatic underplating). Mafic magmatism in the Kalba-Narym zone occurs as dike swarms of the Myrolyubovka complex that intrude all granitic rocks (see Figs. 2 and 8), about 10 dike swarms, with 3–4 to 15–20 dikes in each unit. All dikes strike in the NE direction and are up to 4–5 meter thick and 2–3 km long. The dikes of the complex are mostly mafic though some have other compositions. The rocks are subalkaline and belong to high-K calc-alkaline series, have low contents of magnesium (Mg# ~39 %),

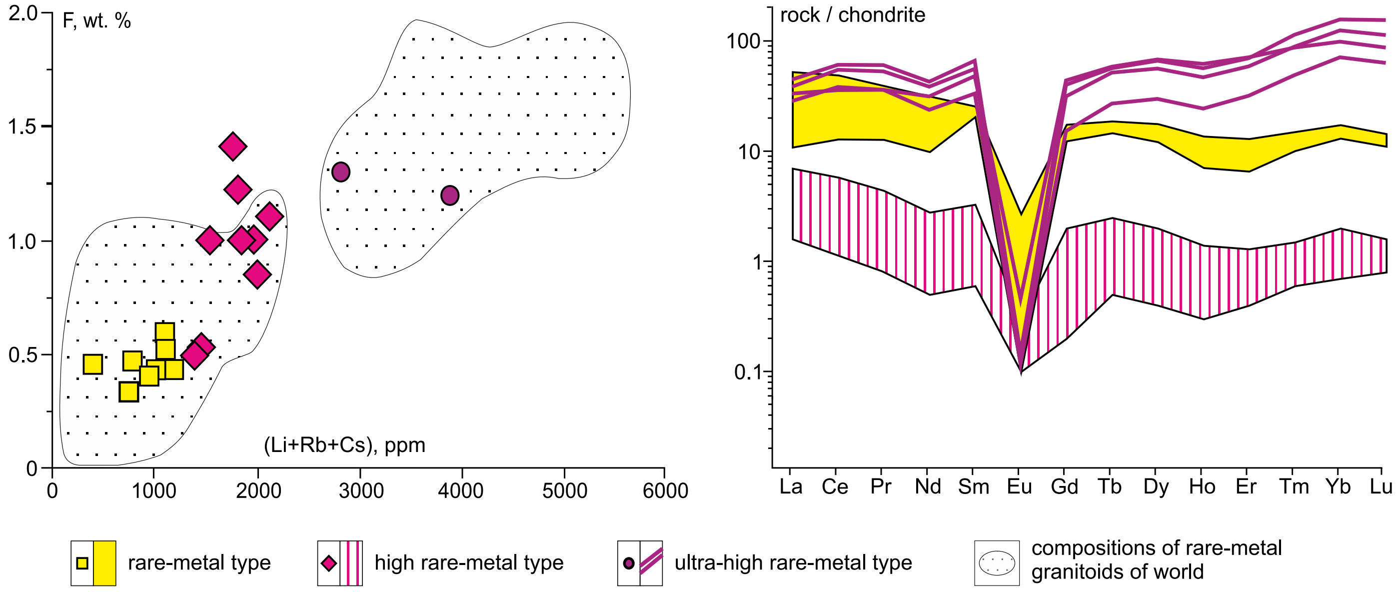

Fig. 11. Composition features of ongonites from Chechek and Akhmirovka dike belts [*Sokolova et al., 2016*].

Рис. 11. Особенности состава онгонитов из Чечекского и Ахмировского дайковых поясов [*Sokolova et al., 2016*].

and high TiO_2 (~1.6 wt. %), K_2O (~1.7 wt. %), P_2O_5 (~0.6 wt. %) and REE (sum ~195 ppm, Fig. 12, *a*–*d*). In addition, they contain greater concentrations of rare metals, fluorine and boron than the Kalba-Narym granitic rocks: 3–7 ppm Li, 0.9-3.5 ppm Cs, 16–38 ppm Rb, 0.4–0.8 ppm Sn, 0.1–0.5 ppm Be, 2–16 ppm Nb, 0.7–1.1 ppm Ta, 120–140 ppm F, and 1–3 ppm B. Therefore, the dike mafic rocks are derived from the mantle magmas that were the source of metals for the rare-metal granitic magmas. The available age constraints are LA-ICP-MS zircon U-Pb dates of 279±3 Ma for dolerite of the Manat dike and 267±1 Ma for spessartite of the Monastery dike (Fig. 12, *e*–*f*).

