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Layered Gabbroids of the Pekulney Ridge, Chukotka, Northeastern Russia: Geology, Petrography, Age, and Geodynamics

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Additional information is available at the end of the chapter

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Abstract

The author has actualized the data obtained by her own research and from publications to conclude that gabbroids in the northern part of the Pekulney Ridge build a large intrusion, named Svetlorechensky. It belongs to the type special for the region: it possesses features of layered plutons and multiphase intrusions. It is classified as a petrotype of a gabbro complex of the same name, whose bodies are present in the southern part of the ridge, as well. The establishing of the Svetlorechensky complex took place in the Early Cretaceous (most probably in the Hauterivian). The original composition of the parent magma was characterized as typical island arc tholeiitic basalt. Amphibole-two-pyroxene rocks of the Pekulneyveem River basin, supposedly dated back to the Archean by previous researchers, build the marginal series in the first intrusive phase of the Svetlorechensky pluton. Among the host complexes, the author has established stratified high-temperature metamorphic formations, supposedly Paleozoic, and "pre-Svetlorechensky" gabbroids. The deep structure reconstruction for the pluton permitted to interpret it as a heavily asymmetric harpolith, localized in the hanging side of a long-developed ancient island arc uplift.

Keywords: petrographic convergence, Cretaceous magmatism, layered gabbroids, high-alumina basalt, island arc, Chukotka region

1. Introduction

Large linear structures, housing great volume of basites and ultrabasites, in its current understanding, are interpreted as fossil boundaries of lithospheric plates, where geodynamically heterogeneous complexes are mechanically joined. Simultaneously, they have

to be autonomous structures of sufficiently long development, as, parallel to collision and (or) accretion deep processes of the earth crust neof ormation occur. Distinguishing the in situ-formed complexes remains one of the least developed aspects of the geodynamics. The Pekulney Ridge is extremely favorable for this purpose.

The Pekulney Ridge is located in the farthest part of northeastern Asia, in the Chukotka Autonomous District of the Russian Federation. As a weakly bent arc, it stretches for 250 km from the Anadyr River Valley north northeastward, between its largest left tributaries, the Tanyurer and Belaya rivers (**Figure 1**, Inset map). It is a young, highly dissected mountain system, which joins Cenozoic depressions and the Chukotka Upland. The clearly expressed axis of the system (the ridge *s. stricto*) is 15–25 km wide. Its section, comprehensively characterized below, is about 50 km long (**Figure 1**) and located in the highest elevated part of the ridge. The relief here is of an alpine-type. Relative height differences between watersheds and valleys reach 1000 m, absolute elevations of the highest peaks approach 1400 m. Exposure is good everywhere with numerous bedrock yields. At the trough valley bottoms, abundant are enormous glacier blocks composed of the strongest types of gabbroids. On their ideally prepared surfaces, one can observe fine peculiarities of intrusive body structures. In particular, in this way, rare spheroidal gabbros, or orbicular allivalites, were found and comprehensively studied [1].

In the course of time, the number of disputable issues increases and the debate sharpens. It is determined, firstly, by the ridge location at the joint of two largest tectonic units, traditionally distinguished in the Far North-East of Asia: the Chukotka Folding System, a part of the single Verkhoyansk-Chukotka Mesozoic Area and the Anadyr-Koryak Folding System, which refers to the Cenozoic Koryak-Kamchatka Area; and, second (and important), by the fact that the boundary between Mesozoides and Cenozoides is concealed under Cretaceous accumulations of the Okhotsk-Chukotka Volcanogenic Belt (**Figure 1**, Inset map). Scholars, based on the plate tectonics, also suggest contradictory models of relations between Mesozoides and Cenozoides. Recently, the Chukotka Mesozoides began to be regarded as a part of the Arctic Craton. In this situation, the Pekulney Ridge structures attract more and more attention, especially since they are exposed far better than the two other pre-Cenozoic elevations of the Anadyr-Koryak System, located on the left bank of the Anadyr River (from the west to the east): Kanchalan and Zolotogorsky (the entry part of the Anadyr River).

The present work introduces the results of studying the Pekulney Ridge holocrystalline basites, exposed on the area about 200 km² north from the latitude 66°00' N (it serves as a conventional border between the northern and the southern parts of the ridge, differing in their geological structures). On top of everything, these rocks are interesting because in the late 1970s, when the USSR activated the research of the transitional zone from the Asian continent to the Pacific Ocean, a new interpretation of their origin was offered. If the first geologists had considered them intrusive gabbroids of the Early Cretaceous [2–4], later these rocks were interpreted as an uplift of the Archaean continental crust, which radically changed the view of the area tectonics [5, 6].

In order to possibly solve disputable issues, in 1981–1984, the author performed specialized geologic and petrologic research of basites in the northern part of the Pekulney Ridge. They included the geological mapping of the area of presumably Precambrian complexes on the topographic base, the comprehensive study of their petrographic and geochemical peculiarities

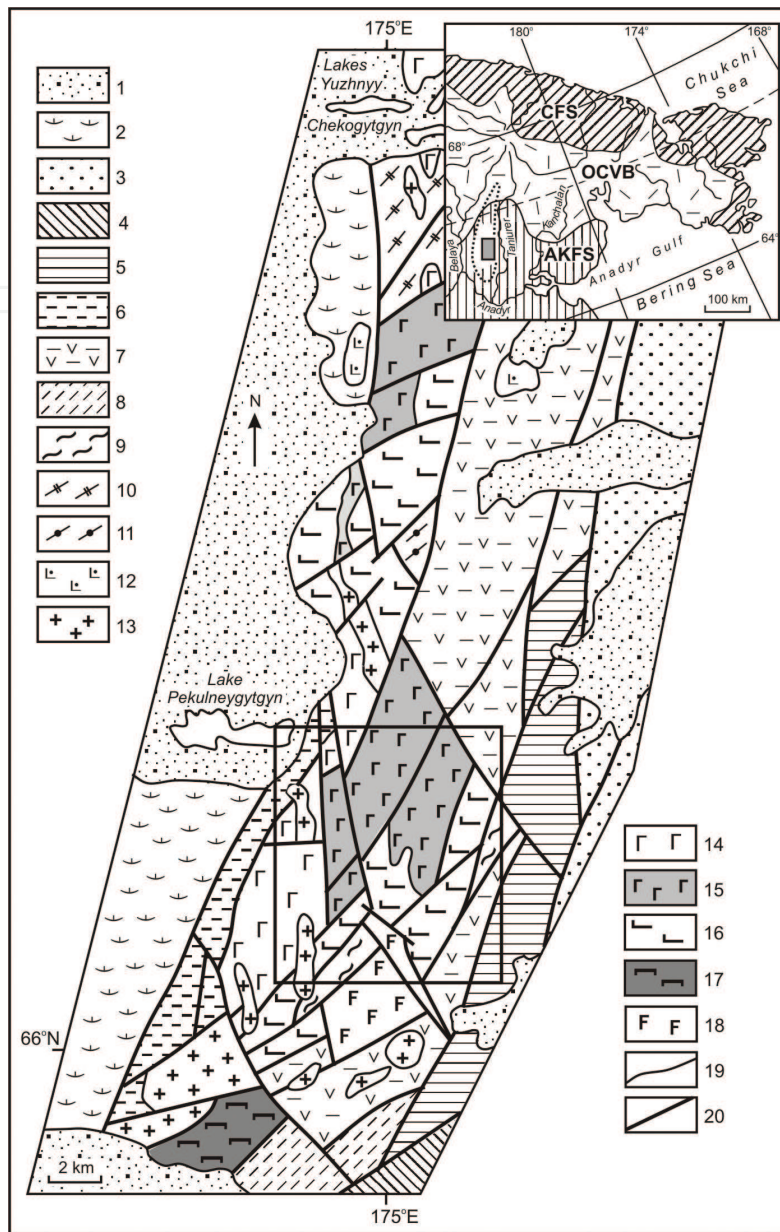


Figure 1. Schematic geological map of the northern part of the Pekulney Ridge (compiled by Zhulanova using [4, 14]): 1—quaternary sediments; 2—Upper Cretaceous and Paleogene terrigenous and volcanic deposits; 3—Upper Cretaceous terrigenous and volcanic deposits; 4—Aptian-Albian terrigenous and volcanic deposits; 5—Hauterivian-Barremian terrigenous deposits (sandstones, aleurolites, gravelites, conglomerates); 6—Tythonian-Valanginian volcanogenic and terrigenous deposits (Gruntovskaya Strata); 7—Middle Jurassic-Lower Cretaceous siliceous-volcanogenic deposits (Pekulneyveemskaya Suite); 8—Greenschists (Pekulneyveemskaya Suite dynamometamorphism products); 9—presumably Middle-Upper Paleozoic metasandstones, metalevolites, graphite-biotite, sericite-siliceous schists, metariolites, metabasalts (Pekulneygytgyinskaya Strata); 10–11—presumably Paleozoic metamorphic formations (Sbornenskaya Strata): 10—amphibolites, biotite-amphibole schists granitized, 11—garnet-biotite-hypersthene paragneisses, garnet-sericite-graphite microschists; 12–17—intrusive complexes: 12—Paleocene-Eocene Televeemsky (gabbonorites), 13–17—Early Cretaceous: 13—Yanranaysky (granodiorites, granites), 14–16—Svetlorechensky two-phase: 14—additional phase (amphibole, biotite-amphibole gabbro), 15–16—main phase: 15—edge series (amphibole microgabbnorites, pyroxene-amphibole gabbro), 16—layered series (plagioclase peridotites, troctolites, olivine gabbro, gabbroanorthosites, anorthosites); 17—Ostantsovogorsky (picrites, metadolerites, peridotites); 18—pre-Cretaceous uralitized gabbro; 19—geological boundaries; 20—tectonic disturbances. Black frame indicates area of **Figure 2**. *Inset map:* Tectonic Scheme of the Chukotka Peninsula: AKFA—Anadyr-Koryak Fold Area, CFS—Chukotka Fold System, OCVB—Okhotsk-Chukotka volcanogenic belt. The points outline shows the Pekulney Ridge. A gray rectangle indicates area of **Figure 1**.

and the chemical composition of minerals. Pertsev, the then alumnus of the Lomonosov State University in Moscow, participated in field works and material processing. Analytical research was performed at NEISRI and VSEGEI (St. Petersburg, Russia).

Our general task within the framework of the research program was the problem of the basement of the Anadyr-Koryak System with its numerous ophiolite complexes [7, 8]. Respectively, beside basites of the northern part of the Pekulney Ridge, we studied metamorphic formations, basites, and ultrabasites, spread in the south, in the upper flows of the Levaya Bychya and Severny Pekulneyveem rivers. According to the common viewpoint, they belong to the ophiolite association forming a sovereign tectonic structure. Our observations yielded some principally new data that permit to interpret the history of its geological development within a holistic geodynamic model [9, 10]. Later on, Pertsev paid most attention to petrologic peculiarities of depth ultramafites [11].

Field works were conducted in a close contact with geologists from the Anadyr Expedition of the North-East Geological Association of the USSR Ministry of Geology, who performed geological 1:50,000 mapping and prospecting (the party manager Semyonov). In the summer of 1981, there worked a field party from the Far East Geological Institute (Vladivostok, Russia), headed by Shul'diner [12], a prominent expert in the Siberian and Far Eastern Archaean. Thus, during the field season of 1981, we had an opportunity to perform a series of fundamental observation together with experienced practitioners and scholars. Finally, our research permitted to conclude that the pioneers were right about the intrusive nature and the Early Cretaceous age of basites of the northern part of the Pekulney Ridge. According to our data, these rocks make a large layered pluton with an additional phase of amphibolic gabbro, followed by veins of amphibolic plagiogranites. We named the massif Svetlorechensky (after the Svetlaya River), and consider it a petrotype of the cognominal two-phase intrusive complex of Early Cretaceous gabbro [13]. Among complexes housing the Svetlorechensky layered pluton, stratified metamorphic formation of the supposedly Paleozoic age and "pre-Svetlorechensky" gabbroids were established for the first time.

The acute discussion of the 1980s interested a wide range of experts in the Pekulney Ridge, which resulted in additional data on geochemistry and isotopic age of the basites. They are discussed further within the context of our main task. In 2009, the Federal Unitary Enterprise "Georegion" (City of Anadyr) had completed the second-generation sheets of the Federal Geological Map with the scale 1:200,000 for the Pekulney Ridge to the south of the latitude 66°40' N (map author Gul'pa), which have adequately reflected most of our data [14].

