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# MARBLE MÉLANGE: COMPOSITION VARIATIONS AND FORMATION MECHANISMS

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**ABSTRACT.** The Olkhon terrane in the Western Baikal area accommodates four types of carbonate-silicate mixtures: injection (protrusion), metamorphic-boudinated, mingling, and tectonite marble mélange. The outcrops of injection mélange consist of a carbonate matrix with inclusions of native silicic rocks found in the immediate vicinities, commonly cover large areas and lack any distinct linearity in the map view. Mélange of the metamorphic boudinage type comprises diopsidite and tremilote-diopsidite fragments in a dolomitic or calcite-dolomitic matrix. Its origin is apparently due to tectonism and related metamorphism of quartz sandstones in Neoproterozoic strata on the passive margin of the Siberian craton. Mingling mélange appears as calcite marble or carbonate-silicate (calciphyre) veins with metadolerite and granite inclusions of different sizes. The veins formed by intrusion of carbonate and silicate melt batches and subsequent fragmentation of silicate rocks that crystallized earlier. Marble tectonites localized in narrow zones record the late phase of ductile marble injection.

**KEYWORDS:** mélange; marble; strike-slip tectonics; metamorphism; deformation; Olkhon terrane

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# МРАМОРНЫЙ МЕЛАНЖ: ВАРИАЦИИ СОСТАВА И МЕХАНИЗМЫ ОБРАЗОВАНИЯ

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**АННОТАЦИЯ.** В пределах Ольхонского террейна (Западное Прибайкалье) выделены и охарактеризованы четыре типа «мраморно-силикатных смесей», для которых мы используем термин «меланж»: инъекционный (протрузивный), метаморфогенно-разлинзованный, инъекционно-минглинговый и мраморные тектониты. Для инъекционного (протрузивного) типа меланжа характерны проявления, занимающие значительные площади и не имеющие в плане отчетливой линейной (пластовой) конфигурации, в качестве включений в карбонатном матриксе всегда находятся фрагменты силикатных пород, присутствующих в ближайшем окружении. Метаморфогенно-разлинзованный тип меланжа характеризуется присутствием фрагментов диопсидитов и тремолит-диопсидовых пород в доломитовом или кальцит-доломитовом матриксе. Его образование объясняется тектонометаморфическим преобразованием кварцевых песчаников неопротерозойских осадков пассивной окраины Сибирского кратона. Инъекционно-минглинговый тип меланжа представлен жильными телами кальцитовых мраморов или карбонатно-силикатных пород (кальцифиров) с разноразмерными фрагментами метаморфизованных долеритов и гранитов. Они образовались в результате внедрения порций карбонатного и силикатного расплавов с последующим фрагментированием закристаллизовавшихся раньше силикатных пород. Мраморные тектониты фиксируют позднюю стадию инъекционного внедрения мраморов в вязкопластическом состоянии, локализуясь в узких зонах в пределах мраморного меланжа.

**КЛЮЧЕВЫЕ СЛОВА:** меланж; мрамор; Ольхонский террейн; сдвиговый тектогенез; метаморфизм; деформации

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## 1. INTRODUCTION

In 1993 Valentin S. Fedorovsky and his co-authors [Fedorovsky et al., 1993] described a previously unknown type of geological mélange occurring as marble bodies with mm to n·10 m inclusions of silicate rocks in the Olkhon terrane, Western Baikal area. Surprisingly, the Western Baikal area remains the only known location where marble mélange is quite abundant: such mélange has never been reported from elsewhere since that publication. The Olkhon terrane may be exceptional in this respect, though the lack of reports may have other causes. First, the term *marble mélange* may be met with criticism because silicate inclusions in marbles have been traditionally attributed to boudinage of originally sedimentary or volcanosedimentary silicate layers amidst less competent carbonates. This formation mechanism of carbonate-silicate mixtures in metamorphic complexes appears quite realistic, which would give no motives for search of other explanations. Another reason may be that [Fedorovsky et al., 1993] published in a Russian journal "Geotectonics" poorly known in the international community. Finally, and most importantly, the description of the Olkhon silicate-carbonate mixtures and the explanation of their origin by [Fedorovsky et al., 1993] possibly mismatched the idea of mélange other people would have, as the term itself still has ambiguous definitions. The question whether *mélange* is the right term for the carbonate-silicate mixtures from Olkhon terrane, which have been studied for decades, requires separate discussion. It is reasonable, however, to start with their characteristics. Following [Fedorovsky et al., 1993], we apply the terms *marble mélange* and *carbonate-silicate mixture* to carbonate rocks with silicate inclusions of different sizes.

Comprehensive studies for almost thirty years since the first report [Fedorovsky et al., 1993] have revealed several types of marble mélange occurrences in the Olkhon terrane. They apparently originated by different mechanisms, but none would correspond to the classical boudinage. More precisely, boudinage did work in this case, but not as metamorphism or deformation of the primary volcanosedimentary material which would cause syntectonic fragmentation of silicate layers. In this paper, we describe four types of marble mélange in the Olkhon terrane and try to reveal their formation mechanisms.

## 2. OLKHON TERRANE: GEOLOGICAL BACKGROUND

The Olkhon block has been termed in different ways: terrane, composite terrane, superterrane, collisional system, or accretionary-collisional system [Fedorovsky et al., 1995, 2017, 2020; Sklyarov, 2005; Dobretsov, Buslov, 2007; Fedorovsky, Sklyarov, 2010; Buslov, 2011, 2014; Donskaya et al., 2017; Sklyarov et al., 2020; etc.]. We here choose the term *terrane*, which is short and broadly used, more so that neither its tectonic setting nor its evolution are in focus.

For the decades of studies, the interpretation of metamorphic complexes in Olkhon Island and its surroundings in the western Baikal coast (Olkhon area) changed from high-grade Early Precambrian volcanosedimentary rocks that retained their primary stratification [Pavlovsky, Eskin, 1964; Eskin et al., 1979; etc.] to an ensemble of tectonic elongate fault block differing in origin and age, which underwent magmatism and metamorphism between 500 and 460 Ma [Fedorovsky, Sklyarov, 2010; Donskaya et al., 2017; and references therein]. The Olkhon terrane is a part of the Early Paleozoic Baikal collisional belt [Donskaya et al., 2000] that delineates the Siberian craton in the south (Fig. 1).

In the first approximation, it comprises two major lithological units interpreted previously as metamorphic volcanosedimentary sequences [Pavlovsky, Eskin, 1964]: (i) Olkhon Group of gneisses, with less abundant marbles, amphobolites, and quartzites cut by gabbro and granite intrusions and numerous pegmatitic-aplitic veins; and (ii) Anga Group of carbonates, amphibolites, and gabbro (the latter occupying more than 50 % of the total volume). This division actually holds at present, but the interpretation of the two units has changed notably (Fig. 2). The Anga Group (marbles and amphibolites in Fig. 2) corresponds to the Krestovsky subterrane, whereas the remaining part of the Olkhon terrane is rather a collage

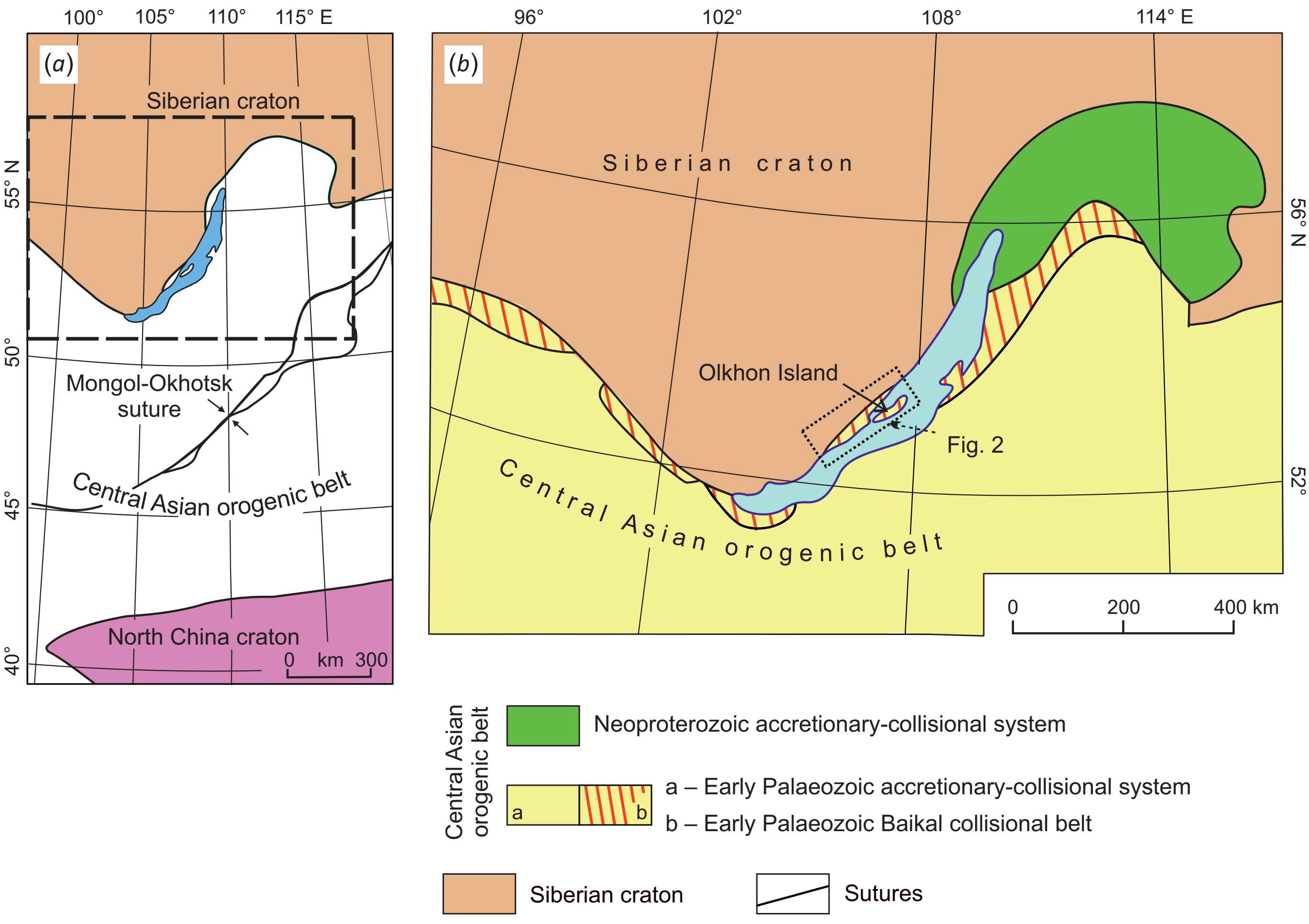


**Fig. 1.** Simplified tectonics of Central Asia (*a*) and metamorphic terranes in the Early Palaeozoic Baikal collisional belt of northern CAOB (*b*), modified from [Donskaya et al., 2017].

**Рис. 1.** Тектоническая схема Центральной Азии (*a*) и схема метаморфических террейнов в обрамлении Сибирского кратона (*b*) (по [Donskaya et al., 2017], с изменениями).

of several large blocks derived from protoliths of different ages and settings [Donskaya et al., 2017]. According to the ideas of [Fedorovsky et al., 1995], the terrane formed in several events of thrusting, doming, and strike-slip faulting, with syntectonic high-temperature metamorphism and intrusions of mafic and granitic magmas. The largely described rocks that represent the three tectonic events formed in the Early Paleozoic as a result of microcontinent-island arc and microcontinent-continent collisions [Sklyarov, 2005; Fedorovsky, Sklyarov, 2010]. The tectonic framework of the Olkhon area shaped up during large-scale strike-slip faulting that produced shear zones differing in composition, morphology, and structure.

The terrane rocks underwent at least two metamorphic events under different P-T conditions [Sklyarov et al., 2020]. Granulite-facies metamorphism, about 500 Ma [Gladkochub et al., 2008], was restricted to a narrow zone along the collisional suture between the Olkhon terrane and the Siberian craton. Metamorphic facies over the greatest part of terrane vary from granulite to low-amphibolite and correlate with 460–470 Ma collisional events [Volkova et al., 2010; Sklyarov et al., 2020].