9. CORRELATION OF MAGMATIC EVENTS AND MECHANISMS OF PLUME-LITHOSPHERE INTERACTION

Thus, voluminous mantle and crustal magmatism affected the whole Eastern Kazakhstan in the interval of 300–270 Ma (Fig. 13, *a*). The rocks of mantle origin are enriched in alkalis, phosphorus, titanium and incompatible elements notably different from the older accretionary mafic-ultramafic complexes with subduction signatures [*Safonova et al., 2012, 2018*]. The appearance of enriched mantle magmas at the post-orogenic stage usually indicates their deeper sources. There are also assumptions that the appearance of enriched mantle magmas may be caused by remelting of metasomatised mantle wedges [*Konopelko et al., 2017*]. Anyway, melting of the mantle indicates an increasing thermal gradient. The high thermal gradients most likely resulted from the activity of the Tarim mantle plume which produced the early Permian Tarim LIP [*Ernst, 2014; Gao et al., 2014; Wei et al., 2014; Xu et al., 2014; Yarmolyuk et al., 2014; Yu et al., 2017*]. Based on the reported data, we infer that the Tarim LIP extends to the north, into the region of Eastern Kazakhstan (Fig. 13, *b*). The far-reaching influence of the Tarim LIP may have been facilitated by post-orogenic lithospheric extension [*Buslov, 2011*] after the Siberia-Kazakhstan collision. The extension led to rheological weakening of the lithosphere, whereby deep mantle melts could intrude into the sublithospheric mantle. The style of the mantle-crust interaction varied over the region depending on the permeability of the lithospheric blocks [*Khromykh et al., 2017b*]. In the central part of the region (see Fig. 2), where the fragments of accretionary and paleooceanic complexes still exist, mafic magmas could easily penetrate into the lower crust through the quite thin lithosphere. This may lead to intensive interactions of the mafic magmas with the crustal substrates and anatectic melts, forming the gabbro-monzonite-granite intrusions with a wide spectrum of rocks and mingling and mixing processes, and the appearance of syn-plutonic Mafic Microgranular Enclaves (MME) and combined mafic-felsic dikes [*Wiebe, 1973; Furman, Spera, 1985; Litvinovsky et al., 1995; Barbarin, 2005; Renna et al., 2006; Burmakina, Tsygankov, 2013; Burmakina et al., 2018*] In the northeastern part of the territory, clastic sediments (sandstones and siltstones) deposited in the Devonian-Early Carboniferous within the Kalba-Narym terrane were deformed and metamorphosed in the course of collisional processes, and then were molten anatectically at high temperature gradients across the mantle chambers. Mafic

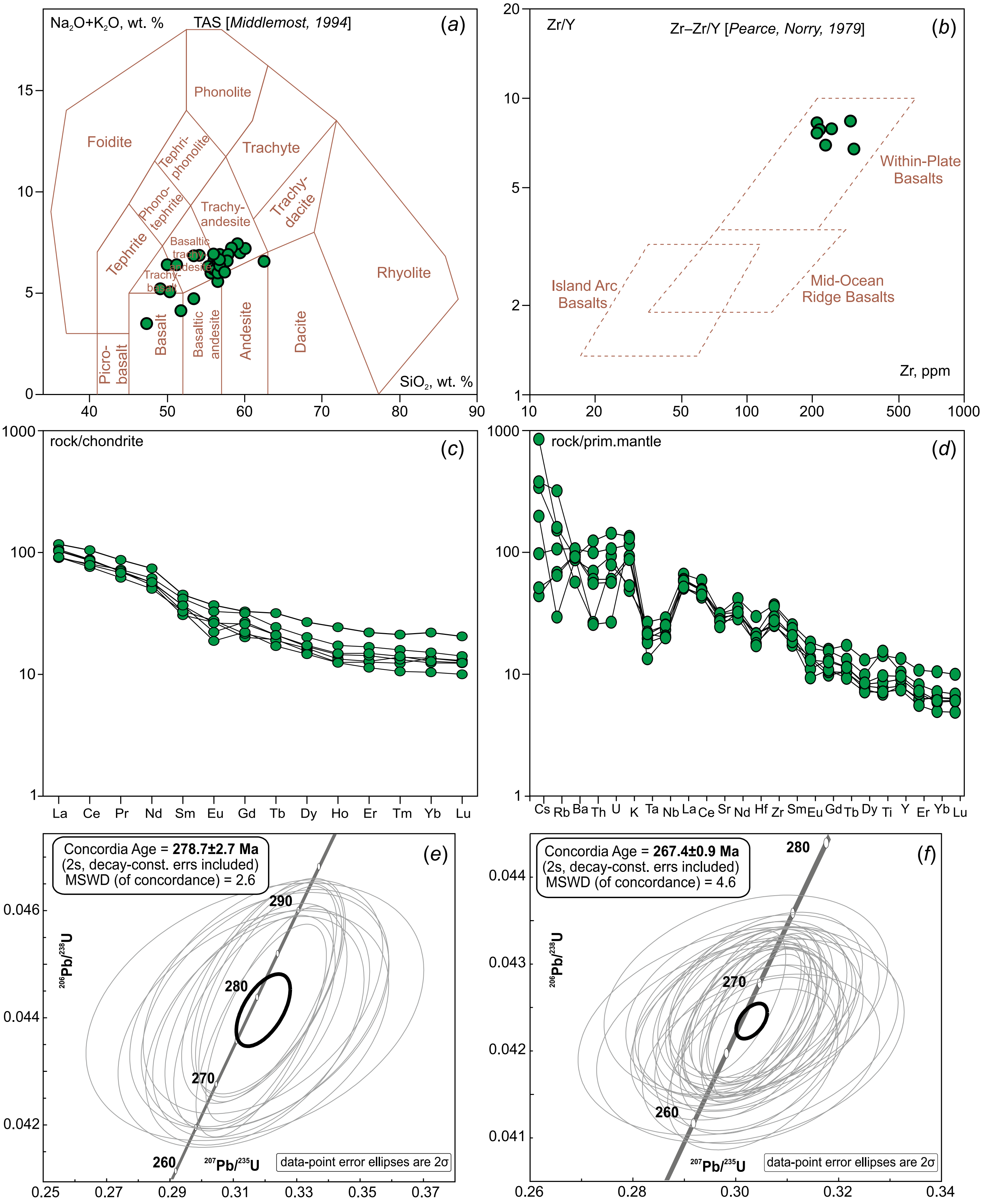

Fig. 12. Mafic rocks of the Mirolyubovka dike belts on the TAS (*a*) and Zr-Zr/Y (*b*) diagrams, and their REE (*c*) and trace-element (*d*) compositions; U-Pb ages of dolerite from the Manat dike (*e*) and spessartite from the Monastery dike (*f*).