2. Area geology and tectonics: factual data and theoretical discussions in brief retrospective

2.1. Historical background

The geological study of the Anadyr area was pioneered by a prominent Russian geologist of a tragic fate, Polevoy (1873–1938). Today, however, various activities of his expedition, which

worked in 1911–1913, are rather of historic than of geological interest [15–17]. The systematic study of the Belaya and Tanyurer interfluvium has lasted a little longer than 50 years. Since the mid-1950s, organizations responsible to the USSR Ministry of Geology conducted geological survey and prospecting of various scales and directions here; the data obtained were generalized on sheets of Federal Geological Maps of 1:1,000,000 and 1:200,000 scale (further referred, respectively, as FGM-1000/1 and FGM-200/1). The first important advance was the production of a small-scale map including the whole Pekulney Ridge (FGM-1000/1 Q-60 Sheet) [2]. The map author Kaygorodtcev diagnosed an Early Cretaceous ophiolite association in the Pekulney Ridge. As ophiolites, he classified (1) siliceous-volcanogenic deposits with dominant basaltoids (mostly spilites), (2) ultramafites, (3) gabbroids, (4) products of metamorphism and metasomatism of formations, including eclogite-like rocks, which he had originally established [18, 19]. Siliceous-volcanogenic deposits were described under the name of the Pekulneyveemskaya Suite of the supposedly Late Jurassic-Valanginian age, the oldest in the stratigraphic section of the area. The opinion of eclogite-like rocks as products of selective alteration of magmatic rocks was supported by the researchers who later studied the ultramafite-mafite magmatism of the Anadyr-Koryak System as a whole; they also reported the first epidote blueschists found in the Pekulney Ridge [20]. It was found that the ophiolite association in its complete manifestation is spread only in the axis part of the southern half of the ridge, and essential differences in the structures of its eastern and western slopes were exposed. On the western slope, Lower Cretaceous terrigenous-volcanogenic masses were mapped, in which andesite and dacite tuffs and lavas predominate, while basic volcanites are rare. On the eastern slope, stratigraphically above the Pekulneyveemskaya Suite, the Valanginian mass (conglomerates, sandstones, aleurolites, basalts, andesites, rhyolites, their tuffs) was distinguished, which is covered by Aptian-Albian terrigenous rocks laid with angular displacement and basal conglomerates. Late Cretaceous deposits spread in the eastern and western slope foothills visibly differ from each other. Besides, developed only on the western slope are intrusive granitoid massifs; the pebbles of those were found in the Aptian-Albian conglomerates. Summarizing the exposed peculiarities, Kaygorodtcev interpreted the Pekulney Ridge as an inherited anticline elevation, whose history, starting at least from the Valanginian, had been controlled by an axis deep fault, which he named Pekulney [18, 19].

In the northern part of the ridge, among intrusive formations, gabbroids play the main part; the western slope of the ridge is almost completely composed from them (**Figure 1**). Valanginian deposits, shown as the Pekulneyveem Suite, are exposed mostly on the eastern slope here; however, their composition (terrigenous variations of sedimentary rocks, andesites, dacites) is similar to that of the pre-Upper Cretaceous section of the western slope. In the sand-gravelite-conglomerate mass with intermittent components, presumably referred to the Hauterivian, pebbles of greenschists, spilites, jaspers, gabbro, and granitoids were found. The issue of tectonics in this part of the ridge attracted no special attention at that time.

The data on Early Cretaceous ophiolites present in the southern part of the Pekulney Ridge were sufficient for making a conclusion on the tectonic kinship of the left bank of the Anadyr River with the Koryak Upland and considering both area elements of the Anadyr-Koryak Cenozoic Folding System. Within the system, the Pekulney Ridge structures are most often

included in the Talovsk-Pekulney ophiolite zone as its northeasternmost section. As a whole, the zone is a narrow arc, weakly bent southeastward, over 750 km long. Its southern flank reaches the eastern coast of the Penzhinskaya Bay, Sea of Okhotsk; some of it is traced on its western coast (Taygonos Peninsula) and farther goes into the sea [21].

The situation dramatically changed in the mid-1970s. Ideologically, the research was based on the concept formulated by the Director of GIN, Member of RAS Peive in the late 1960s; in the USSR, it was coined as the new geosyncline theory, or the concept of constructive tectogenesis. According to the concept, ophiolites were interpreted as products of the early (oceanic) stage of geosyncline development, regularly followed by the middle (island arc) and the final (orogenic) stages, which determines the formation of the continental-type earth crust. The originality, therefore, was in matching primary geosynclines with oceans and interpreting their evolution as the process of turning the oceanic crust into the continental one [22, 23].

Nekrasov was the first to analyze the structure of the Pekulney Ridge from this viewpoint [5]. He defined geological complexes of the southwestern and northern parts of the ridge as autochthon, on which ophiolites are thrust from the southeast. In the contact zone between the autochthon and allochthon, serpentinite *mélange* was distinguished. In Nekrasov's scheme, basites of the northern part of the ridge, revealed on the right bank of the Pekulneyveem River between Lake Pekulneygytgyn and Lake Romb (**Figure 2**), played the main part. Their amphibole-two-pyroxene composition, fine-grain structures with orientation elements, and the presence of the clearly separate leucocratic ("enderbitic", according to Nekrasov) phase, sometimes likening the rocks to migmatites, made the set of attributes that permitted to define those formations as crystalline schists of the granulite facies of metamorphism. According to the original interpretation by Nekrasov, they compose the core of the dome-like swell of the autochthon basement and are sequentially followed, at its eastern wing (upward), by gabbro-norites, gabbroic anorthosites, olivine-pyroxene gabbro, gabbro-pegmatites, amphibolic gabbro, diorites, and plagiogranites. He compared the whole rock association with the Archaean granulite complex of the Anabar Shield of the Siberian Platform, and interpreted it as a swell of the granulite-basite ("basalt") layer of the continental-type earth crust. Ultramafic rocks of the Pekulney Ridge southern part, shown on FGM-1000/1 and FGM-200/1 as Earle Cretaceous intrusions (lherzolites, wehrlites, dunites, etc.), as well as eclogite-like rocks, were interpreted as tectonic fragments (rafts) from the mantle basement, underlaying the Archaean continental crust revealed in the north of the ridge [5]. Those data, together with their tectonic interpretation, made a veritable sensation for geologists studying the North-East of Asia, because by the mid-1970s, the view of the epi-oceanic nature of the Koryak-Kamchatka Folding Region, including its western half, the Anadyr-Koryak System, was widely acknowledged.

By the time we started our research (1981), some new data on the ridge geology had appeared. Thus, in the upstream of the Pekulneyveem River, the carbonate-terrigenous-coaly mass (supposedly Late Paleozoic-Early Mesozoic and believed to be laid above granulite-basites) was distinguished. The idea of Late Jurassic-Early Cretaceous ophiolites in the southern part of the Pekulney Ridge having been formed in the zone of stretching of the old continental crust, analogous to the Chukotka Mesozoic basement, was formulated. It was suggested that two petrographically close gabbroid complexes presented in the northern part of the Pekulney Ridge: (1) Early Precambrian; (2) Mesozoic, simultaneous to the process of the earth crust

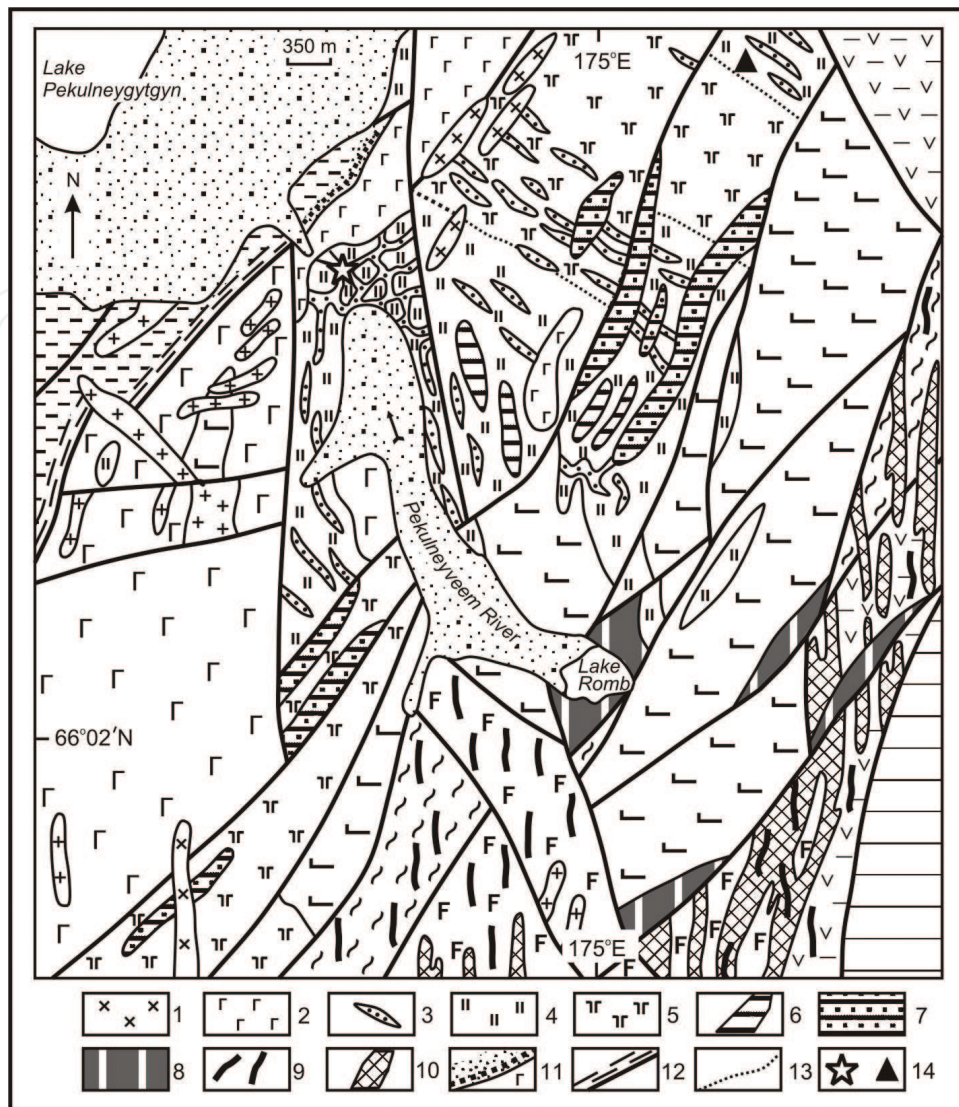


Figure 2. Geological map of the Pekulneyveem River upper basin area (compiled by I. Zhulanova): 1–8—Svetlorechensky pluton: 1–2—additional intrusive phase: 1—amphibole plagiogranites, 2—amphibole gabbro; 3–8—main intrusive phase: 3–5—edge series: 3—hypersthene tonalites veins, 4—amphibole microgabbronorites, 5—pyroxene-amphibole gabbro; 6–8—layered series: 6—ophitic leucogabbro, 7—olivine-amphibole gabbronorites, 8—melanocratic troctolites, plagioclase peridotites; 9—Early Cretaceous Poperechninsky Complex (the parallel gabbro-metadolerites—plagiogranite-porphry dikes); 10—Middle Jurassic-Early Cretaceous Ostrozubsky Complex (metadolerites—plagiogranites), 11—hornfelses in the exocontact of the gabbro intrusion; 12—dynamometamorphism zones; 13—facies boundaries within the intrusions; 14—the asterisk indicates the mouth of the Raysky Creek, the triangle is the sample 5656 location. See **Figure 1** for the remaining symbols.

stretching. Soon this model was theoretically shaped in the hypothesis on the two types of ophiolites present in the Anadyr-Koryak System: the first are fragments of the primary oceanic crust, on which Early Paleozoic geosynclines were laid; the second appeared in mid-Paleozoic and Late Jurassic-Cretaceous marginal seas on the island-arc stage of geosyncline development as result of gapping the continental crust [24].