Carbonate (calcitic, dolomite-calcitic, and dolomitic marbles) and carbonate-silicate (calciphyre) rocks occupy about 20 vol. % of the total Olkhon collisional zone (Fig. 3). Marbles often occur as relatively thin (10–100 m) kilometers long sheets, which were often interpreted as a simple slightly deformed sequence of metamorphic volcanicsedimentary rocks. However, the apparent simplicity of the sequence obviously contradicts the structural data and the presence of numerous shear zones mapped in the area to a high resolution [Fedorovsky, Sklyarov, 2010]. Carbonate rocks are often mixed with quartzite and mafic rocks (amphibolite or granulite) in complex irregularly shaped bodies, which made us [Sklyarov et al., 2013a] hypothesize previously an exotic origin for most of carbonate lithologies in the area. On the other hand, it is fair to note that, according to [Fedorovsky et al., 1993], no more than a half of all marble bodies have preserved their original stratigraphic position, while the others became involved in tectonic protrusion and thrusting.

## 3. COMPOSITION, STRUCTURE, AND OCCURRENCE OF MARBLE MÉLANGE

Before characterizing the carbonate-silicate complexes of the Olkhon terrane, it is pertinent to summarize main postulates of [Fedorovsky et al., 1993] as a basis for further consideration.

– Marble mélange is composed of white or grey fine- to coarse-grained marble matrix that encloses small to large fragments (mm to n·10 m) of silicate rocks or less often other marbles that differ from the matrix in color and structure.

– The silicate inclusions are compositionally diverse: mafic granulite, gneisses, amphibolite, metamorposed gabbro and dolerite, granite, calciphyre, quartzite, and various metasomatic rocks produced by carbonate-silicate interactions. Importantly, the inclusions are of native origin and are never exotic rocks absent from the terrane: e.g., granulite occurrences are within zones of granulite metamorphism.

– The mélange matrix mainly consists of calcitic marble, with less abundant calciphyre, and contains up to 30 % of silicate material; dolomites and dolomitic-calcitic marbles are much rarer.

– Marble mélange can occur either as long layers and lenses or as irregularly shaped bodies from tens of meters to a few kilometers in size.

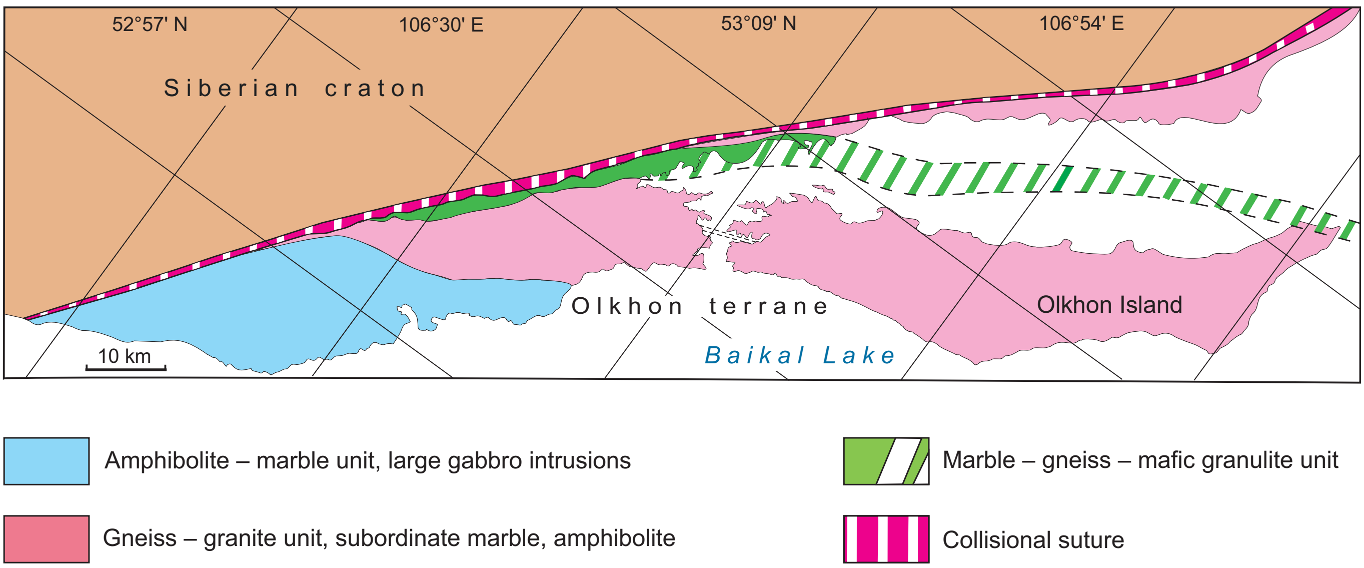


**Fig. 2.** Simplified tectonics of the Olkhon terrane, modified after [Donskaya et al., 2017].

**Рис. 2.** Упрощенная тектоническая схема Ольхонского террейна (по [Donskaya et al., 2017], с изменениями).

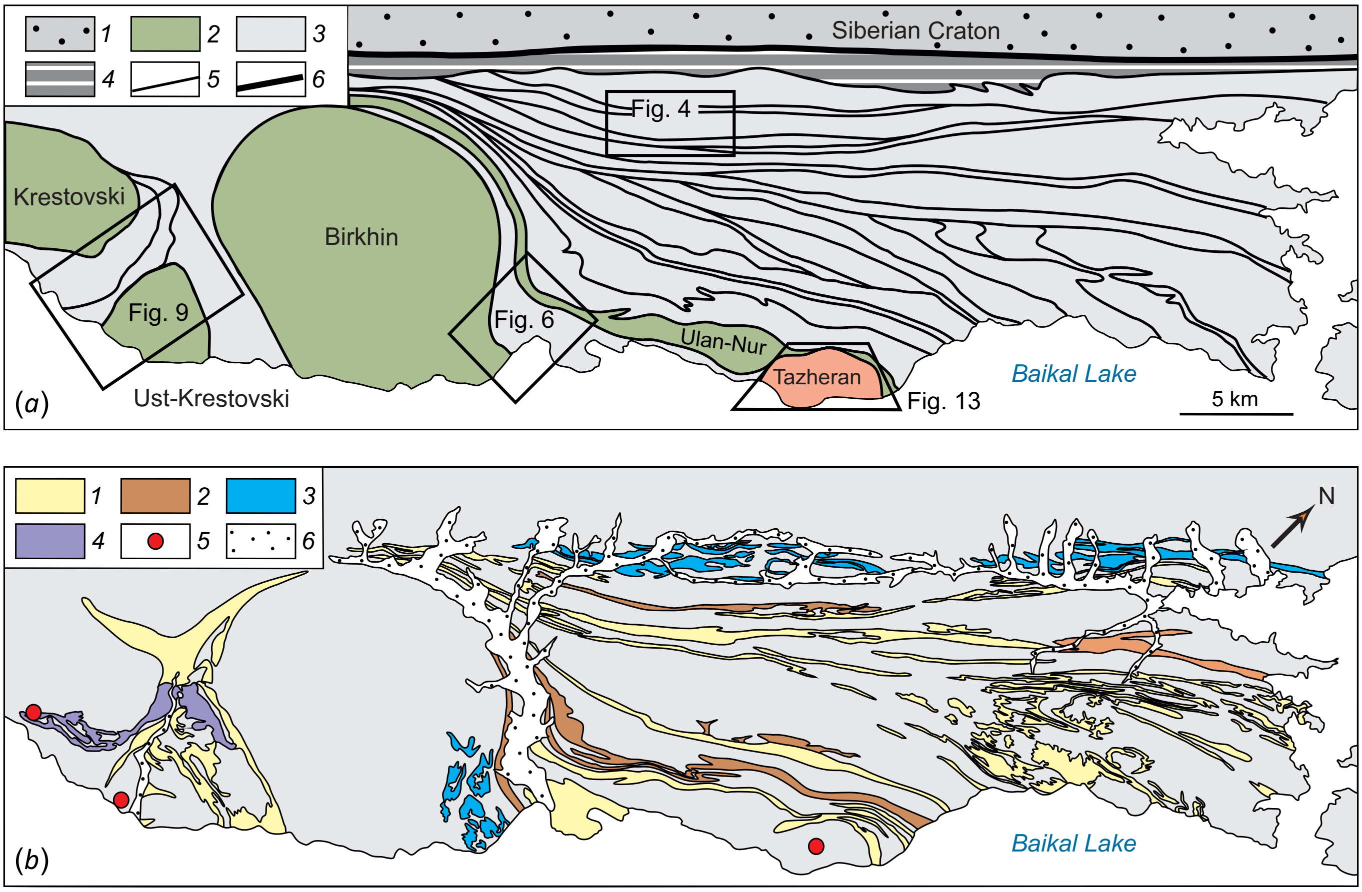


**Fig. 3.** Main shear zones (*a*) and carbonate rocks (*b*) of the central Olkhon terrane.
(*a*): *1* – Early Precambrian complexes of the Siberian craton; *2* – large gabbro intrusions; *3* – metamorphic complexes of the Olkhon terrane; *4* – Early Paleozoic collisional suture zone; *5* – shear zones; *6* – Cenozoic suture. (*b*): *1* – calcite marble; *2* – dolomite and calcite-dolomite marbles; *3* – injection mélange; *4* – metamorphic-boudinated mélange; *5* – mingling mélange; *6* – recent alluvium.
**Рис. 3.** Схема основных сдвигов (*a*) и распространения карбонатных пород (*b*) центральной части Ольхонского террейна.
(*a*): *1* – раннедокембрийские образования Сибирского кратона; *2* – крупные массивы габбро; *3* – метаморфические комплексы Ольхонского террейна; *4* – раннепалеозойский коллизионный шов; *5* – вязкопластические сдвиги; *6* – кайнозойский шов. (*b*): *1* – кальцитовые мраморы; *2* – доломитовые и кальцит-доломитовые мраморы; *3* – инъекционный тип меланжа; *4* – метаморфогенно-разлинзованный тип меланжа; *5* – инъекционно-минглинговый тип меланжа; *6* – современные алювиальные отложения.

– Marble mélange can be interpreted as a sort of protrusion rooted deep in the crust. Their origin is due to local pressure increase, possibly, as a result of strike-slip faulting at high strain rates.

– The Olkhon carbonate-silicate mixtures generally fit the definition of mélange (see below).

The structure and composition of marble mélange were studied in detail for the case of the Tonta zone of granulite metamorphism and two zones of low-amphibolite metamorphism within the Krestovsky subterrane: Anga – Begul interfleuve and Shirokaya Pad' valley. Indeed, marble mélange is especially widespread in the Tonta zone and in the Krestovsky subterrane, though being present elsewhere as well. Recent studies have extended the inventory of marble mélange occurrences and allowed distinguishing four types, which can be conventionally called injection (protrusion), metamorphic-boudinated, mingling mélanges and marble tectonite. Below the four types are described separately and their designations are considered further in Discussion.

### 3.1. Injection (protrusion) mélange

Marble mélange of this type typically occurs in a perfectly exposed plateau between the Tonta and Ulan-Khargana localities (Fig. 4), within a belt of compositionally diverse granulite-facies metamorphic rocks. About a half of all carbonate bodies are linear and are located among pyroxene and two-pyroxene mafic granulites, gneisses, and quartzites. Linear carbonate bodies often enclose small to large fragments of various silicate rocks and crosscut the gneiss and quartzite structures. Inclusions in marble mélange compositionally correspond to native rocks from the immediate vicinities. The other half of mélange bodies appear as large nonlinear features with tortuous contours in the plan view.

The silicate inclusions in the carbonate matrix are from a few centimeters to a few meters in size (Fig. 5, a, b), though thin mélange bodies quite often coat rather big silicate blocks up to hundreds of meters long. Locally, marbles appear as tongues in silicate rocks, with cm thick reaction rims at the contact (Fig. 5, c). At most of the documented mélange sites, the carbonate matrix is structurally homogeneous. The grain sizes vary from fine to coarse, both within a single mélange body or between different bodies. The carbonate rocks often lack signatures of plane or linear elements; less frequently they enclose fragments of different sizes with typical tectonite structures (see below). The amounts of silicate inclusions in marbles vary from 70 vol. % to almost zero.