Рис. 12. Составы базитовых пород миролюбовского комплекса на классификационных диаграммах TAS (*a*) и Zr-Zr/Y (*b*); спектры распределения РЗЭ (*c*) и мультиэлементные спектры (*d*) для базитовых пород; U-Pb диаграммы с конкордией для цирконов из долеритов дайки Манат (*e*) и из спессартитов дайки в Монастырском массиве (*f*).

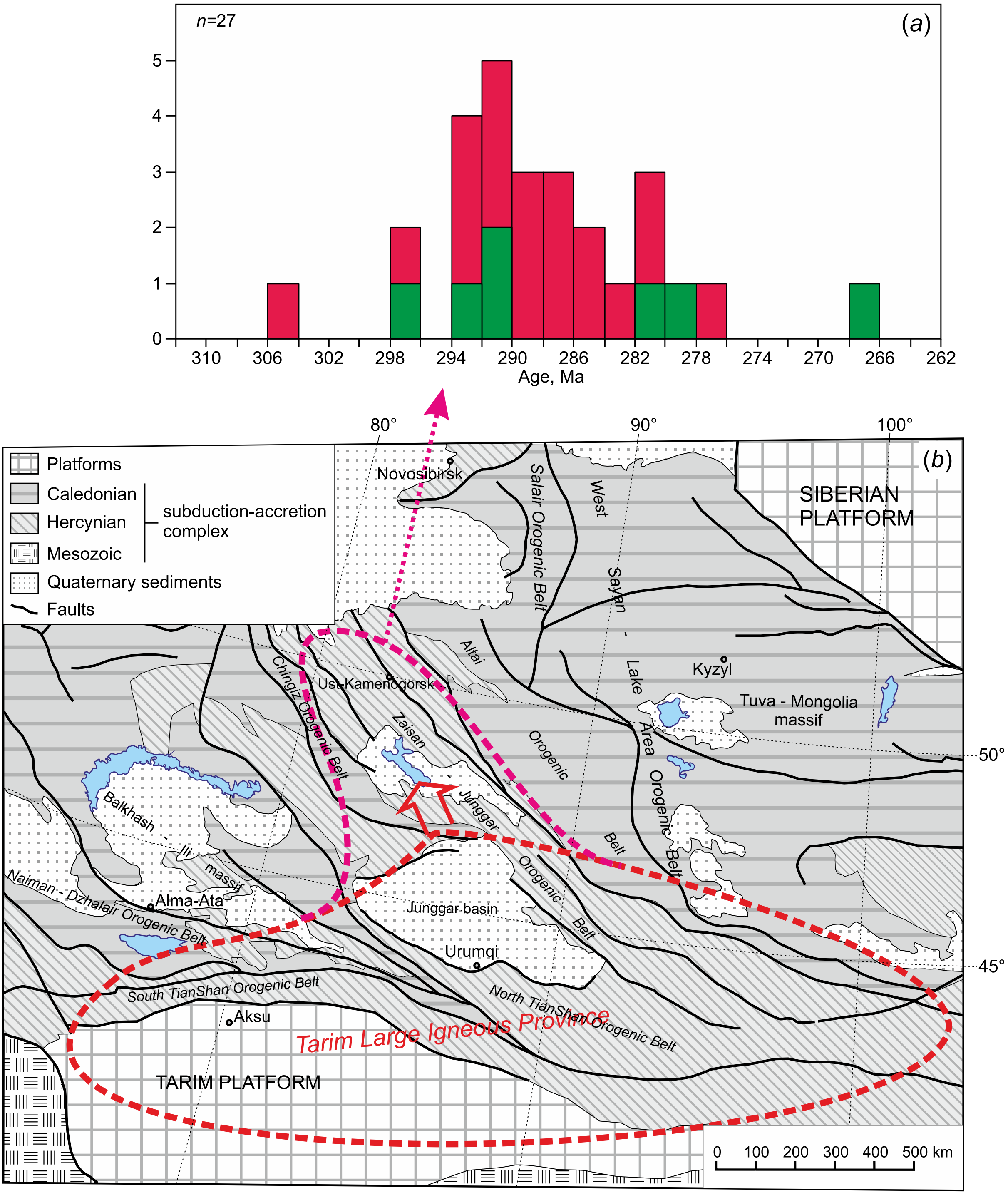

Fig. 13. (*a*) – age histograms of the post-orogenic magmatic complexes from the Eastern Kazakhstan; (*b*) – the proposed boundaries of the Tarim Large Igneous Province taking into account the new data on magmatism of Eastern Kazakhstan.