The next discovery was the information about the fact that the mélangé zone (cement and outliers) in the southern part of the Pekulney Ridge is not laid by serpentinites but by ultrabasic volcanites: meimechites and picrites [25]. Most geologists concluded that they referred to the

Hauterivian, and that their composition corresponded the picrite-basalt volcanic-plutonic complex [26]. The data on the Pekulney Ridge structure combining the complex of the old continental crust with Mesozoic ophiolites and ultrabasic volcanites made the area one of the most interesting ones in the Anadyr-Koryak System. In the early 1980s, the USSR Ministry of Geology chose the Pekulney Ridge as the primary test site for arranging methodological works on implementing new geodynamic concepts into the geological mapping practice. The new concepts included the lithospheric plate tectonics; its most acknowledged supporter in the USSR was the world-famous geologist Zonenshain (1929–1993) [27–29]. The first works on this topic at the Pekulney Ridge and in some other areas within the Anadyr-Koryak System were performed by employees of the Federal Association “Aerogeologiya” (Moscow) in 1983–1990. The main scientific result was presented in a publication [30]. It considered the Pekulney Ridge structures together with other uplifts of the left bank of the Anadyr River: Kanchalansky, Zolotogorsky, though their geological structures differ. The two orthogonal island arcs, Pekulney and Kanchalan-Zolotogorsky, were reconstructed for Late Jurassic-Early Cretaceous stage of the area development. This explanation is principally close to the one offered earlier [21].

The view of the current tectonic structure of the Pekulney Ridge, elaborated on the base of plate tectonics postulates, is at first sight close to that suggested in publications [5, 6]: both distinguish the autochthon, the allochthon, and the neoautochthon. However, if in the first model, the Mesozoic ophiolite zone interpreted as result of old continental crust rifting, in the plate tectonics model, the main place is taken by the data permitting to conclude that the formation of the Late Jurassic-Early Cretaceous island arc and Mid-Jurassic-Early Cretaceous masses, currently building the allochthon (ophiolites) was divided by the vast space of the Paleopacific. The issue of the nature of the Early Mesozoic island arc basement drew no special attention in this context. Here, the author of monograph [30] followed the compromising interpretation of the nature of basites in the northern part of the Pekulney Ridge, proposed by Nekrasov in the late 1980s [31, 32]. Works by the “Aerogeologiya” team, ideologically following Zonenshain, practically completed the history of the Pekulney Ridge geological studies in the twentieth century.

2.2. Modern problems and opportunities

The first decade of the twenty-first century is marked with compiling the second-generation sheets of the Federal Geological Map of the Russian Federation 1:200,000 scale (further referred to as FGM-200/2), published in 2009 [14]. The methodology for this kind of work allows to compile new medium-scale maps significantly advanced deciphering the geological structure of the unique, from many viewpoints, area of the Pekulney Ridge. According to the requirements of the Stratigraphic and the Petrographic Codes of the Russian Federation, all mapped units (series, suites, and strata of stratified deposits, magmatic and metamorphic complexes) obtain proper names [33, 34]. Some of them correspond to earlier distinguished subdivisions, but many units received such names for the first time. It is most essential for us that the Legend of the Koryak Sheet Series (LKS-200) includes basites of the northern part of the Pekulney Ridge as a two-phase Svetlorechensky gabbro complex of the Early Cretaceous age (breaks through the Tithonian-Valanginian Gruntovskaya Strata, is overlaid by the Hauterivian Ostantsovogorsky Strata). Stratigraphic units have been distinguished: presumably Middle-Upper Paleozoic, essentially Pekulneygytgynskaya Strata and Sbornenskaya

Strata of high-temperature metamorphic rocks conventionally dated by the Paleozoic [14]. The LKS-200 team also supported our conclusion that in the southern part of the Pekulney Ridge, among deep rafts spatially joining ultramafites, there also is a wide enough set of metamorphic rocks, petrographically identical to cognominal Lower Archaean rocks from the basement of the Omolon Massif and the Avekovsky crystalline block of the Taygonos Peninsula [10]. They are included in LKS-200 as an supposedly Archaean Plagiogneiss Strata. The author of this chapter has offered the name for it—Kruglogorskaya (after Mt. Kruglaya) [35].

At the turn of the twentieth century, the range of scientific research in Russia, including geological studies, was significantly reduced for the reasons beyond academia. Nevertheless, many holders of the Pekulney Ridge rocks collections continued laboratory research; some managed to conduct field works, and some new data were obtained [36–43]. The overwhelming majority have been concentrated in the southern half of the Pekulney Ridge. The exception is the generalizing publication [44] devoted to the geodynamical interpretation of $^{40}\text{Ar}/^{39}\text{Ar}$ dates for mafites of the Anadyr-Koryak Region, as well as the latest elaborations by Nekrasov, where the Pekulney Ridge structures are discussed in the wide tectonic context as one of the elements of a complex zone of the Arctic Craton joining structures of the Koryak-Kamchatka and Verkhoyansk-Chukotka folding areas [45, 46]. So far, to our utter regret, the perspectives for further studying the Pekulney geology remain obscure.

3. Svetlorechensky gabbro complex: general issues

3.1. Why distinguish

It has been noticed above that, for a long while, the northern part of the Pekulney Ridge had been significantly less studied than its southern part. Therefore, an opportunity to revise the views of one of geological complexes in a less studied area could not be excluded a priori. Discussions on Precambrian or Phanerozoic age of some formations in Northeast Asia have been occasionally raised these days, as well. But they are all characteristically associated with metamorphic rocks. The “Precambrian foundation or Mesozoic intrusive massif” alternative has emerged in the area for the first time. Its solution certainly required stronger reasoning than that Nekrasov had restricted himself to [5, 31, 32]. He observed proper crystalline schists at the site of approximately 20 km², while the total area, occupied with fully crystalline basites in the northern part of the Pekulney Ridge, is no less than 200 km² [2–4]. We have mapped the basic rock massif from its southern end in the outflows of the Levaya Svetlaya River (some farther to the south of 66°00' N) to the South Chekogytgyn Lake, which makes two-thirds of its total length and about three-fourths of its area (**Figure 1**). The host rocks have also been studied; most comprehensively, three sites, where FGM-200/1 [3, 4] shows crosscutting relations of basites with Lower Cretaceous deposits. The obtained data permitted to reconstruct a large intrusive massif named Svetlorechensky layered pluton, and to grant it the status of a petrotype of the Early Cretaceous Svetlorechensky gabbro complex. This meant that the homologs to Svetlorechensky pluton might be found in other areas within the Pekulney Ridge, as well.

This conclusion was quite explicitly grounded. Parallel to our works (1980–1982), Sterligova (Central Complex Topical Expedition, City of Magadan) studied magmatic complexes in the

southern part of the Pekulney Ridge. On the right bank of the Severny Pekulveyem River, for the first time, she mapped and comprehensively described the gabbro massif (named Pravoberezhny, in whose identity with Svetlorechensky complex we did not doubt). Further on, our opinion was convincingly confirmed [14]. Additional study of the area exposed that Svetlorechensky-type gabbroids were quite widely spread in the southern part of the Pekulney Ridge (**Figure 3**). Data on their relations with hosting Tithon-Valanginian deposits (Gruntovskaya Strata) and other intrusive complexes in the area as well as new definitions of isotopic age are of particular importance.

3.2. Svetlorechensky layered pluton: geology, petrography, genesis issues, age

3.2.1. Preliminary notes

Starting our works in the northern part of the Pekulney Ridge, we formulated two main questions: (1) what is the nature of finely grained amphibole-two-pyroxene rocks described as

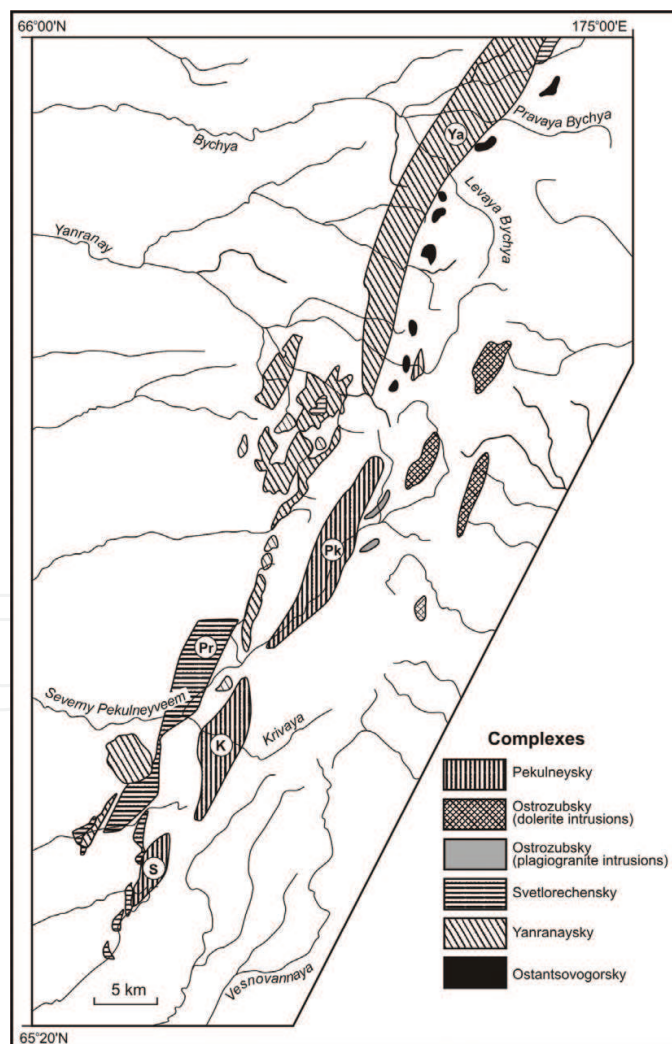


Figure 3. Scheme for placing intrusions within the boundaries of the Q-60-XIX Sheet of the State Geological Map (according to [14], with simplification): the letters in the circles indicate intrusions: K—Krivorechensky, Pk—Pekulneysky, Pr—Pravoberezhny, S—Stoybishchny, Ya—Yanranaysky. Explanations are in the text.

crystalline schists of the granulite facies of metamorphism [5]? and (2) what are interrelations of “crystalline schists” with certainly magmatic rocks (gabbro-anorthosites, anorthosites, olivine-pyroxene gabbro, amphibole gabbro, amphibole-biotite diorites, tonalites, and plagiogranites), the second component of the Archean “granulite-basite” association, according to [5]? We should notice immediately that the “finely striped garnet gabbro-norites,” which originally were considered a linchpin between “crystalline schists” and “coarsely striped magmatic gabbroids” [5, 6], were not further on proved to be present in the Pekulney Ridge [1, 7, 10, 14, 30–32]. From the very beginning, it was clear that in such a complicated area, in the absence of paleontologically dated Late Precambrian and Paleozoic deposits, the problem of the Early Precambrian cannot be solved by direct geological observations. The most efficient appeared the multilateral study of finely grained “amphibole-two-pyroxene crystalline schists” and their comparison with eponymous Archean rocks by a maximally possible number of characteristics. The task was easier to solve due to the extensive factual materials on authentic Archean granulites of the Omolon-Taygonos District of Northeast Asia (summarized somewhat later [47]). The question on “crystalline schists” interrelations with layered gabbroids required systematic geological mapping of the “granulite-basite” spread area. We used it as a base for the Federal Topographic Map of 1:25,000 scale.