The Anga – Begul interfleuve, another site of this mélange type (Fig. 6), is composed mainly of the Begul metagabbro compositionally different from all other gabbro in the area. Calcitic marble, commonly fine-grained, is the second most widespread lithology in the Begul area. Quite many marble bodies have linear shapes delineated by thin veins or quartz lenses. The marbles lack silicate inclusions in the western part of the area but often enclose 2–3 m to 40–50 m metagabbro fragments (Fig. 7, a) in the central and southeastern parts. Gabbro inclusions become more abundant toward the marble-gabbro contacts, but are generally within 5 vol. % relative to all carbonate bodies. The gabbro fields include tens of meters long marble fragments, which look elongate in outcrops but are of unknown actual geometry because of poor exposure.

Injection marble mélange (Fig. 7, b, c) is also widespread in northern Olkhon Island, as linear bodies from a few meters to tens of meters long. In most cases, they have foliated structure, with bands of marbles containing greater or smaller amounts of fine silicate

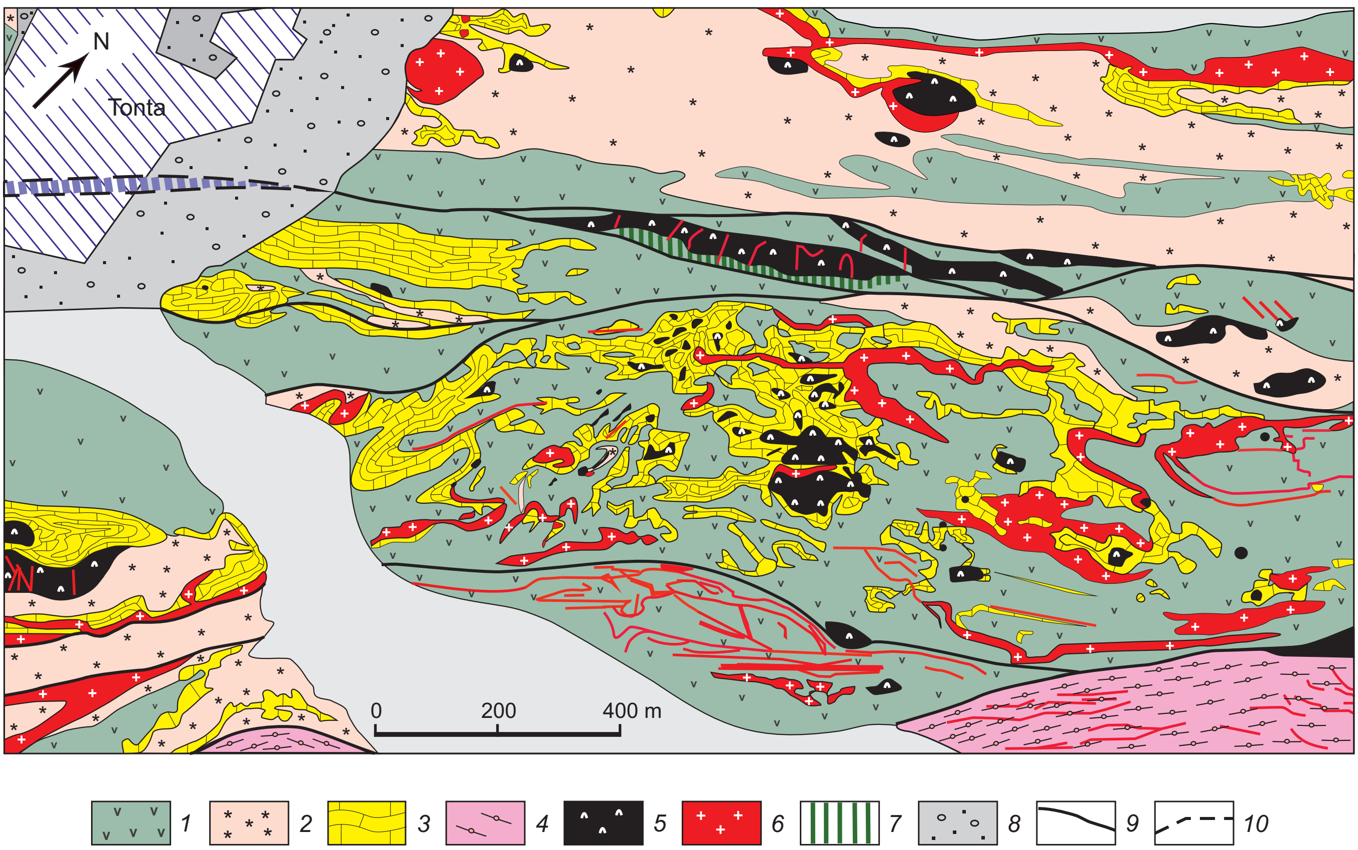


**Fig. 4.** Aerospace geological map of the southwestern Chernorud and Tonta zones. A fragment [Fedorovsky et al., 2012].
*1* – hyperthene and two-pyroxene gneiss and mafic granulite; *2* – quartzite; *3* – marble mélange; *4* – biotite and garnet-biotite gneisses; *5* – fassaite pyroxenite and gabbro; *6* – synmetamorphic granite; *7* – skarn and skarnoids; *8* – Quaternary glacial boulders and gravity sliding features; *9* – geologic boundaries; *10* – sutures.

**Рис. 4.** Фрагмент аэрокосмической геологической карты юго-западной части зон Черноруд и Томота Ольхонского региона (по [Fedorovsky et al., 2012]).
*1* – гиперстеновые, двупироксеновые гнейсы и базитовые гранулиты; *2* – кварциты; *3* – мраморный меланж; *4* – биотитовые, гранат-биотитовые гнейсы; *5* – фассаитовые метапироксениты и метагаббро; *6* – синметаморфические граниты; *7* – скарны и скарноиды; *8* – четвертичные гляциогравитационные валунники; *9* – геологические границы; *10* – сутуры.

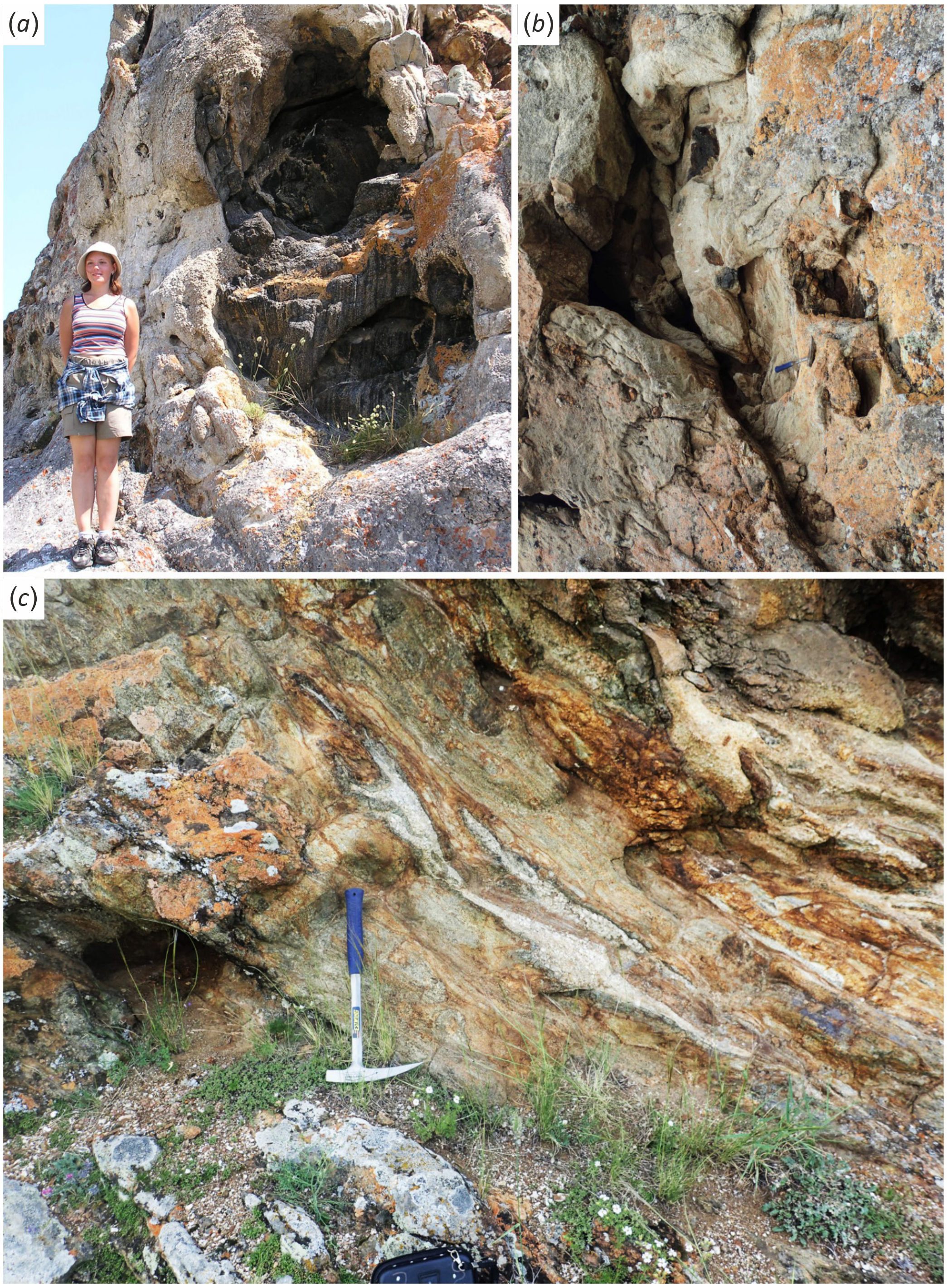

**Fig. 5.** Marble mélange in the Tonta zone.
(*a*) – large fragment of mafic granulite in massive coarse-grained calcite marble; (*b*) – mafic granulite, pyroxene gneiss, metagabbro, and granite inclusions in medium-grained calcite marble; (*c*) – injections of medium-grained calcite marble in pyroxene gneiss, with a marble-gneiss pyroxene reaction zone.

**Рис. 5.** Детали мраморного меланжа участка Тонта.
(*a*) – крупный фрагмент мафитовых гранулитов в крупнозернистых мраморах; (*b*) – мелкие фрагменты (от первых сантиметров до десятков сантиметров) мафитовых гранулитов, пироксеновых гнейсов, метагаббро и гранитов в среднезернистых мраморах; (*c*) – инъекции среднезернистых мраморов в пироксеновых гнейсах, на контакте мрамора и гнейса реакционная кайма существенно пироксенового состава.