Рис. 13. (*a*) – гистограмма возрастов, полученных для посторогенных магматических комплексов Восточного Казахстана; (*b*) – предполагаемые границы распространения Таримской крупной изверженной провинции с учетом новых данныха по магматизму Восточного Казахстана.

magmas could not penetrate through thick viscous migmatite-granite lenses (‘density filter’) [*Huppert, Sparks, 1988*]. This mechanism includes interaction of the juvenile mantle fluids with the crust or with granitic magma in the chambers, as well as the inputs of some elements responsible for rare-metal mineralization in granites [*Abramov, 2004; Annikova et al., 2006; Zagorsky et al., 2014; Sokolova et al., 2016*]. Thus, we revealed two main types of mantle-crust interaction: (1) direct interaction of mantle magmas with crustal material and anatectic melts that produced large gabbro-granite intrusions, volcanic structures, and numerous small gabbro-picrite intrusions in central part of studied region; and (2) the effects of mantle heat and fluids on the crust. The intrusion of the mafic magmas into the middle and upper crust became possible only after large-scale granitoid magmatism had completed and the lithosphere had cooled down and deformed. This led to the formation of the Mirolyubovka dike swarms.

Thus, the early Permian history of Eastern Kazakhstan was controlled by the interplay of the plate tectonic and plume processes: plate-tectonic accretion and collision formed the structural framework, and the Tarim mantle plume provided a heat source to maintain voluminous magmatism.

10. ACKNOWLEDGEMENTS

We wish to thank Richard Ernst, Nikolai Dobretsov and Boris D'yachkov for fruitful discussions and valuable advice. Thanks are extended to Erzhan Sapargaliev for his assistance in the field and to Inna Safonova and Tatiana Perepelova for their help in manuscript preparation. This study was conducted according to the state assignment of IGM SB RAS. It was also supported by the Ministry of Science and Higher Education of the Russian Federation (Projects no. 5.1688.2017/4.6 and 14.Y26.31.0018) and the Russian Foundation for Basic Research (Projects no. 16-35-00209, and 17-05-00825).

11. REFERENCES

Abramov S.S., 2004. Formation of fluorin-rich magmas by fluid filtration through silicic magmas: petrological and geochemical evidence of metamagmatism. *Petrology* 12 (1), 17–36.

Annikova I.Yu., Vladimirov A.G., Vystavnoi S.A., Zhuravlev D.Z., Kruk N.N., Lepekhina E.N., Matukov D.I., Moroz E.N., Palesskii V.S., Ponomarchuk V.A., Rudnev S.N., Sergeev S.A., 2006. U-Pb and ^{39}Ar/^{40}Ar dating and Sm-Nd and Pb-Pb isotopic study of the Kalguty molybdenum–tungsten ore-magmatic system, southern Altai. *Petrology* 14 (1), 81–97. https://doi.org/10.1134/S0869591106010073.

Barbarin B., 2005. Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: nature, origin, and relations with the hosts. *Lithos* 80 (1–4), 155–177. https://doi.org/10.1016/j.lithos.2004.05.010.

Bryan S.E., Ernst R.E., 2008. Revised definition of large igneous provinces (LIPs). *Earth-Science Reviews* 86 (1–4), 175–202. https://doi.org/10.1016/j.earscirev.2007.08.008.

Burmakina G.N., Tsygankov A.A., 2013. Mafic microgranular enclaves in Late Paleozoic granitoids in the Burgasy quartz syenite massif, western Transbaikalia: Composition and petrogenesis. *Petrology* 21 (3), 280–303. https://doi.org/10.1134/S086959111303003X.

Burmakina G.N., Tsygankov A.A., Khubanov V.B., 2018. Petrogenesis of composite dikes in granitoids of western Transbaikalia. *Russian Geology and Geophysics* 59 (1), 19–40. https://doi.org/10.1016/j.rgg.2018.01.002.

Buslov M.M., 2011. Tectonics and geodynamics of the Central Asian Fold belt: The role of Late Paleozoic large-amplitude strike-slip faults. *Russian Geology and Geophysics* 52 (1), 52–71. https://doi.org/10.1016/j.rgg.2010.12.005.

Dobretsov N.L., 2003. Evolution of structures of the Urals, Kazakhstan, Tien Shan, and Altai-Sayan region within the Ural-Mongolian fold belt (Paleoasian ocean). *Geologiya i Geofizika* (*Russian Geology and Geophysics*) 44 (1–2), 5–27.

Dobretsov N.L., 2011. Early Paleozoic tectonics and geodynamics of Central Asia: Role of mantle plumes. *Russian Geology and Geophysics* 52 (12), 1539–1552. https://doi.org/10.1016/j.rgg.2011.11.003.

Ermolov P.V., Izokh E.P., Ponomareva A.P., Tyan V.D., 1977. Gabbro-Granitic Rocks in the Western Zaisan Orogenic System. Nauka, Novosibirsk, 246 p. (in Russian) [*Ермолов П.В., Изох Э.П., Пономарёва А.П., Тян В.Д.* Габбро-гранитные серии западной части Зайсанской складчатой системы. Новосибирск: Наука, 1977. 246 с.].

Ermolov P.V., Vladimirov A.G., Izokh A.E., Polyansky N.V., Kuzebny V.S., Revyakin P.S., Bortsov V.D., 1983. Orogenic Magmatism of Ophiolitic Belts (on the Example of East Kazakhstan). Nauka, Novosibirsk, 206 p. (in Russian) [*Ермолов П.В., Владимиров А.Г., Изох А.Э., Полянский Н.В., Кузебный В.С., Ревякин П.С., Борцов В.Д.* Орогенный магматизм офиолитовых поясов (на примере Восточного Казахстана). Новосибирск: Наука, 1983. 191 с.].