The studied area is peculiar not only for its highly dissected alpine-type relief but also for its tense inner, primarily fault, tectonics. On any geological map [2, 4, 14], it is conspicuous that almost all contacts between geological bodies of more or less significant volume go along faults (**Figure 1**). In the contemporary structure, the basite massif, from which “Precambrian” was distinguished, looks like a large fissure body with its length (about 60 km) 10-fold exceeding its width (2–8 km). In the summer of 1981, field observations were started together with colleagues from Anadyr and Vladivostok (see Introduction), in the area of the Raysky Creek (right tributary of the Pekulneyveem River near its outlet from the mountains), which had been known as a key for the “Archean crystalline schists and enderbites” [5, 6] (**Figure 2**). Our thorough and purposeful observation allows to suggest that the metamorphic rocks are absent in the area. Moreover, the very first routes showed that even in their Pekulney, “crystalline schists” are limitedly spread, and that they promptly change to evenly grained gabbro, rich in hornblende and possessing all characteristics of magmatic rocks, very fresh, at that. In other words, similarity of Pekulney amphibole-two-pyroxene basites and minerally identical crystalline schists of the granulite facies is exterior. In the case discussed here, it is associated with the influence of the Earth gravity field, which determines both supracrustal mass layering and most of oriented textures observed in endogenous formations. The same conclusion applies to “enderbites” supposedly associated with “amphibole-two-pyroxene crystalline schists” [5]. In fact, observed in rock exposures along the Raysky Creek are crosscutting veins of hypersthene tonalities, whole mutually parallel orientation, vaguely resembling the layered migmatite texture, is determined by host basites banding (see below). We define Nekrasov’s amphibole-two-pyroxene “crystalline schists” as amphibole microgabbro-norites. This name does not imply all distinctive structural characteristics of these rocks, but is convenient because it promptly distinguishes a disputable group of rocks from other variants of gabbro rich in hornblende, mostly medium-grained, in the studied area. Medium-grained hornblende-rich gabbro falls into three petrographic groups: (1) pyroxene-amphibole, (2) amphibole, and (3) biotite-amphibole.

3.2.2. Hornblende-rich gabbro

Spatially, all the four groups of hornblende-rich gabbro are closely interconnected and inclined to the western part of the ridge (**Figures 1, 2**). All of them form a petrographically unified series, where each consequent phase exposes similarity to the preceding one, while the end members significantly differ from each other. Simultaneously, geological relations among rocks of the distinguished groups are more sophisticated. Let us characterize the rocks that served as the subject of discussion in more detail.

Amphibole microgabbro *norites: structure, composition, correlation with basic crystalline schists of the granulite facies:* Amphibole microgabbro *norites* of the discussed area are notable for their quite original banded structure, really making them look somewhat similar to crystalline schists. On the background of finely grained (0.1–0.8 mm) bluish-dark-gray basic mass, they contain boldly distinguished lenticular polycrystalline aggregates of black “cribrose” hornblende, reaching a few centimeters in length (most frequently 0.5–1.5 cm). They are always mutually parallel-oriented and concentrate into bands to a few centimeters wide, separated by much wider bands, where amphiboles cannot be distinguished through a naked eye. Similarity of the basites described here with metamorphous formation is strengthened by the presence of weak leucogabbro veinlets similar to the migmatite leucosome. Characteristically, in the vicinity of leucogabbro veinlets, lenticular segregations of hornblende are absent, but on their boundaries, its subautomorphic crystals and nests are often differentiated (**Figure 4**).

Through the microscope, signs of the magmatic origin of the rocks under discussion are established unequivocally. The fine-grained mass (plagioclase 50–60%, clinopyroxene 20–25%, hornblende 10–15%, hypersthene 5–8%, magnetite 5–10%, singular grains of apatite, ilmenite, zircon) exposes the clear trachytoid structure determined by the oriented location of strongly elongated plagioclase laths. They are almost always weakly zonal. The anorthite molecule content is most frequently about 80% but subject to noticeable fluctuations (95–55%). Chemical composition of rock-forming minerals is presented in **Table 1**.

Characteristic is microbanding of spots that externally seem homogeneous. It is associated with varied granularity and layer composition. Millimeter “leucosomes” are utmost in grain size and plagioclase content in the range of such differentiation. Characteristics for clinopyroxene-pale diopside are its reactional ratios with hornblende, inside which it is often kept as separate inclusions, fading simultaneously. General mafic index is about 25%; alumina content, 0.69–1.68%; sodium is completely absent. Large subsolidus calcium hornblende aggregation, with its typical brownish-gray or brownish-green color, has poikilocytic structure due to chaotically oriented inclusions represented by finest plagioclase laths and hypersthene grains. General mafic index of hornblende is 33–35%. The equation calculation showed that practically all the alumina in it is within the quarter coordination. Hypersthene most frequently forms small, partly automorphic crystals with clear pleochroism. Its general mafic index is slightly higher than that of hornblende (36–38%). The typomorphic peculiarity of microgabbro *norites* is a high content of magnetite, which forms large independent aggregation, as well as numerous smaller inclusions in plagioclase and clinopyroxene. According to the data from the microprobe analysis, it is practically pure magnetite with small admixtures of Ti, Al, Mg, Mn, and Ca. The comparative petrographic and mineralogical characteristics of amphibole microgabbro *norites*

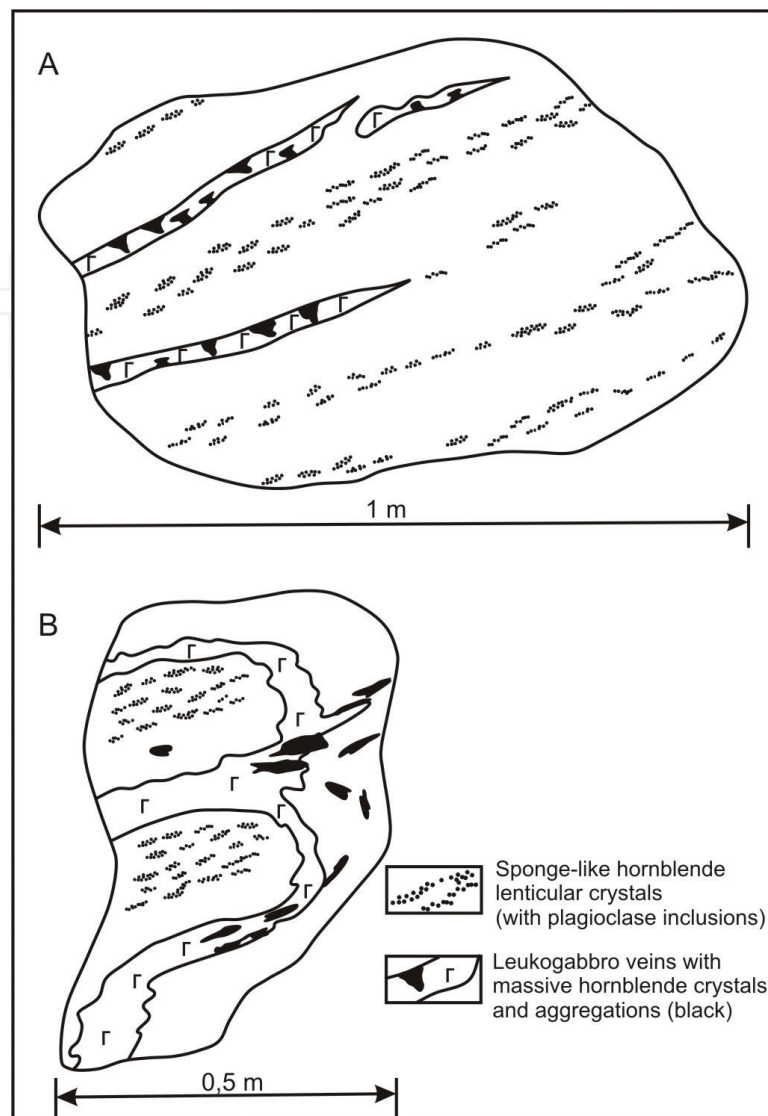


Figure 4. Banded texture of amphibole microgabbronorites in a natural outcrop (sketch by I. Zhulanova): the sections orient respectively: A—perpendicular, B—parallel to banded texture.

and mineralogically identical (amphibole-two-pyroxene) Archean crystalline schists obviously confirm the genetic difference between the two groups of rocks (**Tables 2 and 3**).

But the deep genetic difference between amphibole microgabbronorites and basic granulites is most completely revealed by the analysis of peculiarities of the bulk chemical composition of the rocks (**Table 4**, column 1). The available selection of nine analyses is sufficiently homogeneous. Among general peculiarities, the most conspicuous is the low grade of silicic acid in some samples. Only one of nine analyses has an average of this parameter (48%). All the rest are at the lower limit of SiO_2 content accepted for normal basic rocks (45%), and even go lower (to 41%). Extremely low is also the content of metalloids, especially potassium. On the other hand, the alumina content in amphibole microgabbronorites is sufficiently high (to 17%). Simultaneously, the total Fe_2O_3 iron, magnesia, and lime are maximal for its group [34]. The ratio of ferrous iron and protochloride iron is typical for iron-rich leucobasals (8:6, oxidation ratio is 60%).

Component	Sample 528			
	Pl	Hbl	Opx	Cpx
SiO ₂	46.72	48.23	51.77	52.81
TiO ₂	n.d.	1.58	0.21	n.d.
Al ₂ O ₃	33.00	6.29	0.66	0.69
Fe ₂ O ₃ *	0.66	15.15	25.82	10.18
MnO	n.d.	0.29	0.76	0.27
MgO	n.d.	15.19	22.28	14.61
CaO	17.21	11.28	0.81	22.29
Na ₂ O	1.95	0.55	n.d.	n.d.
K ₂ O	0.11	0.03	n.d.	0.05
Total	99.65	98.59	102.31	100.90
F		33	36	26

Component	Sample 645-1				Sample 645	
	Pl	Hbl	Opx	Cpx	Pl	Opx
SiO ₂	51.03	50.50	52.28	52.75	52.03	52.69
TiO ₂	n.d.	0.87	0.14	0.13	0.00	0.16
Al ₂ O ₃	31.14	5.91	0.76	1.38	29.83	0.91
Fe ₂ O ₃ *	0.53	15.41	26.60	10.77	0.30	25.95
MnO	n.d.	0.36	1.07	0.35	0.06	0.91
MgO	n.d.	14.31	20.95	13.51	0.00	21.01
CaO	14.56	11.78	0.78	22.26	14.36	1.01
Na ₂ O	2.89	n.d.	n.d.	n.d.	3.37	n.d.
K ₂ O	n.d.	0.05	n.d.	n.d.	0.07	n.d.
Total	100.15	99.19	102.58	101.15	100.02	102.64
F		36	38	28		38

Note. Here and below: Ol—olivine, Opx—orthopyroxene, Cpx—clinopyroxene, Hbl—hornblende, Pl—plagioclase, Sp—spinel. Fe₂O₃* = FeO + Fe₂O₃ (as Fe₂O₃), F = Fe₂O₃* / (Fe₂O₃* + MgO + MnO), n.d.—the element was not detected or was not determined. Mineral analyzes were performed using a microprobe Camebax by V.V. Knauf (VSEGEI, St. Petersburg).

Table 1. Microprobe analyses of rock-forming minerals from amphibole microgabbro-norites, wt. %.

The basic peculiarity of amphibole microgabbro-norites is the unusually low SiO₂ content at a large amount of Al₂O₃; it is naturally explained by the reliably established fact of the early segregation of a large amount of magnetite from magma. This forms the deficiency of metals for building mafic silicates, rocks are dressed with plagioclase, and finally remains noncompensated silica, involved in forming later acid differentiates quartz gabbro and hypersthene tonalities. This route of crystallization is provided by high oxygen (or water) potential within

Structural features	
1	Idiomorphic lath-like shape of plagioclase grains indicates its early fast crystallization
2	Simple character of twins determined by their formation simultaneous to the growth of crystals; parallel location of twin planes determined by crystal reorientation in the process of subsidence
3	Direct plagioclase zoning, emerging in the course of its crystallization from the melt
4	Porphyry-like form of hornblende grains indicates its late magmatic growth under free matter access
5	Presence of chaotically oriented smaller laths of plagioclase within large hornblende isolations; testifies to successive crystal sorting from the melt
6	Reactionary relationships between hornblende and clinopyroxene associated with the longer growth of the former
7	Presence of smallest magnetite grains within plagioclase and clinopyroxene testifies to crystallization of the former preceding that of silicates
Mineral composition features	
8	Plagioclase contains 55–95% anorthite molecule (most frequently 80–85%)
9	Orthopyroxene contains less than 1% (0.66–0.91%) Al_2O_3
10	Clinopyroxene contains practically no Na_2O
11	Hornblende contains (wt. %): TiO_2 0.9–1.6, Al_2O_3 –5.9–6.3, $Fe_2O_3^*$ – 15.15–15.41, Na_2O – 0.0–0.5, K_2O – 0.03–0.05; mafic index (F) = 33–35%

Note. The composition of minerals and symbols are shown in Table 1.