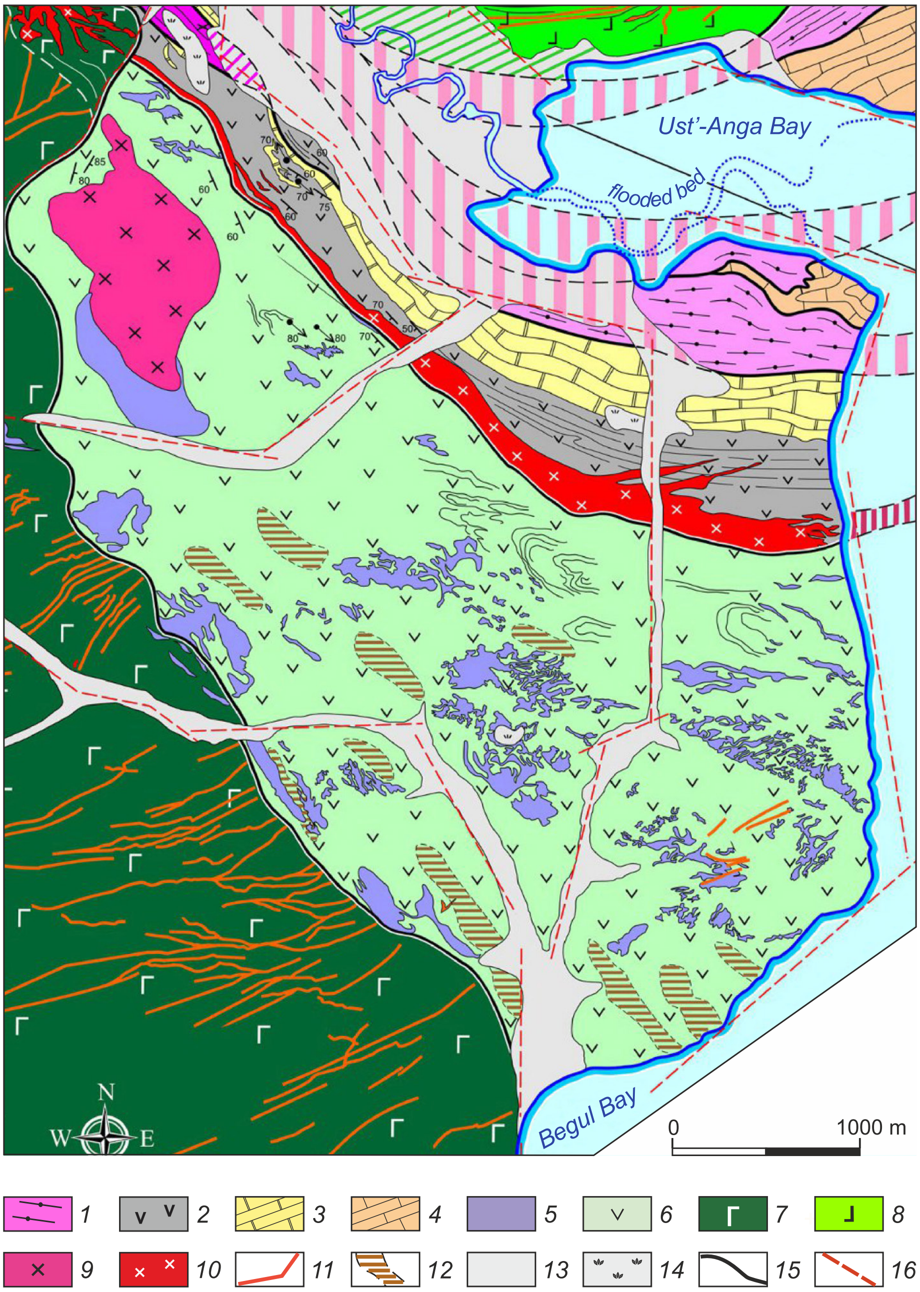


**Fig. 6.** Aerospace geological map of the Anga – Begul interfluve (Baikal). Right Anga zone. A fragment [Sklyarov et al., 2013b].

*1* – fine-grained Bt-Ms and Grt-Bt-Ms gneisses; *2* – foliated amphibolite; *3* – dolomitic and calcite-dolomitic marbles; *4* – calcite marble; *5* – injected calcitic rocks; *6* – microgabbro and amphibolite after them; *7* – Birkhin complex of monzogabbro, monzogabbronorite, and monzodiorite; *8* – amphibolite and mafic blastomylonite after Birkhin gabbro; *9* – Maly Krestovsky complex of Bt-diorite and granodiorite; *10* – Aya complex of Bt, Grt-Bt, Grt-Bt-Ms aplite, granite, and less abundant pegmatite; *11* – Upper Birkhin complex of Bt, Grt-Bt aplite, granite, and pegmatite; *12* – zones of synmetamorphic metasomatism; *13* – recent alluvium; *14* – Cenozoic geyserite; *15* – large strike-slip faults; *16* – Cenozoic faults.

**Рис. 6.** Фрагмент аэрокосмической геологической карты междуречья Анга – Бегул (Байкал). Зона Правая Анга (по [Sklyarov et al., 2013b]).

*1* – биотит-мусковитовые, гранат-биотит-мусковитовые микрогнейсы; *2* – тонкоплитчатые амфиболиты; *3* – доломитовые и кальцит-доломитовые мраморы; *4* – кальцитовые мраморы; *5* – инъекционные карбонатные (кальцитовые) породы; *6* – микрогаббро и амфиболиты по ним; *7* – Бирхинский комплекс: монцогаббро, монцогаббро-нориты, монцодиориты; *8* – амфиболиты и базитовые бластомилониты по габброидам Бирхинского комплекса; *9* – малокрестовский комплекс: биотитовые диориты и гранодиориты; *10* – Аинский комплекс: биотитовые, гранат-биотитовые, гранат-биотит-мусковитовые аплиты, граниты, реже пегматиты; *11* – Верхнебирхинский жильный комплекс: биотитовые, гранат-биотитовые аплиты, граниты, реже пегматиты; *12* – зоны синметаморфической метасоматической проработки; *13* – современные аллювиальные отложения; *14* – гейзериты; *15* – основные сдвиги; *16* – кайнозойские разломы.

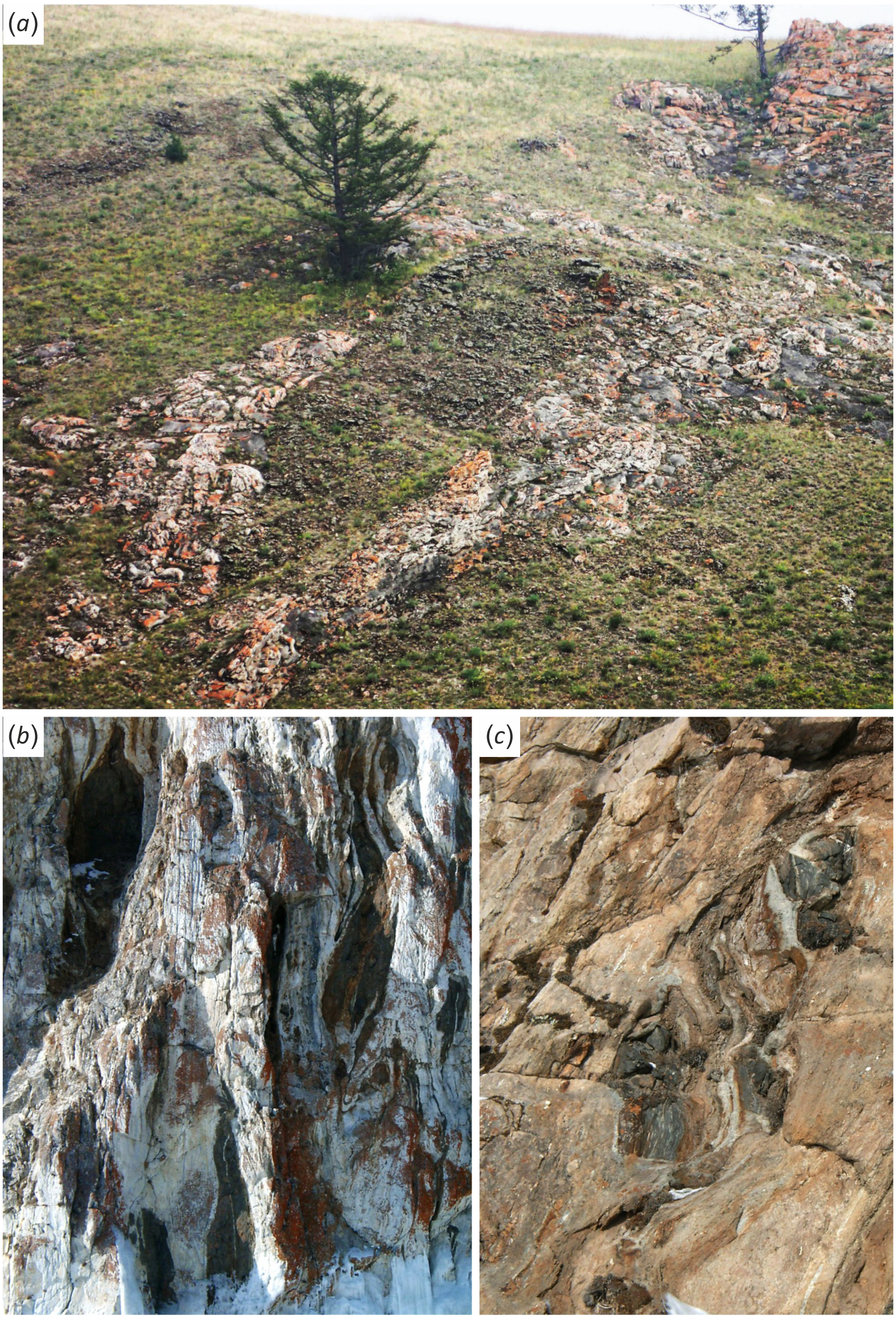


**Fig. 7.** Marble mélange in the Begul zone and in northern Olkhon Island.
(*a*) – metagabbro block (20×5 m) in calcite marble, Begul zone; (*b*, *c*) – lenses of amphibolite and amphibole gneiss in calcite marble (*b*) and fragments of amphibolite in calc-silicate rocks (*c*), Olkhon Island.

**Рис. 7.** Детали мраморного меланжа на участке Бегул (а) и на севере о. Ольхон (*b*, *c*).
(*a*) – крупный фрагмент метагаббро (20×5 м) в кальцитовом мраморе; (*b*) – линзовидные фрагменты амфиболитов и амфиболовых гнейсов в кальцитовом мраморе; (*c*) – фрагменты амфиболитов в полосчатых силикатно-карбонатных породах (кальцифирах).

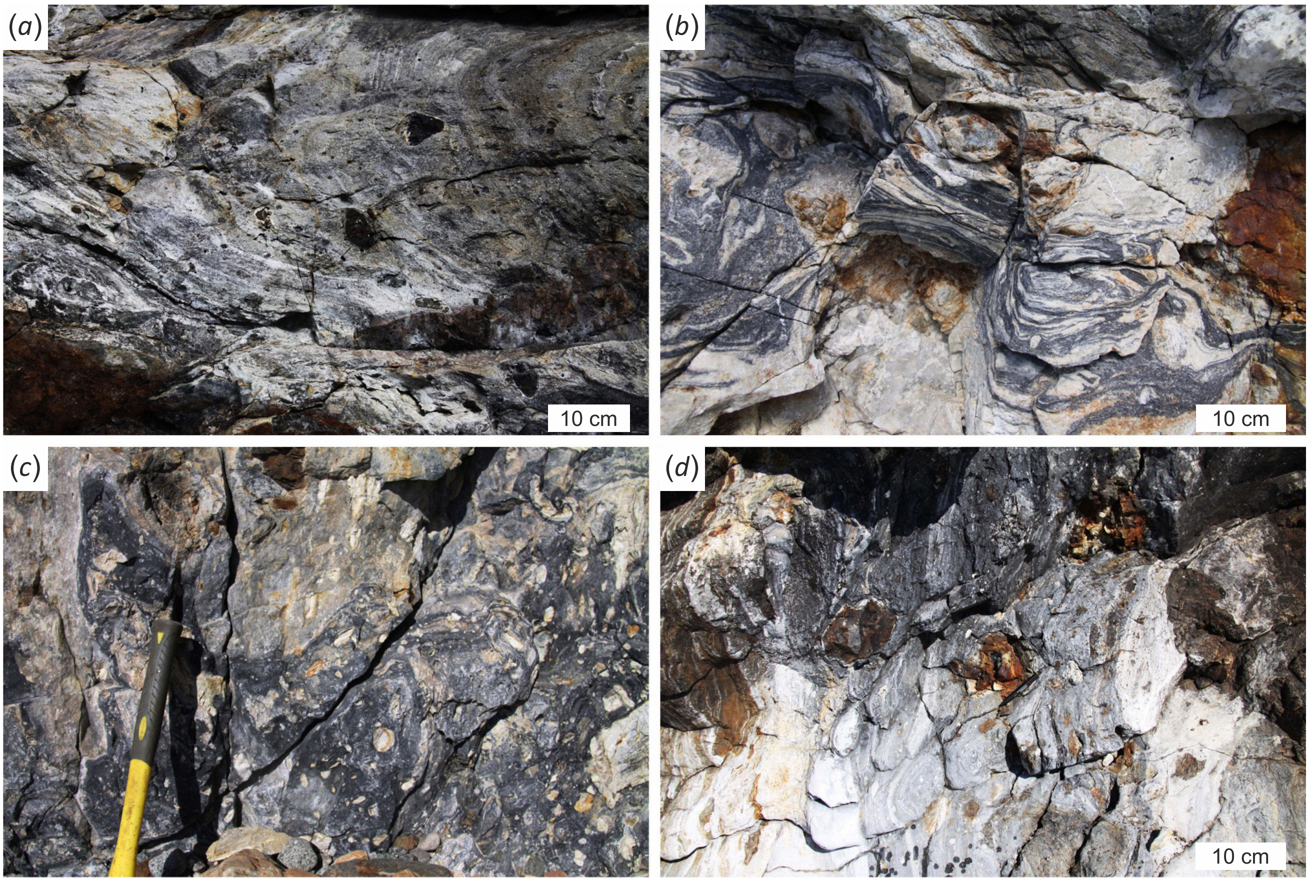


**Fig. 8.** Marble tectonites (Shirokaya Valley).
(*a*) – flow fold in marble tectonite, with mainly amphibolitic inclusions; (*b*) – foliated marble tectonite, with intercalated graphite-rich and graphite-poor bands, with mainly granitic large inclusions; (*c*) – complex ductile structures in graphite-rich marble tectonite, with mainly quartz and granitic inclusions; (*d*) – foliated marble tectonite, with metadolerite, granite, quartz, and skarned mafic inclusions.