Ernst R.E., 2014. Large Igneous Provinces. Cambridge University Press, Cambridge, 653 p. https://doi.org/10.1017/CBO9781139025300.

Ernst R.E., Buchan K.L., Campbell I.H., 2005. Frontiers in large igneous province research. *Lithos* 79 (3–4), 271–297. https://doi.org/10.1016/j.lithos.2004.09.004.

Furman T., Spera F.J., 1985. Co-Mingling of acid and basic magma with implications for the origin of mafic I-type xenoliths: field and petrochemical relations of an unusual dike complex at Eagle Lake, Sequoia National Park, California, U.S.A. *Journal of Volcanology and Geothermal Research* 24 (1–2), 151–178. https://doi.org/10.1016/0377-0273(85)90031-9.

Gao R., Xiao L., Pirajno F., Wang G.-C., He X.-X., Yang G., Yan Sh.-W., 2014. Carboniferous–Permian extensive magmatism in the West Junggar, Xinjiang, northwestern China: its geochemistry, geochronology, and petrogenesis. *Lithos* 204, 125–143. https://doi.org/10.1016/j.lithos.2014.05.028.

Huppert H.E., Sparks S.J., 1988. The generation of granitic magmas by intrusion of basalt into continental crust. *Journal of Petrology* 29 (3), 599–624. https://doi.org/10.1093/petrology/29.3.599.

Izokh A.E., Vishnevskii A.V., Polyakov G.V., Kalugin V.M., Oyunchimeg T., Shelepaev R.A., Egorova V.V., 2010. The Ureg Nuur Pt-bearing volcanoplutonic picrite-basalt association in the Mongolian Altay as evidence for a Cambrian-Ordovician Large Igneous Province. *Russian Geology and Geophysics* 51 (5), 521–533. https://doi.org/10.1016/j.rgg.2010.04.003.

Khromykh S.V., Burmakina G.N., Tsygankov A.A., Kotler P.D., Vladimirov A.G., 2017a. Interactions between gabbroid and granitoid magmas during formation of the Preobrazhensky intrusion, Eastern Kazakhstan. *Geodynamics & Tectonophysics* 8 (2), 311–330. https://doi.org/10.5800/GT-2017-8-2-0243.

Khromykh S.V., Kotler P.D., Sokolova E.N., 2017b. Mantle-crust interaction at the late stage of evolution of Hercynian Altai collision system, western part of CAOB. *Geodynamics & Tectonophysics* 8 (3), 489–493. https://doi.org/10.5800/GT-2017-8-3-0270.

Khromykh S.V., Kuibida M.L., Kruk N.N., 2011. Petrogenesis of high-temperature siliceous melts in volcanic structures of the Altai collisional system of Hercynides (Eastern Kazakhstan). *Russian Geology and Geophysics* 52 (4), 411–420. https://doi.org/10.1016/j.rgg.2011.03.004.

Khromykh S.V., Sokolova E.N., Smirnov S.Z., Travin A.V., Annikova I.Y., 2014. Geochemistry and age of rare-metal dyke belts in Eastern Kazakhstan. *Doklady Earth Sciences* 459 (2), 1587–1591. https://doi.org/10.1134/S1028334X14120174.

Khromykh S.V., Tsygankov A.A., Burmakina G.N., Kotler P.D., Sokolova E.N., 2018. Mantle-crust interaction in petrogenesis of gabbro-granite association in Preobrazhenka intrusion, Eastern Kazakhstan. *Petrology* 26 (4), 368–388. https://doi.org/10.1134/S0869591118040045.

Khromykh S.V., Tsygankov A.A., Kotler P.D., Navozov O.V., Kruk N.N., Vladimirov A.G., Travin A.V., Yudin D.S., Burmakina G.N., Khubanov V.B., Buyantuev M.D., Antsiferova T.N., Karavaeva G.S., 2016. Late Paleozoic granitoid magmatism of Eastern Kazakhstan and Western Transbaikalia: Plume model test. *Russian Geology and Geophysics* 57 (5), 773–789. https://doi.org/10.1016/j.rgg.2015.09.018.

Khromykh S.V., Vladimirov A.G., Izokh A.E., Travin A.V., Prokop'ev I.R., Azimbaev E., Lobanov S.S., 2013. Petrology and geochemistry of gabbro and picrites from the Altai collisional system of Hercynides: Evidence for the activity of the Tarim plume. *Russian Geology and Geophysics* 54 (10), 1288–1304. https://doi.org/10.1016/j.rgg.2013.09.011.

Kiselev A.I., Yarmolyuk V.V., Ivanov A.V., Egorov K.N., 2014. Middle Paleozoic basaltic and kimberlitic magmatism in the northwestern shoulder of the Vilyui Rift, Siberia: Relations in space and time. *Russian Geology and Geophysics* 55 (2), 144–152. https://doi.org/10.1016/j.rgg.2014.01.003.

Konopelko D., Seltmann R., Mamadjano Y., Romer R.L., Rojas-Agramonte Y., Jeffries T., Fidaev D., Niyozov A., 2017. A geotraverse across two paleo-subduction zones in Tien Shan, Tajikistan. *Gondwana Research* 47, 110–130. https://doi.org/10.1016/j.gr.2016.09.010.