Table 2. Petrographic and mineralogical characteristics of amphibole Microgabbronorites.

the system, and, after pioneering works by Osborn [48], has been known as “crystallization at the constant general composition.” Early magnetite segregation also explains noticeably lower mafic index of dark-colored minerals in comparison with bulk mafic index of rocks. The emergence of orthopyroxene is naturally associated with low alkalinity and high alumina of the original magma. Under these conditions, most calcium is associated within plagioclase, which explains its high alkalinity, and hypersthene is crystallized instead of some part of monocline pyroxene. Hornblende is formed on the magmatic stage with the alkaline concentration rise within the system and probably lends some calcium from plagioclase.

Thus, the main factors of specific peculiarities of microgabbronorites are high pressure of volatiles in the melt by the start of its crystallization, as well as the low alkalis and high aluminum in the parent magma. All the revealed proofs of the genetic difference between amphibole microgabbronorites and basic granulites are logically completed with the data on the general pressure value for rocks to be formed.

Since the main reason for Nekrasov to distinguish Archean rocks of the granulite facies in the northern part of the Pekulney Ridge was their amphibole-two-pyroxene mineral composition, above we have deliberately compared them with reliably Archean rocks containing analogous mineral paragenesis. Now, we would notice that, by the chemical composition, amphibole

Structural features	
1	Isometric shape of plagioclase grains with irregular blastic boundaries resulted from crystallization under pressure
2	Very fine polysynthetic twinning of plagioclase with characteristic wedging of one of twin individual systems, indicating the deformational nature of twinning; non-oriented (isotropic) location of twin planes within the rock, pointing at the lithostatic character of pressure
3	Azonal structure of plagioclase or its vague reverse zoning, determined by Na entering clinopyroxene due to the increased general pressure
4	Mostly similar sizes of all mineral grains at possible growth of any of them (metamorphic differentiation)
5	No impurities within hornblende, particularly no minerals with elements of idiomorphism
6	Stable structural (blastic) relations among all minerals without signs of reactionary relationships
7	Equidistance of magnetite grains within the rock indicating its crystallization simultaneously to that of other minerals
Mineral composition features	
8	Plagioclase contains 47–55% anorthite molecule (due to the transition of part of calcium into garnet)
9	Orthopyroxene contains over 1% (1–6) Al_2O_3
10	Clinopyroxene contains 0.2–1% Na_2O
11	Hornblende contains (wt. %): TiO_2 – 2, Al_2O_3 – 12, Fe_2O_3 – 23, Na_2O – 1.5, K_2O – 2.2; mafic index (F) = 58–60%

Note. These properties, including mineral compositions, refer to the amphibole-two-pyroxene crystalline schists from the Aulandzha Block of the Omolon Massif basement [49]. Their Paleoproterozoic age is confirmed by the latest results of U–Pb SHRIMP-RG dating of zircons [51].

Table 3. Petrographic and mineralogical characteristics of amphibole-two-pyroxene crystalline schists.

microgabbroic rocks of the Pekulney Ridge do not correspond to amphibole-two-pyroxene crystalline schists but to eclogite-like rocks: only for them typical is low silicic acid with high alumina and iron [47, 49]. Under high general pressure, characteristic for Archean granulite complexes, such component ratio determines crystallization of garnet, a barophilic mineral rich in alumina and iron but silica-poor. High pressure also provides including a large amount of calcium in garnet, which determines stably low alkalinity of plagioclase in eclogite-like schists [50]. Simultaneously, sodium (jadeite molecule) goes from plagioclase into diopside, but its amount is not large and does not compensate the loss of calcium. Similar composition peculiarities are typical for eclogite-like rocks of the Southern Pekulney, as well [10].

The discussion was finalized by the results obtained by Siberian geologists in the course of large-scale program works on the comparative study of ophiolite petrogenesis conditions in intracontinental folding systems and of ocean-continent transition zones (Siberia, Urals, Mongolia, Chukotka, Kamchatka and others), a few years after our works [51, 52]. Plagioclases and clinopyroxenes from the Pekulney Ridge rocks, described in [5–7] as Precambrian amphibole-two-pyroxene crystalline schists, contain melt inclusions, which is

Component	Gabbro				Veins		
	1	2	3	4	5	6	7
SiO ₂	44.6	44.50	45.7	49.00	53.9	68.30	72.04
TiO ₂	0.9	0.70	0.60	0.60	0.5	0.57	0.40
Al ₂ O ₃	17.30	18.70	17.50	17.10	20.8	15.44	14.27
Fe ₂ O ₃ *	14.20	11.10	10.20	9.80	6.5	4.41	3.32
MnO	0.21	0.17	0.15	0.14	0.1	0.06	0.06
MgO	7.40	8.50	8.80	8.00	4.8	1.64	1.04
CaO	12.10	12.50	13.10	11.00	10.4	5.56	3.90
Na ₂ O	2.20	2.40	2.20	2.60	2.8	3.49	4.66
K ₂ O	0.29	0.39	0.28	0.45	0.4	0.42	0.46
P ₂ O ₅	0.10	0.07	0.05	0.06	0.06	0.10	0.04
LOI	0.50	1.10	1.30	1.30	0.4	0.62	0.53
Total					100.06	100.61	100.72
Sr	334	318	277	269		339	314
Ca/Sr	258	284	332	298		115	87
F	49	40	37	38	57	58	63
n	9	5	2	3	1	1	1

Note. 1—amphibole microgabbbronorites, 2—pyroxene-amphibole gabbro, 3—amphibole gabbro, 4—biotite-amphibole gabbro, 5—quartz gabbbronorite, 6—hypersthene tonalite 7—amphibole plagiogranite. Here and in **Table 6** rock analyzes were performed using the X-ray spectrometer ARL-72000 under the direction of V.Y. Borchodoev (NEISRI, Magadan); oxide content—wt. %, Sr—pm, n—number of analyzes.

Table 4. The chemical composition of hornblende-rich gabbro, and the accompanying veins.

an indisputable indicator of the magmatic genesis of the rocks under discussion. The author has diagnosed them as gabbbronorites and amphibole gabbbronorites crystallized within the temperature interval 1250–1300°C ([52], p. 142).

Now, let us briefly describe other petrographic groups of gabbro, rich in hornblende, as well as the associated vein formations. In more or less solid blocks, it is established that amphibole microgabbbronorites and *pyroxene-amphibole gabbro* are closely connected with each other within unified geological bodies. It is important that amphibole microgabbbronorites are inclined to a lower hypsometric level, exposing mostly in long core outcrops along canyon-shape valley sides. In general, pyroxene-amphibole gabbro are most widely developed of all hornblende-rich gabbro.

Amphibole gabbro insignificantly differs from pyroxene-amphibole ones in samples and thin sections. From the outside, they are somewhat larger-grained and homogenous. At the same time, on the background of amphibole microgabbbronorites, amphibole gabbros are mapped as independent bodies with borders sufficiently clear, because they clearly crosscut microgabbbronorite banding as well as systems of parallel leucogabbro veinlets, characteristic for

microgabbro and pyroxene-amphibole gabbro. *Biotite-amphibole gabbro*, in turn, has a lot in common with amphibole gabbro but presents the type already normal for Russia's North-East: medium-grained basic rocks with columnar hornblende and plagioclase more acid than the one in the previous group, which is seen in the sample by its dull white (not glass-gray, as in previous groups) coloring. Biotite-amphibole gabbro composes the southwestern part of the Svetlorechensky Massif and is separated from other types of amphibole gabbro by faults (**Figure 1**). A rather monotonous petrographic outlook of the "amphibole microgabbro-biotite gabbro" series is significantly varied in the geological sense by vein leucocratic rocks. They fall into three groups: (1) leucogabbro, (2) hypersthene tonalities, and (3) amphibole plagiogranites.

Leucogabbro is a relatively largely grained differentiate characteristic for all types of the amphibole gabbro. However, in dark-colored microgabbro and pyroxene-amphibole gabbro, they are distinguished with more contrast than in lighter amphibole and biotite-amphibole gabbro. Irrespective of the host rock composition, in all leucogabbro, short-prismatic hornblende prevails among dark-colored minerals. In amphibole microgabbro and pyroxene-amphibole gabbro, it is joined by hypersthene, associated with quartz. However, plagioclase maintains its high basicity, and by their bulk chemical compositions, such variations stay within the gabbro group. *Hypersthene tonalities* are largely grained greenish-white rocks of stroke texture; they compose veins to a few meters thick, which, on the one side, do not go beyond the pyroxene-bearing gabbro contours and, on the other side, act independently in the geological sense. At some sites, the volume of hypersthene tonalities exceeds that of the substance, and the latter acts as xenolites with traces of dislocation and deformation. With parallel vein location, rocks generally acquire the outlook resembling layered migmatites; with chaotic substance block orientation, agmatites. *Amphibole plagiogranites* have the outlook similar to that of hypersthene tonalities (inside large bodies, they may be linked with them by gradual transitions). In general, however, they have a much larger area of distribution. In amphibole and biotite-amphibole gabbro, plagiogranites sometimes form compound branching veins that give these rocks an agmatite-like outlook, as well. The largest volume of plagiogranites is found at the western slope of the ridge, where they are traced along its piedmont as a system of independent thick (to 20 m) and long veins.

Geological data permit to conclude that amphibole and biotite-amphibole gabbro characterize different levels of erosional exposure of the same magmatic bodies. The issue of correlations between amphibole microgabbro and pyroxene-amphibole gabbro is more complex. It is discussed below. Chemical compositions of rocks described in Section 3.2.2 are presented in **Table 4**.

3.2.3. Layered series

Hornblende-rich fine- and medium-grained rocks, including amphibole microgabbro, made a total of about two-thirds of the massif part. The rest is built from medium-, large-, and giant-grained gabbroids, which we call the "layered series" (LS). While mapping it, we have distinguished (1) plagioclase peridotites, (2) leucocratic troctolites, and (3) gabbroanorthosites. They compose unified geological bodies with well-expressed banding, from course (dozens meters) to centimeters and even millimeters. Parallel-banded packs frequently are

adjacent to those deformed to different degrees, up to “isoclinally folded” ones. The series is accompanied by lode differentiates: gabbro-pegmatites, ophitic leucogabbro, magnetite gabbro-norites, microferrogabbro.

For field research, the LS is relatively simple. Large sizes of mineral individuals allow to diagnose rock types through the naked eye, and banded textures, clearly expressed in various scales, facilitate drawing boundaries between distribution fields of individual facial variations. On spots of a significant erosion incision, it is systematically exposed that voluminously significant outcrops of melanocratically extreme series members (melanocratic troctolites, plagioclase peridotites) are located in the lower parts of mountain slopes and are upper replaced by leucocratic troctolites. Boundaries between large bodies of both rocks are rather sharp. Leucocratic troctolites and mesocratic olivine gabbro are interconnected by more gradual transitions. In some cases, leucocratic troctolites act toward melanocratic ones as a later active phase. Both variations of troctolites are characterized by weak (2–5 cm) crossveins of finely grained magnetite gabbroanorthosites and even finer blind veinlets of dark-gray microferrogabbro. The largest volume in the series composition is taken by large-grained gabbroanorthosites; distinguished on their gray background are light bands to half-meter thick, build from anchimonomineral anorthosites. Of dark-colored minerals, clinopyroxene always prevails in gabbroanorthosites.

The characteristic member of the LS is made from geologically independent bodies of olivine-amphibole gabbronorites (**Figure 2**). They are highly melanocratic at the maximally complete set of dark-colored minerals in the primary magmatic paragenesis (olivine, two pyroxenes, hornblende). The simplest mineral composition distinguishes ophitic amphibole leucogabbro (further briefly referred to as leucogabbro), which build bodies of the same type as those built from olivine-amphibole gabbronorites. They differ from compositionally close amphibole leucogabbro, described above as differentiates of amphibole microgabbronorites, by reverse structural ratios of plagioclase and hornblende (large idiomorphic tablets of plagioclase are well recognized in ophitic leucogabbro even through the naked eye); but most importantly, by their geological independence. They are spatially attached to large outcrops of the LS rocks (**Figure 2**).