**Рис. 8.** Детали структуры мраморных тектонитов (падь Широкая).
(*a*) – складка течения в полосчатых мраморных тектонитах; во фрагментах силикатных пород резко преобладают амфиболиты; (*b*) – полосчатость в мраморных тектонитах, обусловленная чередованием богатых и бедных мелкой сыпью графита мраморов; в более крупных фрагментах преобладают граниты; (*c*) – сложные вязкопластичные структуры в богатых графитом мраморных тектонитах; во фрагментах преобладают кварц и граниты; (*d*) – полосчатые мраморные тектониты, в обломках метадолериты, граниты, кварц, скарнированные метабазиты.

clasts or boudin-like amphibolite and calciphyre inclusions.

### 3.2. Marble tectonites

Carbonate-silicate rocks we call marble tectonites occur at all sampled marble sites and look like mylonites or blastomylonites, with abundant small inclusions of various silicate rocks (metadolerite, granite, and quartz aggregates) in foliated marble (Fig. 8). Unlike the injection mélange, tectonites appear as linear bodies, ≥20 cm thick or, rarely reaching a few meters. In few cases, they fill zones between silicate blocks but quite often occur among the injection marble mélange as 20–40 cm thick zones, occasionally as thick as 1–2 m. The silicate inclusions in the marble matrix coexist with newly formed silicate minerals: forsterite, diopside, amphibole or phlogopite, and rarely plagioclase or feldspar.

### 3.3. Metamorphic-boudinated mélange

Carbonates of this mélange type are diverse dolomitic and calcite-dolomitic marbles, diopsidite, quartz-diopside, or diopseide-calcite-dolomite rocks in a tectonic slice within the Krestovsky island arc subterrane, whereas those in the remainder part of the subterrane are limited to calcitic marble and calciphyre. The tectonic slice has an S-shaped geometry and is heterogeneous in structure and composition changing in the E–W direction (Fig. 9).

In its easternmost part, the tectonic slice is composed of dolomitic and calcite-dolomitic marbles with sporadic patches containing fine prismatic tremolite. In the central part of the tectonic slice, almost monomineralic coarse diopsidite, with numerous quartz veins and veinlets that often produce reticulate-banded patterns, crop out locally among dolomitic marble. The reticulate-banded structure is easily spotted on

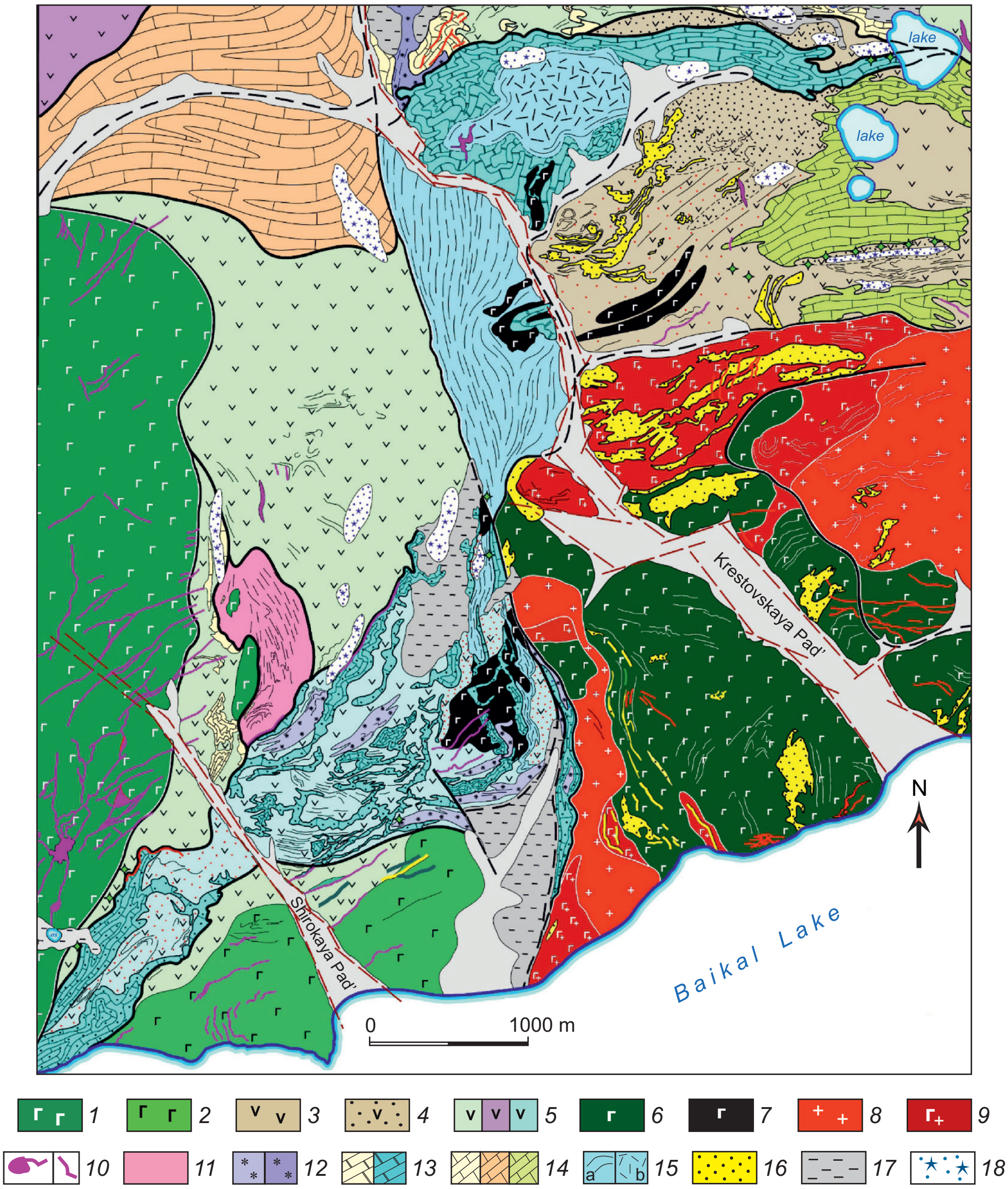


**Fig. 9.** Aerospace geological map of the southwestern Olkhon terrane. A fragment [Sklyarov et al., 2012].
*1–2* – Birkhin complex of phase (*1*) pyroxenite, olivine gabbro, gabbronorite, and anorthosite, and phase (*2*) monzogabbro and monzogabbronorite; *3* – metaporphyrite; *4* – sheared and metasomatized metaporphyrite; *5* – amphibolitized metaporphyrite in different tectonic zones; *6–7* – Ust'-Krestovsky complex of phase 1 phlogopite-bearing monzogabbro (*6*), phase 2 Ti-fassaite monzogabbro (*7*); *8* – biotite granodiorite and granite of the Maly Krestovsky complex; *9* – mingling dikes and intrusions; *10* – granite of the Upper Birkhinsky complex; *11* – biotite and garnet-biotite gneisses; *12* – quartzite; *13* – dolomite and calcite-dolomite marbles; *14* – calcite marble; *15* – diopside-calcite-dolomite (a) and quartz-diopside (b) rocks; *16* – injected calciphyre; *17* – Quaternary sediments; *18* – Cenozoic geyserite.

**Рис. 9.** Фрагмент аэрокосмической геологической карты юго-западной части Ольхонского региона (Байкал) (по [Sklyarov et al., 2012]).
*1–2* Бирхинский комплекс: пироксениты, оливиновые габбро, габбро-нориты, анортозиты и их амфиболизированные аналоги первой фазы (*1*) и монцогаббро, монцогаббро-нориты, монцодиориты и их амфиболизированные разности второй фазы (*2*); *3* – метапорфириты; *4* – метапорфириты интенсивно тектонизированные и метасоматизированные; *5* – амфиболиты по порфиритам из разных тектонических зон; *6–7* – Устькрестовский комплекс: флогопитовые монцогаббро первой фазы (*6*) и титанфассаитовые монцогаббро второй фазы (*7*); *8* – биотитовые гранодиориты и граниты Малокрестовского комплекса; *9* – комбинированные габбро-гранитные интрузии и дайки; *10* – граниты Верхнебирхинского комплекса; *11* – биотитовые и гранат-биотитовые гнейсы; *12* – кварциты; *13* – доломитовые и кальцит-доломитовые мраморы; *14* – кальцитовые мраморы; *15* – диопсид-кальцит-доломитовые (а) и мономинеральные диопсидовые и кварц-диопсидовые (b) породы; *16* – инъекционные кальцитовые и силикатно-карбонатные породы; *17* – четвертичные отложения; *18* – гейзериты.

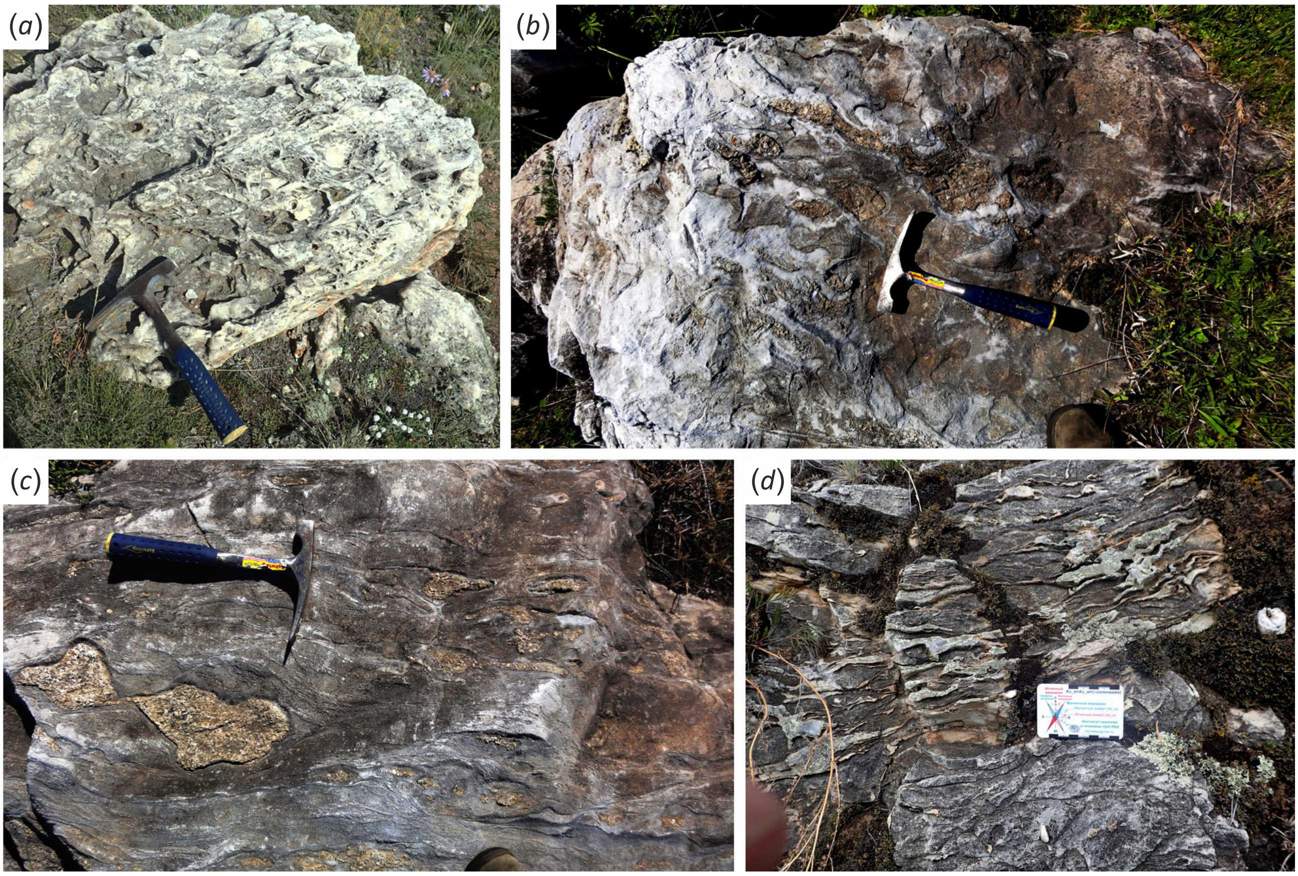


**Fig. 10.** Exposed quartz-diopside-calcite-dolomite rocks of the Olkhon terrane (*a, b, c*) and Neoproterozoic quartz-dolomite rocks of the Goloustnaya Fm. adjacent to the Olkhon terrane in the southwest (*d*).
(*a*) – quartz-diopside rock, reticulate-banded quartz framework and weathered surfaces of diopsides; (*b*, *c*) – diopsidite fragments in calcite-dolomitic matrix; (*d*) – dolomite with quartz layers.