Konopelko D., Wilde S.A., Seltmann R., Romer R.L., Biske Yu.S., 2018. Early Permian intrusions of the Alai range: Understanding tectonic settings of Hercynian post-collisional magmatism in the South Tien Shan, Kyrgyzstan. *Lithos* 302–303, 405–420. https://doi.org/10.1016/j.lithos.2018.01.024.

Kotler P.D., Khromykh S.V., Smirnov S.Z., D'yachkov B.A., Travin A.V., Vladimirov A.G., Yudin D.S., Kruk N.N., 2014. Ar-Ar isotopic dating of rare-metal pegmatites of the Kalba-Narym granite batholith (Eastern Kazakhstan). In: Granites and Earth's evolution: granites and continental crust. Proceedings of the 2nd International Geological Conference. IGM SB RAS, Novosibirsk, p. 104–105.

Kotler P.D., Khromykh S.V., Vladimirov A.G., Navozov O.V., Travin A.V., Karavaeva G.S., Kruk N.N., Murzintsev N.G., 2015. New data on the age and geodynamic interpretation of the Kalba-Narym granitic batholith, Eastern Kazakhstan. *Doklady Earth Sciences* 462 (2), 565–569. https://doi.org/10.1134/S1028334X15060136.

Kozlovsky A.M., Yarmolyuk V.V., Salnikova E.B., Travin A.V., Kotov A.B., Plotkina Ju.V., Kudryashova E.A., Savatenkov V.M., 2015. Late Paleozoic anorogenic magmatism of the Gobi Altai (SW Mongolia): Tectonic position, geochronology and correlation with igneous activity of the Central Asian Orogenic Belt. *Journal of Asian Earth Sciences* 113, 524–541. https://doi.org/10.1016/j.jseaes.2015.01.013.

Kuzmin M.I., Yarmolyuk V.V., 2014. Mantle plumes of Central Asia (Northeast Asia) and their role in forming endogenous deposits. *Russian Geology and Geophysics* 55 (2), 120–143. https://doi.org/10.1016/j.rgg.2014.01.002.

Levashova N.M., Van der Voo R., Abrajevitch A.V., Bazhenov M.L., 2009. Paleomagnetism of mid-Paleozoic subduction-related volcanics from the Chingiz Range in NE Kazakhstan: the evolving paleogeography of the amalgamating Eurasian composite continent. *Geological Society of America Bulletin* 121 (3–4), 555–573. https://doi.org/10.1130/B26354.1.

Li Y.Q., Li Z.L., Yu X., Langmuir Ch.H., Santosh M., Yang Sh.F., Chen H.L., Tang Zh.L., Song B., Zou S.Y., 2014. Origin of the Early Permian zircons in Keping basalts and magma evolution of the Tarim Large Igneous Province (northwestern China). *Lithos* 204, 47–58. https://doi.org/10.1016/j.lithos.2014.05.021.

Litvinovsky B.A., Zanvilevich A.N., Kalmanovich M.A., 1995. The repeated mixing and mingling of coeval syenite and basalt magmas and its role in petrogenesis: a case study in the Ust' Khilok pluton, Transbaikalia (Russia). *Petrology* 3 (2), 125–137.

Lopatnikov V.V., Izokh E.P., Ermolov P.V., Ponomareva A.P., Stepanov A.S., 1982. Magmatism and Metallogeny of the Kalba-Narym Zone, Eastern Kazakhstan. Nauka, Moscow, 248 p. (in Russian) [*Лопатников В.В., Изох Э.П., Ермолов П.В., Пономарева А.П., Степанов А.С.* Магматизм и рудоносность Калба-Нарымской зоны Восточного Казахстана. М.: Наука, 1982. 248 с.].

Mekhonoshin A.S., Kolotilina T.B., Vladimirov A.G., Sokol'nikova Yu.V., Doroshkov A.A., 2017. First data on the concentrations and distribution of noble metals in Ni-Cu sulfide ores of the South Maksut deposit (Eastern Kazakhstan). *Geodynamics & Tectonophysics* 8 (3), 515–519. https://doi.org/10.5800/GT-2017-8-3-0278.

Pirajno F., Seltmann R., Yang Y., 2011. A review of mineral systems and associated tectonic settings of northern Xinjiang, NW China. *Geosciences Frontiers* 2 (2), 157–185. https://doi.org/10.1016/j.gsf.2011.03.006.

Polyakov G.V., Izokh A.E., Borisenko A.S., 2008. Permian ultramafic-mafic magmatism and accompanying Cu-Ni mineralization in the Gobi-Tien Shan belt as a result of the Tarim plume activity. *Russian Geology and Geophysics* 49 (7), 455–467. https://doi.org/10.1016/j.rgg.2008.06.001.

Renna M.R., Tribuzio R., Tiepolo M., 2006. Interaction between basic and acid magmas during the latest stages of the post-collisional Variscan evolution: Clues from the gabbro-granite association of Ota (Corsica-Sardinia batholith). *Lithos* 90 (1–2), 92–110. https://doi.org/10.1016/j.lithos.2006.02.003.

Safonova I., Komiya T., Romer R.L., Simonov V., Seltmann R., Rudnev S., Yamamoto S., Sun M., 2018. Supra-subduction igneous formations of the Char ophiolite belt, East Kazakhstan. *Gondwana Research* 59, 159–179 https://doi.org/10.1016/j.gr.2018.04.001.