The question of interrelations between the LS rocks with hornblende-rich gabbroids, including amphibole microgabbbronorites, is a key to the problem of the origin of basites in the northern part of the Pelkulney Ridge. At the first sight, each of the two large groups (super groups) is so clearly petrographically specific that it should undoubtedly distinguished into an independent complex. This viewpoint seems to be supported by clearly crosscutting relations between olivine-amphibole gabbbronorites and amphibole microgabbbronorites, which was first pointed at by Nekrasov [5] and then confirmed by our observations. In the upstream of the Raysky Creek, in a bedrock exposure, it is clearly seen that the contact line of olivine-amphibole gabbbronorites, complicated by small apophyses, crosscuts the amphibole microgabbbronorite banding, emphasized by the elongated leucogabbro veinlets. In olivine-amphibole gabbbronorites, in their turn, banding oriented discordantly with that of amphibole microgabbbronorites is observed. Observations on body interrelations in exposures are confirmed by the general structure pattern of the area, as well. The north-northeastern spread of most mapped bodies of olivine-amphibole gabbbronorites is sharply crosscutting the general northwestern orientation of the vein leucocratic phase of amphibole microgabbbronorites and

pyroxene-amphibole gabbro (**Figure 2**). Besides, in gabbroanorthosites occurred small xenoliths of amphibole microgabbroanorthosites.

Like our predecessors, we originally tended to overestimate the facts as determinants, though even then some common signs between the LS rocks and amphibole gabbroanorthosites. For instance, in the course of the 1981 field works, it was fixed that when the two-pyroxene-plagioclase basic mass of microgabbroanorthosites has finely or, at some spots, medium-grained structure, these rocks externally closely resemble the finest-structured variations of olivine-amphibole gabbroanorthosites. This resemblance was the more conspicuous that both rocks are spread in one area, in the Raysky Creek upstream. It was also noticed that microgabbroanorthosite sites containing no hornblende are similar to finely grained magnetite gabbroanorthosites, building thin veinlets in largely grained layered gabbro bodies.

But the greatest attention was attracted by the close spatial connection of the LS rocks with hornblende-rich gabbroids. The 1981 mapping of a sufficiently large area showed that rocks exposed in the vicinities of Lake Romb could not be distinguished into a tectonically independent complex, which, according to [5, 6], has direct structural connections with the South Pekulney ophiolites, since characteristically analogous gabbroids spread far to the north, making the typomorphic components of the basite massif in the northern part of the Pekulney Ridge. It has become obvious that the close location of layered and amphibole gabbroids did not result from an occasional tectonic coincidence of different formations but had a regular character.

Petrographic variety of the LS, in general, is great, however, basically determined by variations of quantitative ratios within the unified set of minerals: olivine, orthopyroxene and clinopyroxene, hornblende, plagioclase, magnetite, spinel; their properties change insignificantly practically within the whole range of rocks, from melanocratic troctolites to olivine-amphibole gabbroanorthosites and microferrogabbro (**Table 5**). The only (and expected) exception is plagioclase. Optical measurements showed that in most voluminous rocks, representing the LS s. stricto (largely grained melanocratic and leucocratic troctolites, gabbroanorthosites, anorthosites), plagioclase is characterized by quite high and, generally, weakly varying content of the anorthite molecule (93–97%), while in the lode series rocks, its behavior is more varied: e.g., in ophitic leucogabbro, plagioclase is extremely rich in calcium (No. 98–100), while in polymineral and highly ferruginous gabbroids (olivine-amphibole and magnetite gabbroanorthosites, microferrogabbro) is noticeably more acid (No. 82–95).

Orthopyroxene is represented by bronzite with the general mafic index varying from 19 to 26%. Judging by the available microprobe analysis from olivine-amphibole gabbroanorthosite, clinopyroxene refers to low-iron diopside (**Table 5**, Sample 643a). In all rocks of the series, from melanocratic troctolites to microferrogabbro, primarily magmatic hornblende is present. In most cases, it is xenomorphic. Only in finely grained olivine-amphibole and magnetite gabbroanorthosites are large hornblende crystals of poikilophitic texture sometimes observed. Hornblende from the LS rocks is more magnesian than that from amphibole gabbroids (**Table 5**, Sample 643a, 629-3-1). Troctolites usually contain rare fine grains of green spinel. It is referred to pleonast, has 38% mafic index, and contains no chromium (**Table 5**, Sample 629-3-2).

Rock structures within the typomorphic LS are typical cumulative. Plagioclase-enriched differences have the gabbro structure, sometimes with elements of the ophitic one. Characteristic

Component	Sample 643a				
	Pl	Hbl	Opx	Cpx	Ol
SiO ₂	44.63	45.25	52.77	51.17	37.08
TiO ₂	n.d.	0.04	0.09	0.09	n.o.
Al ₂ O ₃	34.85	11.88	3.37	2.70	1.47
Fe ₂ O ₃ *	0.29	11.04	18.34	6.88	28.92
MnO	n.d.	0.13	0.34	0.28	0.52
MgO	0.16	16.09	25.92	15.96	34.98
CaO	19.11	11.63	0.93	23.25	0.04
Na ₂ O	0.72	1.30	n.d.	n.d.	n.d.
K ₂ O	n.d.	0.03	n.d.	n.d.	n.d.
Total	99.76	97.39	101.76	100.33	103.01
F		26	26	18	29

Component	Sample 629-3-2				Sample 629-3-1			
	Pl	Opx	Ol	Sp	Pl	Hbl	Opx	Cpx
SiO ₂	44.16	53.23	38.40	0.53	45.52	44.26	52.60	51.28
TiO ₂	n.d.	0.18	0.06	n.d.	0.07	1.93	0.10	0.23
Al ₂ O ₃	35.17	3.94	1.55	63.63	34.18	11.22	2.86	3.26
Fe ₂ O ₃ *	0.37	13.62	20.31	20.20	0.43	11.74	19.06	7.61
MnO	n.d.	0.49	0.55	0.14	n.d.	0.54	1.07	0.32
MgO	0.19	29.19	41.26	16.63	n.d.	14.92	25.24	14.85
CaO	19.46	0.55	n.d.	0.05	18.45	11.60	0.86	23.06
Na ₂ O	0.45	n.d.	n.d.	0.29	1.15	1.36	n.d.	n.d.
K ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	0.05	n.d.	n.d.
Total	99.80	101.20	102.13	101.47	99.81	97.62	101.79	100.61
F		19	20	38		28	27	20

Note. 643a—Olivine-amphibole gabbro, 629-3-2—melanocratic troctolite, 629-3-1—microferrogabbro (vein in sample 629-3-2). A special analysis of Sp on Cr gave a negative result. Mineral analyzes were performed using a microprobe Camebax by V.V. Knauf (VSEGEI, St. Petersburg). Other symbols and notes can be found in **Table 1**.

Table 5. Microprobe analyses of rock-forming minerals from layered gabbro, wt. %.

is high freshness of rocks. More or less noticeable secondary alterations (partial development of zoisite and prehnite in plagioclase, achromatic acicular amphibole in pyroxenes, and talc in olivine and bronzite) are fixed only in most highly magnesian members of the series (plagioclase peridotites). Chemical composition peculiarities of the LS rocks confirm the legitimacy of its differentiation offered on the base of geological and petrographic data (**Table 6**). Simultaneously, calculating the average composition of the LS gabbroids, which could at least

approximately reflect the composition of the original nondifferentiated melt, appears practically insurmountable because it requires knowing volumes of single rock varieties, which is impossible. In our case, the solution of the problem is facilitated by the availability of small-volume weakly differentiated bodies of olivine-amphibole gabbronorites: their average composition, judging by the whole set of the LS minerals in their paragenesis, might be considered original for it, in a first approximation.

Certainly, evaluation of those rocks' average composition also faces problems determined by their textural heterogeneity. However, this with a purposeful approach can be overcome, since bodies of olivine-amphibole gabbronorites are often all-out revealed in base rock exposures. At our disposal, there are five analyses of this group of rocks. They are sufficiently homogeneous, and the average obtained can be considered representative (**Table 6**, column 8). Characteristic is low silica (43.3%) and alkali (12%) with high Al_2O_3 and CaO (17.5 and 13.4%, respectively). The average value of mafic index in the selection has turned out comparatively low (30%). The average value of mafic index in the selection has turned out comparatively low (30%). It is possible that, more objectively, mafic index of the original melt of these rocks as well as of the

Component	The main phase							
	Layered series							
	1	2	3	4	5	6	7	8
SiO ₂	40.24	38.86	42.67	45.37	44.00	41.30	40.80	43.30
TiO ₂	0.25	0.09	0.78	0.12	0.60	1.20	1.20	0.40
Al ₂ O ₃	9.02	24.38	22.98	32.24	21.60	16.50	17.30	17.50
Fe ₂ O ₃ *	13.20	6.47	9.94	1.31	8.20	17.30	16.90	10.50
MnO	0.12	0.08	0.13	0.02	0.10	0.21	0.20	0.16
MgO	25.77	11.32	5.20	0.77	6.30	8.60	9.30	12.40
CaO	5.69	14.20	14.66	17.00	13.10	13.30	11.30	13.40
Na ₂ O	0.54	0.76	1.48	1.25	2.20	1.00	1.20	1.10
K ₂ O	0.04	n.d.	0.05	0.04	0.40	0.05	0.21	0.10
P ₂ O ₅	0.03	0.01	0.05	0.01	0.03	0.03	0.03	0.04
LOI	5.66	3.38	2.03	1.68	3.18	0.69	2.00	1.00
Total	100.56	99.55	99.97	99.81	100.03			
Sr	167	312	355	472		258		271
Ca/Sr	238	319	289	252		362	—	352
F	20	22	49	46	39	50	48	30
n	1	1	1	1	1	4	2	5

Note. 1: Troctolite melanocratic, 2: troctolite leucocratic, 3: gabbroanorthosite, 4: anorthosite, 5: ophitic leucogabbro, 6: magnetite gabbronorites, 7: microferrogabbro, 8: olivine-amphibole gabbro.

Table 6. Chemical composition of the Svetlorechensky pluton rocks.

whole LS reflects included in the selection Sample 644 (38%, collection of Zhulanova), which is a maximally homogeneous finely grained variation of olivine-amphibole gabbronorites. The LS differentiates, marginal in the mafic index value, are magnetite gabbronorites and microferrogabbro (in our analyses, 50 and 48%, respectively).

3.2.4. Discussion of nature

Empirical preconditions for choosing a theoretical model: The material presented above testifies to the fact that in each of the two internally heterogeneous basite associations, there are rocks that most completely characterize peculiarities of the parent melt. In the LS, these are, due to their weak differentiation, olivine-amphibole gabbronorites building comparatively small independent bodies (**Figure 2**). Among hornblende-rich gabbroids, amphibole microgabbronorites are the most interesting. Judging by their petrography (**Table 2**), they represent fast-crystallized facies, most precisely reflecting specificity of primary magmas. Peculiarities of structure and composition of pyroxene-amphibole gabbro were to a great extent determined by the impact of the fluid concentrated in the crystallization chamber with the melt solidification. It is even more obvious with amphibole and biotite-amphibole gabbro. The comparison of olivine-amphibole gabbronorites and amphibole microgabbronorites shows that they possess the features of both similarity and difference. It should be emphasized that their similarity is determined by the kinship of their parent magmas, while their differences are connected with different crystallization conditions. The entity of magmas, from which the LS rocks and hornblende-rich gabbroids were crystallized, is testified to by such peculiarities of chemical compositions of olivine-amphibole gabbronorites and amphibole microgabbronorites as stable low silica and alkali with large amounts of alumina and lime (**Tables 4, 6**). The similarity of mineral parageneses also appears nonrandom. The base of both olivine-amphibole gabbronorites and amphibole microgabbronorites is high-calcium plagioclase, with which orthopyroxene and clinopyroxene as well as hornblende are associated. Olivine, typomorphic for the LS, acts as a nonequilibrium phase in olivine-amphibole gabbronorites. It is kept as relics armored by later dark-colored minerals, and is never observed contacting plagioclase in these rocks. The high share of hornblende in olivine-bearing gabbronorites should be specially emphasized. It usually dominates among dark-colored minerals and, besides, is collected in gabbro-pegmatite lodes.