**Рис. 10.** Детали структуры кварц-диопсид-кальцит-доломитовой толщи Ольхонского террейна (*a*, *b*, *c*) и кварц-доломитовой толщи голоустенской свиты, примыкающей на юго-западе к Ольхонскому террейну (*d*).
(*a*) – кварц-диопсидовая порода: сетчато-полосчатый каркас кварца и выветрелые на поверхности фрагменты диопсидитов; (*b*, *c*) – фрагменты диопсидитов в кальцит-доломитовом матриксе; (*d*) – доломиты с «прослоями» кварца.

the weathered surfaces (Fig. 10, a) as pits in the quartz framework in the place of diopside, which is more vulnerable to erosion. Diopside occurs as white (in the absence of iron) prismatic crystals from a few mm to 5 cm long; the percentage of quartz varies from 0 to 90 vol. %, and some quartz veins are up to 1 m thick. The quartz-diopside rocks have sharp contacts with dolomitic marble.

Dolomitic marble grades westward to quartz-diopside-calcite-dolomite and diopside-dolomite-calcite rocks with well-pronounced lineation, often associated with dolomitic marble, in the N–S segment of the S-shaped tectonic slice (see Fig. 9). Diopside and quartz-diopside inclusions form a sort of layers in the carbonate matrix but more often appear as boudin-like lenses, 1 to 20 cm wide and up to 1–2 m long (Fig. 10, b, c). In addition to diopside inclusions, some marble bodies enclose thin elongate quartz lenses. The rocks in the bend of the tectonic slice can be identified as a particular mélange type.

Carbonates in the NE-striking western part of the tectonic slice enclose coarse amphibolite, metadolerite, and quartzite fragments, from a few meters to tens of meters in size. Furthermore, marble tectonites crop out in coastal cliffs in the westernmost end of the tectonic slice, along the fault contact with the Krestovsky gabbro intrusion.

### 3.4. Mingling mélange

Mingling mélange occurs within the Krestovsky subterrane (see Fig. 9) and mainly consists of carbonate and calciphyre veins with metadolerite or less often granite inclusions. The structure of these rocks is especially prominent in cliff outcrops between the Krestovskaya and Shirokaya valleys, where several calcite marble and calciphyre veins (Fig. 11) were mapped along the margin of the Ust'-Krestovsky subalkaline gabbro intrusion [Lavrenchuk et al., 2017]. Some veins are associated with irregularly shaped pyroxene-bearing porphyritic dikes (Fig. 12, a), which

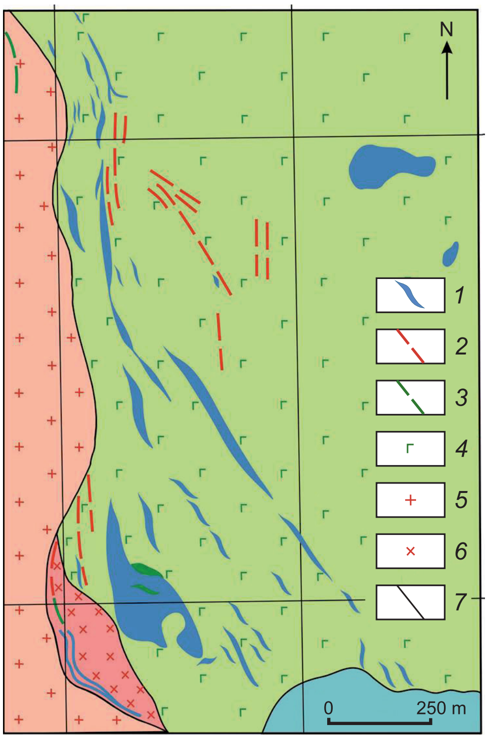


**Fig. 11.** Marble and calc-silicate dikes in gabbro of the Ust-Krestovsky Intrusion.
*1* – marble and calc-silicate dikes; *2* – granite veins; *3* – dolerite dikes; *4* – gabbro; *5* – granite; *6* – diorite; *7* – geological boundaries.

**Рис. 11.** Дайки карбонатных и карбонатно-силикатных пород в габбро Усть-Крестовского массива.
*1* – дайки карбонатных и карбонатно-силикатных пород; *2* – гранитные жилы; *3* – дайки и тела долеритов; *4* – габбро; *5* – граниты; *6* – диориты; *7* – геологические границы.

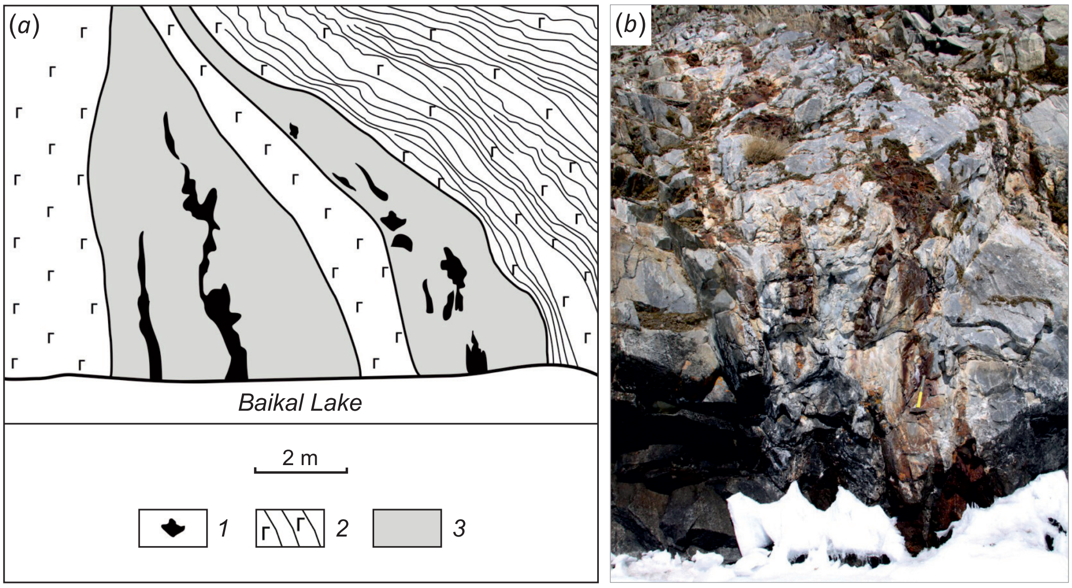


**Fig. 12.** Marble dikes associated with dolerite in gabbro of the Ust-Krestovsky Intrusion. Sketch from photograph (*a*) and photograph (*b*).
*1* – dolerite; *2* – gabbro with magmatic layering; *3* – fine-grained marble. (*a*) – two blind dolerite dikes in marble (left) and dolerite fragments in marble (right); (*b*) – reddish-brown dolerite fragments in marble (right part of the sketch).

**Рис. 12.** Дайки ассоциирующих с долеритами мраморов в габброидах Усть-Крестовского массива. Зарисовка с фотографии (*a*) и фотография (*b*).
*1* – долериты; *2* – габбро с элементами магматической расслоенности; *3* – мелкозернистые мраморы. (*a*) – в мраморной дайке справа две слепые дайки долеритов; (*b*) – на фотографии – фрагменты долеритов красно-коричневого цвета в дайке мраморов.

are occasionally fragmented (Fig. 12, b) and look like marble mélange.

Another variety of this mélange (Fig. 13) appears in the Tazheran complex [Konev, Samoilov, 1974; Sklyarov et al., 2009, 2013a, 2021; Fedorovsky et al., 2009, 2010; Starikova et al., 2014; Doroshkevich et al., 2016]. The complex is an intricate mixture of syenite, nepheline syenite, alkaline and subalkaline gabbro metamorphosed to different grades, brucite marble, and diverse metasomatic rocks, with a strip of dolomite-bearing calcite marble (Fig. 14) coexisting with fassaitic pyroxenite and nepheline-pyroxene rocks in

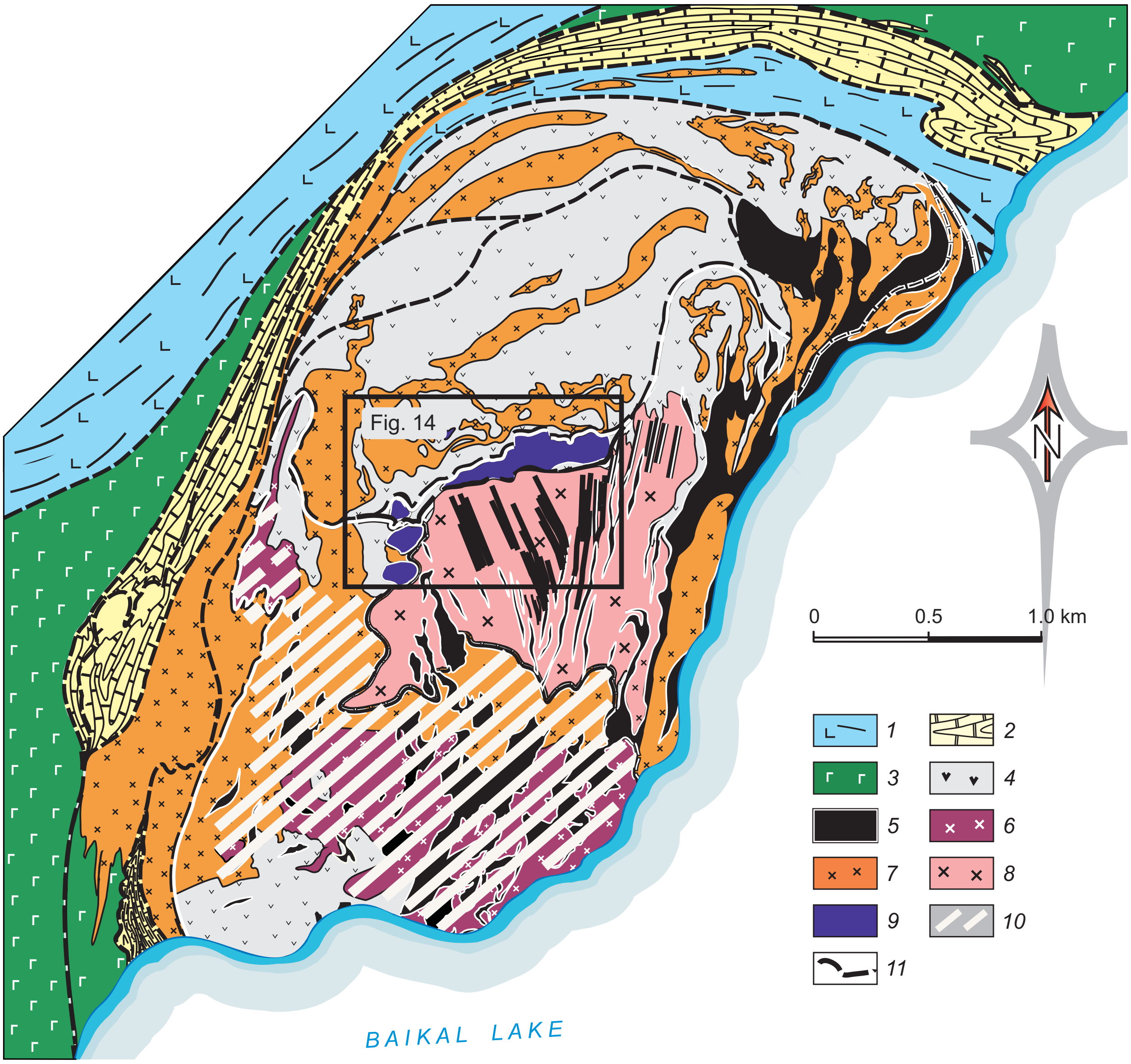


**Fig. 13.** Geology of the Tazheran gabbro-syenite complex, after [Fedorovsky et al., 2009; Sklyarov et al., 2021].
*1–3* – country rocks, 500 Ma: amphibolite, silicate-carbonate gneiss (*1*), calcite marble (*2*), metamorphosed gabbro, monzogabbro, monzonite, and syenite, Birkhin complex (*3*); *4–8* – Tazheran complex, 460–470 Ma: beerbachite after tholeiitic dolerite and gabbro (*4*), subalkaline gabbro and microgabbro (*5*), nepheline syenite (*6*), foliated (*7*) and massive (*8*) syenites; *9* – dolomite-bearing calcite marble in association with pyroxenite; *10* – area of wide distribution of brucite marble and Mg-metasomatic rocks; *11* – synmetamorphic shear zones.