Safonova I.Y., Simonov V.A., Kurganskaya E.V., Obut O.T., Romer R.L., Seltmann R., 2012. Late Paleozoic oceanic basalts hosted by the Char suture-shear zone, Eastern Kazakhstan: Geological position, geochemistry, petrogenesis and tectonic setting. *Journal of Asian Earth Sciences* 49, 20–39. https://doi.org/10.1016/j.jseaes.2011.11.015.

Seltmann R., Konopelko D., Biske G., Divaev F., Sergeev S., 2011. Hercynian post-collisional magmatism in the context of Paleozoic magmatic evolution of the Tien Shan orogenic belt. *Journal of Asian Earth Sciences* 42 (5), 821–838. https://doi.org/10.1016/j.jseaes.2010.08.016.

Şengör A.M.C., Natal'in B.A., Burtman U.S., 1993. Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia. *Nature* 364 (6435), 299–304. https://doi.org/10.1038/364299a0.

Shcherba G.N., D'yachkov B.A., Nakhtigal G.P., 1976. The Zharma-Saur Metallogenic Belt. Nauka, Alma-Ata, 199 p. (in Russian) [*Щерба Г.Н., Дьячков Б.А., Нахтигаль Г.П.* Жарма-Саурский геотектоноген. Алма-Ата: Наука, 1976. 198 с.].

Shcherba G.N., D'yachkov B.A., Stuchevsky N.I., Nakhtigal G.P., Antonenko A.N., Lubetsky V.N., 1998. Great Altai (Geology and Metallogeny). Book 1. Geological Structure. Gylym, Almaty, 304 p. (in Russian) [*Щерба Г.Н., Дьячков Б.А., Стучевский Н.И., Нахтигаль Г.П., Антоненко А.Н., Любецкий В.Н.* Большой Алтай (геология и металлогения). Кн. 1. Геологическое строение. Алматы: Гылым, 1998. 304 с.].

Sokolova E.N., Smirnov S.Z., Khromykh S.V., 2016. Conditions of crystallization, composition, and sources of rare-metal magmas forming ongonites in the Kalba-Narym zone, Eastern Kazakhstan. *Petrology* 24 (2), 153–177. https://doi.org/10.1134/S0869591116020065.

Vladimirov A.G., Izokh A.E., Polyakov G.V., Babin G.A., Mekhonoshin A.S., Kruk N.N., Khlestov V.V., Khromykh S.V., Travin A.V., Yudin D.S., Shelepaev R.A., Karmysheva I.V., Mikheev E.I., 2013. Gabbro-granite intrusive series and their indicator importance for geodynamic reconstructions. *Petrology* 21 (2), 158–180. https://doi.org/10.1134/S0869591113020070.

Vladimirov A.G., Kruk N.N., Khromykh S.V., Polyansky O.P., Chervov V.V., Vladimirov V.G., Travin A.V., Babin G.A., Kuibida M.L., Khomyakov V.D., 2008. Permian magmatism and lithospheric deformation in the Altai caused by crustal and mantle thermal processes. *Russian Geology and Geophysics* 49 (7), 468–479. https://doi.org/10.1016/j.rgg.2008.06.006.

Vladimirov A.G., Kruk N.N., Rudnev S.N., Khromykh S.V., 2003. Geodynamics and granitoid magmatism of collision orogens. *Geologiya i Geofizika* (*Russian Geology and Geophysics*) 44 (12), 1321–1338.

Vorontsov A.A., Fedoseev G.S., Andryushchenko S.V., 2013. Devonian volcanism in the Minusa basin in the Altai-Sayan area: geological, geochemical, and Sr-Nd isotopic characteristics of rocks. *Russian Geology and Geophysics* 54 (9), 1001–1025. https://doi.org/10.1016/j.rgg.2013.07.016.

Wang B., Cluzel D., Jahn B-M., Shu L., Chen Y., Zhai Y., Branquet Y., Barbanson L., Sizaret S., 2014. Late Paleozoic pre- and syn-kinematic plutons of the Kangguer–Huangshan Shear zone: Inference on the tectonic evolution of the eastern Chinese north Tianshan. *American Journal of Science* 314 (1), 43–79. https://doi.org/10.2475/01.2014.02.

Wei X., Xu Y.-G., Feng Y.-X., Zhao J.-X., 2014. Plume-lithosphere interaction in the generation of the Tarim Large Igneous Province, NW China: geochronological and geochemical constraints. *American Journal of Science* 314 (1), 314–356. https://doi.org/10.2475/01.2014.09.

Wiebe R.A., 1973. Relations between coexisting basaltic and granitic magmas in a composite dike. *American Journal of Sciences* 273 (2), 130–151. https://doi.org/10.2475/ajs.273.2.130.

Windley B.F., Alexeiev D., Xiao W., Kröner A., Badarch G., 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society* 164 (1), 31–47. https://doi.org/10.1144/0016-76492006-022.

Xiao W.J., Han C.M., Yuan C., Sun M., Lin S.F., Chen H.L., Li Z.L., Li J.L., Sun S., 2008. Middle Cambrian to Permian subduction-related accretionary orogenesis of North Xinjiang, NW China: implications for the tectonic evolution of Central Asia. *Journal of Asian Earth Sciences* 32 (2–4), 102–117. https://doi.org/10.1016/j.jseaes.2007.10.008.

Xiao W.J., Huang B., Han Ch., Sun Sh., Li J., 2010. A review of the western part of the Altaids: A key to understanding the architecture of accretionary orogens. *Gondwana Research* 18 (2–3), 253–273. https://doi.org/10.1016/j.gr.2010.01.007.