Now, we will outline the most important differences between olivine-amphibole gabbronorites and amphibole microgabbronorites. First, they are detected in rock textures and structures. Olivine-amphibole gabbronorites, in most cases, are medium- to largely grained rocks with the gabbro structure, while amphibole microgabbronorites have the ophitic one. The main petrographic peculiarity of olivine-amphibole gabbronorites is a different position of magnetite in the general mineralization sequence: while in amphibole microgabbronorites, it appears the first, in olivine-amphibole gabbronorites, on the contrary, it completes magmatic crystallization. To estimate petrological similarity and difference between the two basite associations, in general, it is most efficient to compare the character of internal evolution of each. We should start with the fact that among hornblende-rich gabbroids, there are two independent intrusive phases distinguished from geological data: (1) amphibole microgabbronorites and pyroxene-amphibole gabbro and (2) amphibole and biotite-amphibole gabbro; both phases are accompanied by their acid differentiates (hypersthene tonalites and

amphibole plagiogranites, respectively). It is essential that amphibole plagiogranites act as geologically independent bodies. Their large lodes, unlike one order smaller veins of hypersthene tonalites, go far beyond the boundaries of their parent intrusions.

The LS exposes two differentiation levels. The first is the brightest, expressed in formation of banding within large unified geological bodies. The second level is represented by the severance of an autonomous lode facies from partly differentiated volumes of magma. However, inside the LS, no large independent phases of intrusion have been fixed; therefore, it appears correct to compare its evolution with that of just the first (main) phase of hornblende-rich gabbroids. In this case, the following differences seem most conspicuous: (1) direction of mafic index changes in the amphibole microgabbro-norites-pyroxene-amphibole gabbro sequence, from the one hand, and within the LS, from the other hand (**Figure 5**); (2) spalling silica-enriched lode differentiates from amphibole gabbroids, while there is no such process in the LS.

The increase in general rock mafic index at the transition from olivine-amphibole gabbro-norites to magnetite gabbro-norites illustrates the most common trend of chemical differentiation of the LS. The same trend is clearly distinguished within the coarsely banded part of the series, as well, when comparing its two main variations: olivine-bearing (melanocratic and

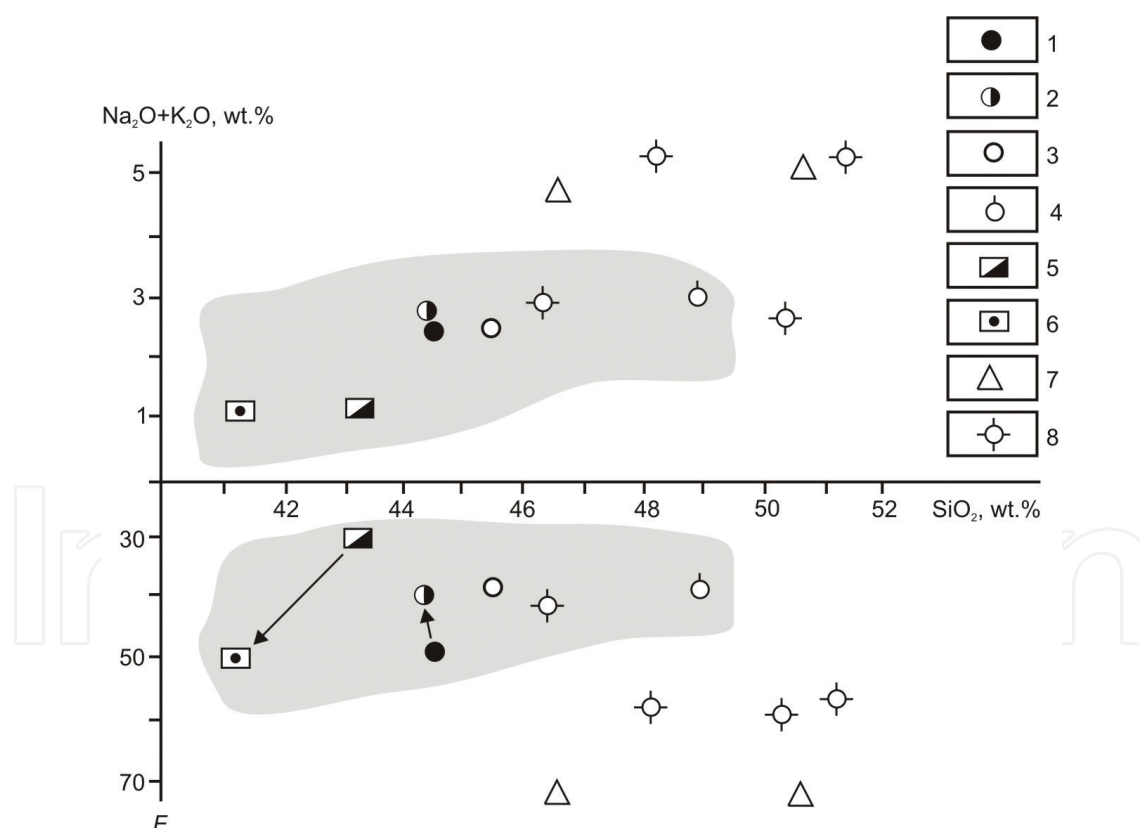


Figure 5. The $\text{SiO}_2 - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ and $\text{SiO}_2 - F$ diagrams for the rocks of the Svetlorechensky complex and gabbroids of other age groups (according to **Tables 4, 6** and [13]): 1–6 – Svetlorechensky complex: 1 – amphibole microgabbro-norites, 2 – pyroxene-amphibole gabbro, 3 – amphibole gabbro, 4 – biotite-amphibole gabbro, 5 – olivine-amphibole gabbro-norites, 6 – magnetite gabbro-norites; 7 – pre-Cretaceous gabbro-norites; 8 – metadolerites of Early Cretaceous Poperechnynsky Complex. The arrows illustrate the opposite trends in the evolution of mafic index F in layered and marginal rock series of the main intrusive phase of the Svetlorechensky pluton. $F = \text{Fe}_2\text{O}_3^*/(\text{Fe}_2\text{O}_3^* + \text{MgO} + \text{MnO})$, $\text{Fe}_2\text{O}_3^* = \text{FeO} + \text{Fe}_2\text{O}_3$ (as Fe_2O_3).

leucocratic troctolites) and olivine-free (gabbroanorthosites, anorthosites) gabbroids (**Table 6**, columns 1–4). Highly ferruginous differentiates (magnetite gabbroanorthosites, microferrogabbro) make one of lode branches of the LS. The second one is represented by ophitic leucogabbro. They are noticeably richer in alkali than all other rocks ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ make 0.58–1.53 and 2.60%, respectively; **Table 6**), sometimes contain quartz, and, by these signs, might be considered a sort of homologs of quartz-bearing differentiates of the amphibole gabbroid group. However, by their silicic acid content, ophitic gabbro practically does not differ from anorthosites (in our analyses, 44.00 and 45.37%, respectively; **Table 6**, columns 5, 4), and by this parameter are not comparable to silicic lode derivatives of the first phase of amphibole gabbroids, quartz gabbroanorthosites and hypersthene tonalities (53.9 and 68.3% SiO_2 , respectively; **Table 4**, columns 5, 6). The analysis of differences in the direction of petrological evolution of the first phase of hornblende-rich amphibole gabbroids, from the one hand, and of the LS, on the other hand, served as a key to deciphering the essence of interrelation between two basite associations in the northern part of the Pekulney Ridge, which, finally, permitted to unite them within a unified magmatic complex. It was found that all exposed peculiarities of basites in the studied area, both similarities and differences, can be consistently correlated if interpreted in accordance with the latest theoretical views of the mechanism of forming layered intrusions.

On factors and conditions of magmatic layering phenomenon: For over a 100 years (since the first experiments of Bowen), layered intrusive massifs have served a basis for developing fundamental problems of magmatism and ore genesis. Widely discussed are the role of volatile components, liquation, assimilation, convection, and other processes in formation of magmatic stratification. Qualitative progress in understanding the mechanism of their development was accomplished due to involving the data on crystallization of metallurgic and petrographic molds. Having generalized those, Sharkov offered the first model of layered intrusion based on the general consolidation theory [53]. Fundamental is the conclusion on the natural division of the liquor, filling the chamber of the future layered intrusion establishing, into two parts, marginal and interior, essentially different in temperature regimes; they are crystallized in principally different ways: the larger is the magmatic mass volume, the more conspicuous are the differences [54].

In *marginal* parts, consolidation occurs in the conditions of sharp supercooling. Since the temperature gradient vector is perpendicular to the heat emission surface, primary textures of marginal faces are conform to contacts. Due to sharp supercooling, in marginal zones, mineral parageneses of solidus are immediately formed. Spots with lowest temperatures may then have compositions identical to that of the parent liquor. Differences in temperature regimes of the subbottom, lateral, and upper endocontact zones determine certain differences in composition and structure of rocks building respective spots. Within bodies of lens- and blanket-like shape, the lateral series can be partly or completely reduced. Low-thickness bodies are totally crystallized according to the marginal series pattern. In *central* parts of large intrusions, separated by the marginal “crust” from cold enclosing rocks, crystallization occurs in conditions maximally close to the equilibrium. As a result, here the crystallization zone is formed: one part of it corresponds to the liquidus isotherm; another, that of solidus. At the crystallization front, highest temperature phases are distinguished. Depending on the density ratio, crystals may sink, remain suspended, or float up. The residual liquor systematically changes its

composition toward enrichment with easily fusible components. Correspondingly, the central series section, in general, reflects the succession of fractional crystallization of the parent liquor. Under the impact of the Earth gravity field, the crystallization front is always horizontally oriented, which determines autonomous inner structure of the intrusion marginal parts in respect to its marginal zones. Textures of the LS rocks are predetermined by the ratio of crystals and liquor density; structures, by interaction of minerals with the interstitial liquor.

For interpreting the nature of the Svetlorechensky pluton, the statement of mandatory presence of rapidly crystallized marginal facies in large layered bodies is of primary interest. This theoretically grounds the close spatial connection between the LS and hornblende-rich gabbroids that we established by geological mapping. The principal similarity of the North Pekulney LS with central series of classical layered intrusions is proved not only by direct structure-texture signs and commonness of chemical composition but also by the fact that minerals, which constitute the classic Bowen reaction succession, create the petrographic diversity of our LS. Of peculiarities of this LS, we should notice (1) leucocratic rocks domination, (2) extremely high plagioclase basicity in all differences, (3) small range of mafic index fluctuations in olivines and rhombic pyroxenes, (4) high-calc composition of clinopyroxene, (5) scarcity of ore minerals, and (6) no chromium in spinel. Ultrabasic members of the series, judging by their geological and petrographic characteristics, are products of the liquidus olivine accumulation in subbottom parts of the crystallization chamber. Specific characteristics of amphibole microgabbro-norites are (1) finely grained structures, (2) trachytoid textures, (3) mutually parallel orientation of lens-like accumulation of hornblende and leucogabbro veinlets; this makes their outlook resemble that of granulites. All the abovementioned unequivocally indicates high velocity of crystallization of amphibole microgabbro-norite parent liquor in physically, chemically, and mechanically anisotropic substance. From the viewpoint presented, one can logically explain not only all signs of petrochemical kinship between the LS and amphibole microgabbro-norites but also all differences between them. Many peculiarities of the inner structure of the Svetlorechensky pluton point at the influence of the thermal shrinking process, whose role in the mechanism of layered plutons establishing is generally quite essential [55].

Uniting the LS and hornblende-rich gabbroids of the first phase into the unified Svetlorechensky pluton, based on Sharkov model [53, 54], permits to make conclusions on possible composition of the parent liquor. It is obvious that minimally differentiated, structurally homogeneous variations of marginal microgabbro-norites, containing no large segregations of later hornblende, have closest similarities to the composition of the parent melt. In our collection, it is Sample 5656, characterizing the pluton marginal zone exposed to the north of the Raysky Creek (see **Figure 2**). In the selection of nine samples, characterizing amphibole microgabbro-norites (**Table 4**, column 1), this rock represents the silica-richest variation. It contains 48.37%—SiO₂, 0.70%—TiO₂, 17.44%—Al₂O₃, 10.82%—(Fe₂O₃ + FeO) in the form of Fe₂O₃, 0.22%—MnO, 6.95%—MgO, 11.03%—CaO, 3.8%—Na₂O, 0.3%—K₂O, 0.09%—P₂O₅, and in these parameters corresponds to the typical basalt in the tholeiite series of island arcs [56].