**Рис. 13.** Геологическая карта Тажеранского габбро-сиенитового массива (after [Fedorovsky et al., 2009; Sklyarov et al., 2021]).
*1–3* – вмещающие породы (500 млн лет): амфиболиты, гнейсы (*1*), кальцитовые мраморы (*2*), метаморфизованные габбро, монцогаббро, монцониты, сиениты (*3*); *4–8* – Тажеранский массив (460–470 млн лет): беербахиты по толеитовым габбро и долеритам (*4*), субщелочные габбро и микрогаббро (*5*), нефелиновые сиениты (*6*), сиениты огнейсованные (*7*) и массивные (*8*); *9* – доломитсодержащие кальцитовые мраморы в ассоциации с пироксенитами; *10* – область распространения бруситовых мраморов с магнезиальными метасоматитами; *11* – синметаморфические шеар-зоны.

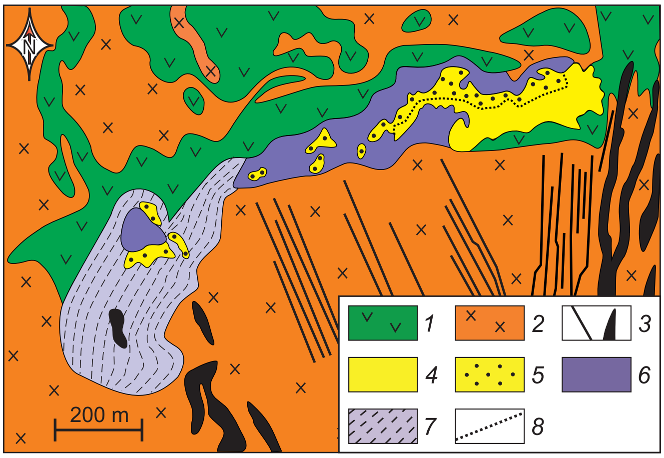


**Fig. 14.** Enlarged simplified local geology of pyroxenite and nepheline-fassaite rocks and their surroundings, after [Sklyarov et al., 2021].
*1* – beerbachite after tholeiitic dolerite and gabbro; *2* – syenite; *3* – subalkaline gabbro and microgabbro; *4, 5* – dolomite-bearing calcite marble (*4*) with abundant pyroxenite fragments (*5*); *6* – pyroxenite and nepheline-fassaite rocks; *7* – garnet-melilite-pyroxene and melilite-wollastonite metasomatic rocks; *8* – boundary between marbles with and without pyroxenite.

**Рис. 14.** Геологическая карта района распространения пироксенитов и нефелин-фассаитовых пород (по [Sklyarov et al., 2021]).
*1* – беербахиты; *2* – сиениты; *3* – субщелочные габбро и микрогаббро; *4–5* – доломитсодержащие кальцитовые мраморы (*4*), насыщенные фрагментами пироксенитов (*5*); *6* – пироксениты и нефелин-фассаитовые породы; *7* – зона распространения гранат-мелилит-пироксеновых и мелилит-волластонитовых метасоматических пород; *8* – граница между мраморами «чистыми» и с фрагментами пироксенитов.

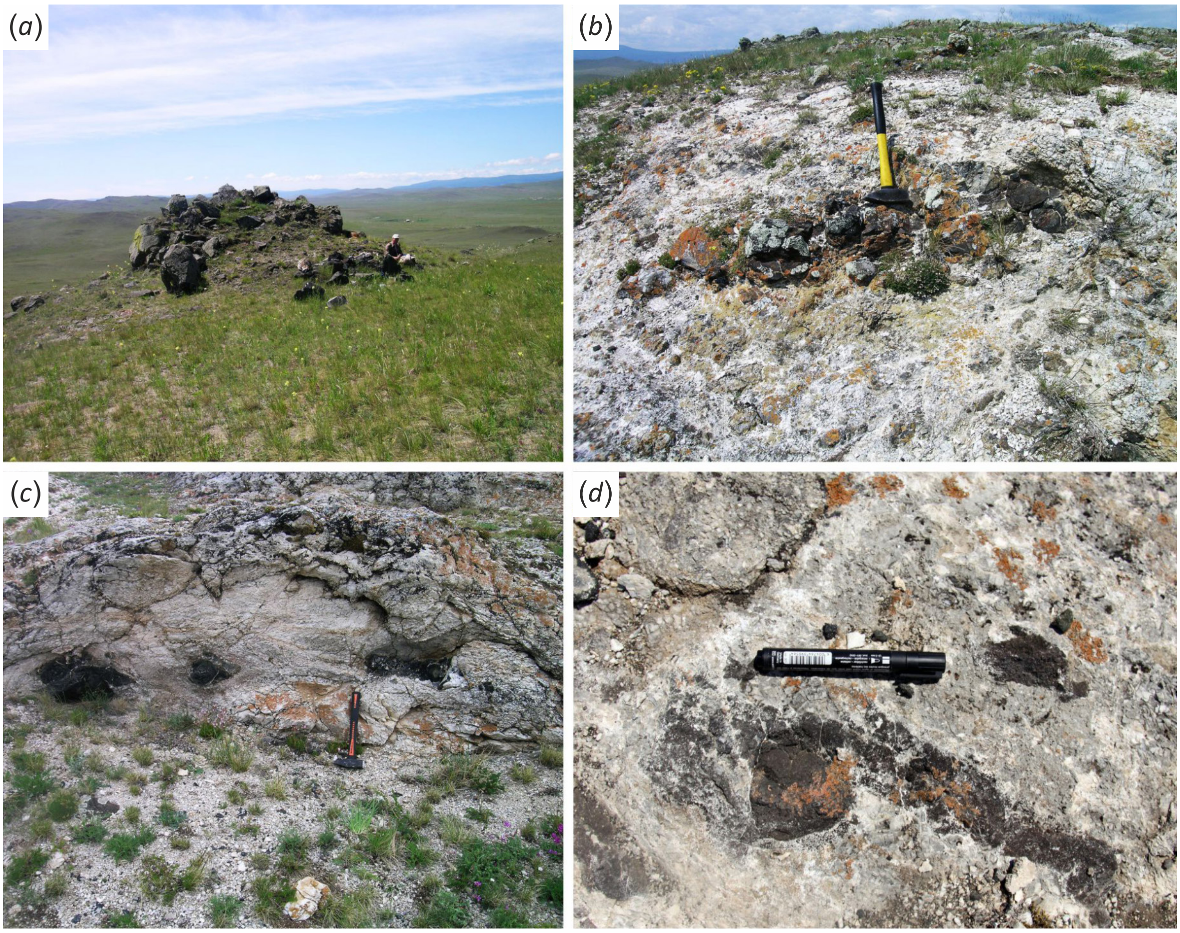


**Fig. 15.** Pyroxenite inclusions in marbles, after [Sklyarov et al., 2021].
(*a*) – large pyroxenite inclusion (up to 15 m in diameter); (*b*) – lens of skarned pyroxenite; (*c*) – pyroxenite inclusion (decimeter sizes); (*d*) – small inclusion of skarned pyroxenite.

**Рис. 15.** Фотографии пироксенитов в мраморах (по [Sklyarov et al., 2021]).
(*a*) – крупный (до 15 м в диаметре) фрагмент пироксенитов; (*b*) – линза скарнированных пироксенитов; (*c*) – несколько фрагментов пироксенитов размером в десятки сантиметров; (*d*) – мелкие фрагменты скарнированных пироксенитов.

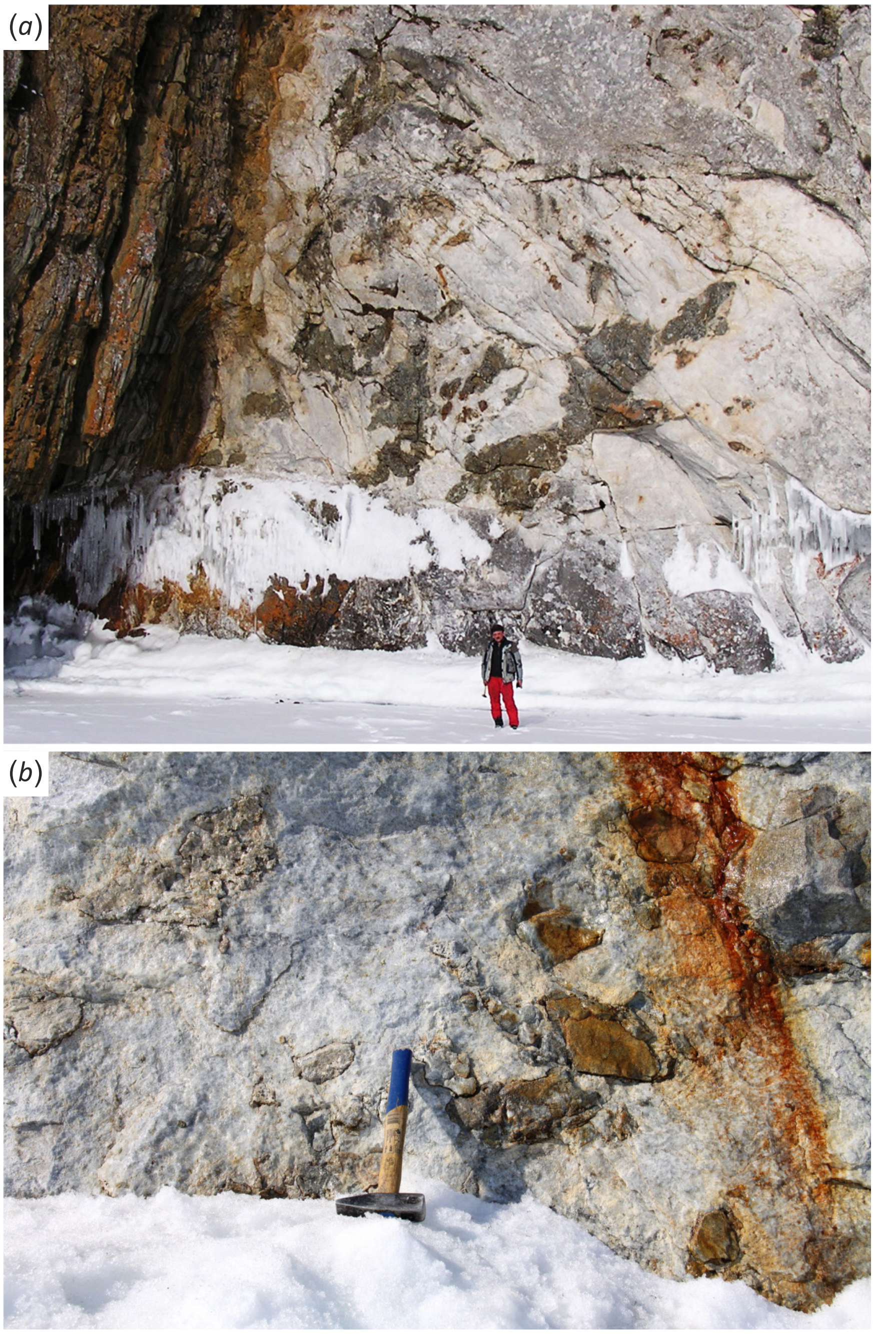


**Fig. 16.** Metagabbro (*a*) and granite (*b*) inclusions in calcite marble. Cliffs in northeastern coast of Olkhon Island.
**Рис. 16.** Фрагменты метагаббро (*a*) и гранитов (*b*) в кальцитовых мраморах. Северо-восточное побережье о. Ольхон.

the central part of the complex [Sklyarov et al., 2021]. The strip borders syenite outcrops in the south and hornfelsed tholeiitic dolerite or beerbachite [Sklyarov et al., 2020], with abundant foliated syenite, in the north. Marbles along the contact with pyroxenite in the complex center (Fig. 15) contain abundant more or less skarned pyroxenite fragments, from few centimeters to few tens of meters, which can be interpreted as marble mélange according to morphology and structure. Mélange of this type occurs elsewhere in the Olkhon terrane as well, e.g., in the northern part of Olkhon Island, where some linear marble bodies enclose metagabbro (Fig. 16, a) or granite (Fig. 16, b) fragments.