Xiao W., Santosh M., 2014. The western Central Asian Orogenic Belt: a window to accretionary orogenesis and continental growth. *Gondwana Research* 25, 1429–1444. https://doi.org/10.1016/j.gr.2014.01.008.

Xu Y-G., Wei X., Luo Z-Y., Liu H-Q., Cao J., 2014. The Early Permian Tarim Large Igneous Province: Main characteristics and a plume incubation model. *Lithos* 204, 20–35. https://doi.org/10.1016/j.lithos.2014.02.015.

Yarmolyuk V.V., Kuzmin M.I., Ernst R.E., 2014. Intraplate geodynamics and magmatism in the evolution of the Central Asian Orogenic Belt. *Journal of Asian Earth Sciences* 93, 158–179. https://doi.org/10.1016/j.jseaes.2014.07.004.

Yu X., Yang S.F., Chen H.L., Chen Z.Q., Li Z.L., Batt G.E., Li Y.Q., 2011. Permian flood basalts from the Tarim Basin, Northwest China: SHRIMP zircon U–Pb dating and geochemical characteristics. *Gondwana Research* 20 (2–3), 485–497. https://doi.org/10.1016/j.gr.2010.11.009.

Yu X., Yang S.F., Chen H.L., Li Z.L., Li Y.Q., 2017. Petrogenetic model of the Permian Tarim Large Igneous Province. *Science China Earth Sciences* 60 (10), 1805–1816. https://doi.org/10.1007/s11430-016-9098-7.

Zagorsky V.Ye., Vladimirov A.G., Makagon V.M., Kuznetsova L.G., Smirnov S.Z., D'yachkov B.A., Annikova I.Yu., Shokalsky S.P., Uvarov A.N., 2014. Large fields of spodumene pegmatites in the settings of rifting and postcollisional shear–pull-apart dislocations of continental lithosphere. *Russian Geology and Geophysics* 55 (2), 237–251. https://doi.org/10.1016/j.rgg.2014.01.008.

Zhang Ch.L., Li Z.X., Li X.H., Xu Y.G., Zhou G., Ye H.M., 2010. A Permian large igneous province in Tarim and Central Asian orogenic belt, NW China: Results of a ca. 275 Ma mantle plume? *Geological Society of America Bulletin* 122 (11–12), 2020–2040. https://doi.org/10.1130/B30007.1.

Zhang Ch.L., Zou H.B., Yao Ch.Y., Dong Y.G., 2014. Origin of Permian gabbroic intrusions in the southern margin of the Altai Orogenic belt: A possible link to the Permian Tarim mantle plume? *Lithos* 204, 112–124. https://doi.org/10.1016/j.lithos.2014.05.019.

INFORMATION ABOUT AUTHORS | СВЕДЕНИЯ ОБ АВТОРАХ

Sergei V. Khromykh
Candidate of Geology and Mineralogy, Senior Researcher

V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of RAS
3 Academician Koptyug ave, Novosibirsk 630090, Russia

Novosibirsk State University
2 Pirogov street, Novosibirsk 630090, Russia

e-mail: serkhrom@mail.ru
https://orcid.org/0000-0001-5951-0660

Сергей Владимирович Хромых
канд. геол.-мин. наук, с.н.с.

Институт геологии и минералогии им. В.С. Соболева СО РАН
630090, Новосибирск, просп. Академика Коптюга, 3, Россия

Новосибирский национальный исследовательский государственный университет
630090, Новосибирск, ул. Пирогова, 2, Россия

Pavel D. Kotler
Candidate of Geology and Mineralogy, Junior Researcher

V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of RAS
3 Academician Koptyug ave, Novosibirsk 630090, Russia

Novosibirsk State University
2 Pirogov street, Novosibirsk 630090, Russia

e-mail: pkotler@yandex.ru
https://orcid.org/0000-0002-9654-6889

Павел Дмитриевич Котлер
канд. геол.-мин. наук, м.н.с.

Институт геологии и минералогии им. В.С. Соболева СО РАН
630090, Новосибирск, просп. Академика Коптюга, 3, Россия

Новосибирский национальный исследовательский государственный университет
630090, Новосибирск, ул. Пирогова, 2, Россия

Andrey E. Izokh
Doctor of Geology and Mineralogy, Professor, Head of Laboratory

V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of RAS
3 Academician Koptyug ave, Novosibirsk 630090, Russia

Novosibirsk State University
2 Pirogov street, Novosibirsk 630090, Russia

e-mail: izokh@igm.nsc.ru

Андрей Эмильевич Изох
докт. геол.-мин. наук, профессор, заведующий лабораторией

Институт геологии и минералогии им. В.С. Соболева СО РАН
630090, Новосибирск, просп. Академика Коптюга, 3, Россия

Новосибирский национальный исследовательский государственный университет
630090, Новосибирск, ул. Пирогова, 2, Россия

Nikolai N. Kruk
Doctor of Geology and Mineralogy, Director of the Institute

V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of RAS
3 Academician Koptyug ave, Novosibirsk 630090, Russia

e-mail: kruk@igm.nsc.ru

Николай Николаевич Крук
докт. геол.-мин. наук, директор института

Институт геологии и минералогии им. В.С. Соболева СО РАН
630090, Новосибирск, просп. Академика Коптюга, 3, Россия