## 4. DISCUSSION

The four types of marble mélange differ in structure and composition and must have formed by different mechanisms. Injection mélange most often occupies large areas and lacks distinct linear contours in the plan view, though some bodies may have linear shapes and align with steeply dipping host silicate rocks, as in the case of the Tonta zone. Silicate inclusions in marbles are from a few centimeters to tens of meters in size and are compositionally similar to the silicate hosts in different domains of the Olkhon terrane. The silicate rocks can be either mafic and intermediate granulites, metagabbro, quartzite, and granite as in the Tonta area, or only metagabbro compositionally different from the gabbro elsewhere in the terrane, as at Begul, or amphibolite and calc-silicate rocks as in Olkhon Island. Metamorphic foliation in mafic and intermediate granulite inclusions (Tonta) is randomly oriented, which is evidence of earlier peak metamorphism and means that the classical boudinage of more competent silicate rocks hardly could work in that case. More so, diverse granulites, rather than only those associated with marble, may occur within small sites of the mélange. These features indicate injection of more ductile marble into upper level, where fragments of silicate host rocks could accumulate during active strike-slip faulting under high pressures and temperatures. Given that the zone underwent two events of high-temperature granulite-facies metamorphism, at 500 and 470 Ma [Sklyarov et al., 2020], it is reasonable to infer that granulite structure formed during the older event whereas marbles emplaced during the later event synchronous with large-scale tectonic activity (strike-slip faulting).

Marble tectonites, with abundant small (no larger than few cm) inclusions of silicate rocks and secondary metamorphic minerals, represent the final phase of tectonic activity, with ductile and brittle deformation localized in narrow zones. The deformation led to further breakdown of silicate fragments in the mélange and produced a distinct foliated structure in the marbles. Actually, the two types of marble mélange may represent different phases of the same strike-slip faulting activity.

Metamorphic-boudinated mélange differs markedly from the injection type in its location within a tectonic slice composed of dolomitic and calcite-dolomitic marbles, as well as in the homogeneous composition of silicates: diopsidite or tremolite-diopside (±quartz) rocks. The formation mechanism of this mélange long remained unclear, especially in the presence of a diopsidite and quartz-diopside block in the zone (see Fig. 9). An explanation came from data on the Neoproterozoic Baikal Group southwest of the Olkhon terrane in the Siberian craton [Khomentovsky et al., 1972]. The Baikal Gr. rocks are thick dolomites and quartz sandstones with dolomitic cement (Goloustnaya Fm.), with strongly variable percentages of quartz and carbonate cement in massive sandstones in the lower Kachergat River, a right tributary of the Buguldeika River. The massive sandstones underwent only late diagenetic alteration, while the Baikal Gr. rocks along the collisional suture between the Olkhon terrane and the Siberian craton were altered more strongly, up to low-temperature greenschist metamorphism. The rocks contain minor amounts of talc and quartz segregated in thin parallel or sometimes reticular-banded veins (see Fig. 10, d). Syntectonic low-amphibolite metamorphism in the Krestovsky subterrane [Sklyarov et al., 2020] led to the formation of diopside by the reaction of quartz and dolomite:

$$CaMg(CO_3)_2+2SiO_2=CaMgSi_2O_6+2CO_2. \quad (1)$$

Metamorphic reactions in the presence of aqueous fluids could also produce tremolite ($Ca_2Mg_5(Si_8O_{22})(OH)_2$), free from Fe, Al, and alkalis, like diopside. All dolomite (cement) became consumed by the reaction if its percentage was much less than that of quartz (clasts), while the residual excess $SiO_2$ in newly formed diopsidite segregated into veinlets (see Fig. 10, a). Otherwise, all $SiO_2$ was consumed if dolomitic matrix in sandstone predominated over detrital quartz, and the rocks acquired diopside-(+tremolite+calcite)-dolomite compositions. Thus, the proportion of carbonate and silicate components in metamorphic rocks depends on relative percentages of clasts and cement in the protolith quartz sandstone. Since metamorphism in the Olkhon terrane was syntectonic and was related with strike-slip faulting, the diopsidite layers and lenses broke down late during the process and thus imparted the mélange look to the middle part of the dolomite zone.

If this idea is correct, the formation of the metamorphic-boudinated mélange in the tectonic slice from the Neoproterozoic Baikal Gr. protolith would undermine the model predicting that the Olkhon terrane originated far from the craton and accreted to the latter in the Early Paleozoic [Gladkochub et al., 2008; Donskaya et al., 2017, and references therein], while the Baikal Gr. belonged to the craton passive margin. On the other hand, the presence of cratonic complexes in the terrane means that its history was more complicated than it has been thought so far.

The features of mingling mélange likewise imply its particular formation mechanism. Mélange of this type occurs mainly as quite thin veins while the silicate inclusions are of igneous origin, often with well preserved magmatic structure and texture despite the metamorphism. The mélange veins and the relations of silicate and carbonate rocks suggest that carbonate and silicate melts intruded quasi synchronously (see Figs. 10, 11), and the earlier crystallized batches of silicate melt (more often mafic) split into fragments while the carbonate material was still flowing.

It is not quite clear whether the carbonate material injected as melt or ductile flow. Previously we [Sklyarov et al., 2013a] hypothesized cautiously that marble veins might result from intrusion of carbonate melt. Crystallization from melt is indicated explicitly by the presence of melt inclusions in newly formed silicate minerals, which hardly can be found in carbonates in our case, given that the system was recrystallized late during its cooling. Recrystallization can be inferred from large-scale polysynthetic twinning of calcite or dolomite corresponding to relatively low temperatures of the system under stress [Burkhard, 1993]. However, silicate minerals in marble dikes from the Olkhon terrane are of metamorphic or metasomatic origin. They were altered upon the interaction between the carbonate and silicate components during cooling, even if the crystallization was from the melt. In this case, the origin of carbonate and carbonate-silicate injections can be revealed implicitly. Namely, injection of carbonate melts is indicated by the vein-like shapes of carbonate bodies and isotropic distribution of new silicate minerals, in the absence of ductile flow signatures.

The injection of molten marble is further supported by evidence of interaction between carbonate and mafic melts in the Tazheran complex, which led to crystallization of particular pyroxenite and nepheline-pyroxene rocks [Sklyarov et al., 2021]. Since pyroxenite crystallizes at higher temperatures before carbonate melts, it could become fragmented, captured by the carbonate melt, and metasomatized while the system was cooling, which made it looking like marble mélange. Thus, we suggest that the carbonate and carbonate-silicate veins are intrusive, like the Tazheran marbles with pyroxenite inclusions.

The Tazheran veins and mélange marbles differ markedly from mantle carbonatite in mineralogy and isotope geochemistry [Doroshkevich et al., 2016] but correspond rather to primary sedimentary carbonate. They most likely originated by melting of carbonate sediments under the crustal conditions, which many petrologists would find unfeasible because the high temperatures (>1200 °C) for melting of carbonates in the mantle [Wyllie, Tuttle, 1960] but hardly can exist in the crust. Meanwhile, already early melting experiments with carbonates showed that their dry and wet liquidus differ markedly, as in the case of silicate systems: in the presence of an aqueous fluid, calcite can melt at 740 °C at 1 kbar [Wyllie, Tuttle, 1960], and even at progressively lower temperature as the pressure increases. Moreover, the melting point decreases further to 600 °C when MgO is added to the system [Fanelli et al., 1986]. At an invariable fluid composition ($X_{CO2}$=0.05), the wet granite solidus approximately coincides with the calcite liquidus, while the dolomite melting curve is 100 °C lower [Lentz, 1999]. It means that dolomite in fluid-saturated crust can melt before the appearance of granite melts which should be synchronous with the melting of calcitic marble. Thus, the existence of carbonate melts in the lower crust is quite realistic in the presence of aqueous fluids, while injection of mantle mafic magmas could maintain the temperature required for nearly synchronous intrusion of mafic and carbonate melt batches at shallow depths.

Turning back to the question whether *mélange* is the appropriate term to describe the carbonate-silicate mixtures from the Olkhon terrane, we note the following. Mélange of Franciscan and Ankara types has been defined and characterized in many publications since the earliest evidence [Greenly, 1919; Belostotsky, 1967; Hsu, 1968; Knipper, 1971; etc.]. The most complete definition belongs to [Great Russian Encyclopedia, 2012], in the respective article of the Great Russian Encyclopedia: "MELANGE (from French *mélange* – mix, mixture) in geology means a chaotic tectonic mixture of rocks, with inclusions of native or exotic rocks in a pervasively sheared pelitic (<0.1 mm) matrix. The inclusions can vary in size from a few cm (clasts), to a few meters (boulders), tens of meters (blocks), or hundreds of meters (slabs). The matrix can be clastic, serpentinite, etc. according to composition and monomictic or polymictic depending on the diversity of inclusions. Mélange can be related to tectonic accretion or to subduction, or can originate during cold intrusion (protrusion) into the overlying rocks, etc. Many mélange bodies reach lengths of several kilometers and appear in geological maps. Mélange is a typical element in orogens of different ages. Serpentinite mélange is often associated with ophiolites and that of clastic composition is commonly found in accretionary prisms". Strictly speaking, none of the four Olkhon mélange types fits the definition of [Great Russian Encyclopedia, 2012]. The metamorphic-boudinated mélange formed by syntectonic metamorphism and lacks exotic inclusions; the mingling mélange neither can be interpreted as classical mélange as it is due to interactions between carbonate and silicate magmas; injection mélange and marble tectonites would be classified as such but they lack "sheared pelitic rock mass" and originate at high temperatures and pressures rather than "during cold intrusion into the overlying rocks". There are two basic possibilities to overcome these contradictions: either not to apply the term *mélange* to the Olkhon marble-silicate mixtures and coin multiple other terms or, more reasonably, to extend the definition with the concept of marble mélange following [Fedorovsky et al., 1993].

## 5. CONCLUSIONS

We have applied the term *mélange* to the marble-silicate mixture from the Olkhon terrane, in the title and in the main text, though being aware that it does not fit perfectly the existing definitions. The Olkhon mélange is of four main types which apparently formed by different mechanisms.

Injection (protrusion) mélange and marble tectonites, with mm to n·10 m native silicate inclusions in a marble matrix, fit the best the definition of mélange. The main difference between the two types is that tectonites are commonly localized in narrow zones (few centimeters to few meters) and enclose numerous small fragments of silicate rocks. Both bear signatures of ductile flow corresponding to protrusion of marble during synmetamorphic strike-slip faulting activity. Marble tectonites record the late phase of the activity.

Metamorphic-boudinated mélange is composed of dolomitic or calcite-dolomitic matrix with lens-shaped inclusions of diopsidite and tremolite-diopside rocks. It may result from tectonic-metamorphic alteration of quartz sandstones that presumably belong to the Goloustnaya Fm. deposited on the passive margin of the Siberian craton.

Mingling mélange occurs as calcite marble or calciphyre veins that enclose metadolerite or less often granite fragments of different sizes. The massive structure and vein-like shapes of the marble bodies imply quasi-synchronous injection of carbonate and silicate melt batches followed by fragmentation of the earlier crystallized silicate material.

The four types of the Olkhon carbonate-silicate mixtures (mélange) are very rare if not unique features of metamorphic complexes, be they termed *mélange* or otherwise. The singularity of the Olkhon terrane in this respect may be due to high rates of synmetamorphic strike-slip faulting activity.

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