Now, we will mark peculiarities that distinguish the Svetlorechensky pluton from classical layered intrusives localized in tectonically stable structures (ancient platforms, Precambrian shields) [54]. Petrologically, the most obvious difference is the wide development of hornblende-rich rocks in the Svetlorechensky pluton. They are systematically present within the

LS, dominate among the marginal group formation, and, besides, build an additional intrusive phase of amphibole and biotite-amphibole gabbro. Abundance of hornblende indicates high content of volatile components in the liquor that generated Svetlorechensky pluton; this had been determined by the special geological and tectonic situation, in which the parent liquor was melted and crystallized (see below).

3.2.5. *Timing of magmatism*

The principal difficulty of geologically dating the Svetlorechensky gabbro complex is connected with low probability of relations between magmatic rocks and surrounding sedimentary-volcanogenic masses, not violated by faults. This, in its turn, is explained by deep erosion of the Svetlorechensky pluton in the course of great neotectonic uplift of the axis part of the ridge. Even purposefully studying contact zones, we managed to observe active relations with Barrias-Valanginian (the Tithonian-Valanginian Gruntovsky Strata [14]) only in amphibole gabbro of the additional intrusive phase (**Figure 2**). The most petrographically perfect (indisputable) hornfels, not only in aleurolites but also in basalts, have been revealed in bedrock exposures in the bottom of the trough valley of the Pekulneyveem River, at the place where it leaves the mountains. The undisturbed active contact of amphibole gabbro with enclosing deposits on this very site is causally associated with peculiarities of its position in the current structure of the Svetlorechensky pluton. The Pekulneyveem River valley is an independent narrow block, vertically taking the intermediate position between the two blocks: the northern (higher elevated) and the southern, relatively subsided (**Figure 2**). Due to a favorable combination of faults of different ages, along the youngest of which the river bed had formed with time, in the bottom of its valley, plowed by a glacier, a good intrusive contact between amphibole gabbro and Gruntovsky Strata deposits has remained.

Exposures of rocks of the LS, building the deep part of the Svetlorechensky pluton, are all along bordered by faults. However, it is characteristic that they are systematically associated by small blocks of layered metamorphic rocks. It was them, that were described as hornfels by the Pekulneyveemskaya Suite, then dated by Valanginian [4]. Our data show that these formations refer to a lower structural level than Bajocian-Hauterivian deposits in their current understanding (Pekulneyveemskaya Suite and Gruntovsky Strata [14]). Compositions of metamorphic formations are different on the eastern and the western slope (**Figure 1**). On the eastern slope, at the foot of the ridge, near Sbornoye Lake, a block built by the parametamorphic thick is mapped. At the bottom of the thick, finely grained heteroblastic garnet-biotite-hypersthene gneisses prevail, while in its upper part, garnet-sericite-graphite microschists dominate. On the western slope of the ridge, in the block to the south of the Yuzhnyy Chekogytgyn Lakes, fragments of high-temperature metamorphic complex, presented by apoterrigenous-volcanogenic schists, amphibolites, and gneisses, have been exposed. Amphibolites, with their characteristically systematic admixture in the primary paragenesis of biotite, preserve clear signs of forming due to the bedded volcanogenic formation, including bedding and crosscutting bodies of isofacially metamorphized gabbroids. In the amphibolite mass, all stages of granitization (debasification) with plagiogranitogness formation are traced. Among dark-colored minerals, in plagiogneisses, along with green hornblende of the replaced (granitized) substrate, cummingtonite is systematically present. In finely grained amphibolites, unique centimeter anatectite "nests" of zonal

structure occur, built from biotite-hypersthene plagiogneisses, where Plagioclase 64 contains 1.56% K_2O (charnokitoid trend of anatexis) ([47], Figure 59). On FGM-200/2 metasedimentary, partly metavolcanogenic, comparatively weakly altered formations are distinguished as the supposedly Middle Paleozoic Pekulneygytgyn Strata (assumedly corresponds the Middle-Upper Paleozoic-Early Mesozoic Strata, first described in [6]). Briefly outline above, high-temperature (amphibolite and granulite facies) aposedimentary and apobasalt metamorphic rocks, associated with the LS gabbroids, are referred to the conventionally Paleozoic Sbornensky Strata [14]. Metamorphic formations are intruded by sills and dykes of gabbronorites, diabases, plagiogranites, among which pre- and postmetamorphics are distinguished. On the eastern slope of the ridge, where parametamorphic rocks always contact with the LS gabbroids, both in gneisses and in intrusive bodies (including diabases identical to those of Early Cretaceous), crosscutting them, clear signs of hornfelsing by LS gabbro have been revealed. The only reliable data on the upper age border of the Svetlorechensky pluton are given by biotite plagiogranites, cutting through them: all researchers unanimously refer them to the Early Cretaceous Yanranaysky complex (**Figures 1, 2**). To the north of Lake Pekulneygytgyn, biotite plagiogranites cut through the LS (**Figure 1**). Besides, the Yaranay complex granitoids are interesting for numerous xenoliths of basic rocks and act as their inseparable attribute (typomorphous peculiarity). Our collection contains amphibole and biotite-amphibole hornfels by volcanogenic rocks, amphibolites identical to the Sbornensky mass rocks, finely grained two-pyroxene basites—most probably, “pre-Svetlorechensky.”

In the area of the Pekulney Ridge, to the south of 66°00' N (conventional border between geologically different southern and eastern parts of the ridge, corresponding the border of FGM-200—see above), the total area of the Svetlorechensky complex rocks is estimated approximately 35 km² (**Figure 3**) [14]. It has been established that on the western boundary of the Pravoberezhny intrusion, on a site about 3 km long, the contact of gabbro with terrigenous-volcanogenic deposits of the Tithonian-Valanginian Gruntovsky Strata has the intrusive nature. It is expressed by the hornfelsing zone, top tens of meters thick. In its northern part, the Pravoberezhny intrusion is cut through by an intrusion of the Yanranaysky complex plagiogranites; at the contact with the intrusion, gabbro had been brecciated and overlappingly amphibolized [14]. The age of the Svetlorechensky gabbro complex on FGM-200/2 sheets has been accepted as Valanginian, with a reference to the combination of geological and geochronometric data [14]. They are critically discussed below (Part 4), with all other materials that permit to estimate the time of the Pekulney Ridge basalts formation with maximum correctness, from today's viewpoint. Obviously, without it, any advance in geological, tectonic, and geodynamical discussion on the issue would be impossible.

4. Svetlorechensky gabbro complex as a geodynamical indicator

Reconstruction of the Inner Structure of the Svetlorechensky Layered Pluton: The offered pattern of the inner structure of the Svetlorechensky pluton (**Figure 6**) is a “composite construction” with all elements observed on the contemporary erosional section of the ridge but in an offset position. The Pekulney Ridge belongs to the category of young mountain structures, where relief forms directly depend on the amplitude of the Earth crust uplift, which, as a rule, is inherited. The researched part of the ridge, located between the upper Bychya River and the

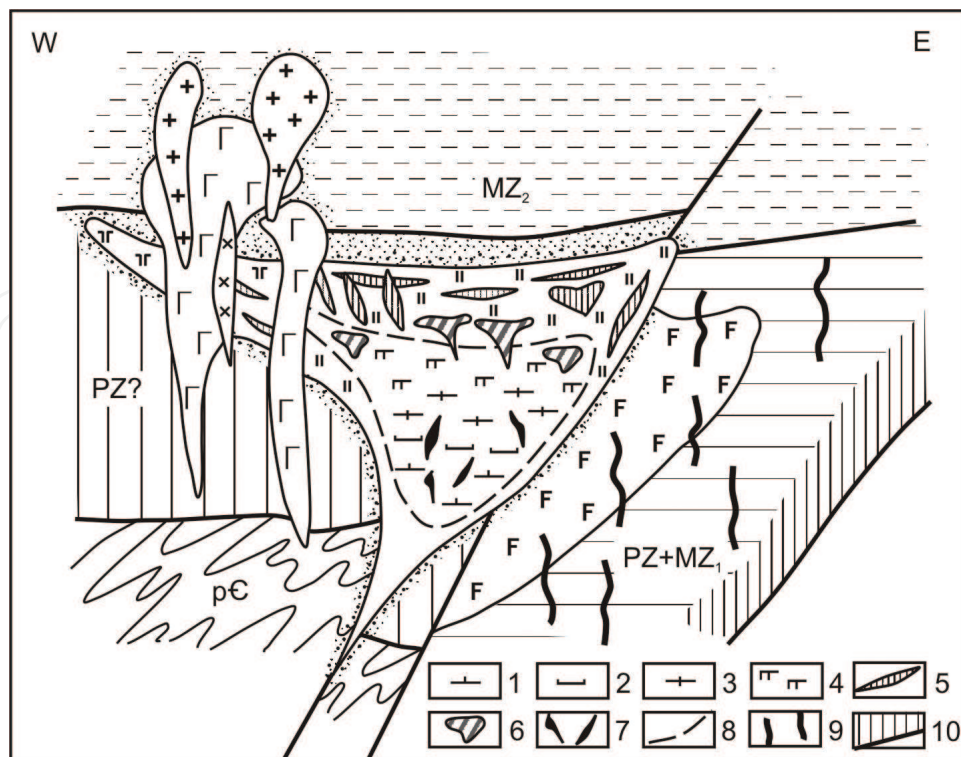


Figure 6. Reconstruction scheme of the internal structure of the Svetlorechensky layered pluton (at the latitude of the Pekulneyveem River): 1–7—stratified series: 1—plagioclase peridotites, melanocratic troctolites, 2—leucocratic troctolites, olivine gabbro, 3—gabbroanorthosites, anorthosites, 4—amphibole-olivine gabbroanorthosites, 5–7—vein facies of a stratified series: 5—olivine-amphibole gabbroanorthosites, 6—ophitic leucogabbro, 7—magnetite gabbroanorthosites and microferrogabbro; 8—boundary between stratified and edge series; 9—dykes and small intrusions of the Ostrozubsky and the Poperechninsky complexes; 10—general inclined fault. See **Figure 2** for the remaining symbols. Explanations are in the text.

through valley, housing the South Chekogytgyn Lakes (**Figures 1, 3**), is the most uplifted and dissected fragment of the ridge. In its turn, it is longitudinally asymmetric: its eastern half is noticeably more uplifted than the western one. It was this fact that permitted to assume already on the first stage of the research that the successive replacement of hornblende-rich gabbro by the LS, observed on the right bank of the Pekulneyveem River from the west to the east (**Figure 2**), characterizes pluton sections differing in depth. Henceforth, a solid pro for such interpretation was the data of the parametamorphic rocks (lower parts of the conventionally Paleozoic Sbornensky Strata [14]) systematically attached to the LS.

The next item that requires a comment is the general asymmetry of the Svetlorechensky pluton. Geological mapping has established that the layered section rocks are always located more to the north than hornblende-rich gabbroids. Only on the western slope, amphibole and biotite-amphibole gabbro are observed, building the additional intrusive phase bodies and amphibole plagiogranite lodes. Only in the western part of the ridge are outcrops of granitized apoterrigenous-volcanogenic amphibolites (upper part of the Sbornensky Strata) known. In the north of the area, they build a large block cut through by small bodies of the additional phase amphibole gabbro (**Figure 1**); in the south, by xenoliths in the Yanranaysky granitoid complex.

We assume that the eastern contact of the Svetlorechensky pluton subsides to the west, and that such body morphology fixes the principal position of the canal (fault system), along which the magma of the main intrusive phase had intruded. In this case, the formation of

large volumes of layered gabbroids at the eastern edge of the pluton establishing chamber would be explained by the fact that here, due to the heat flow along the faults, the liquor was crystallized slowly, in the conditions close to the equilibrium, which is the main factor causing layering [54]. The pluton western part, built from finely grained marginal facies, appears a lopolith-like “tongue,” extending rather far from the main chamber into enclosing rocks. Subhorizontal location of this part of the massif is directly witnessed by the dominating gentle sloping of such inner elements as the system of hypersthene tonalite lodes, leucogabbro veinlets, hornblende bands in amphibole microgabbro norites. Our data imply that the vertical thickness of gabbroids of the Svetlorechensky pluton marginal series in the western part of the ridge is not large. The most unbalanced facies of the Svetlorechensky gabbro complex (amphibole microgabbro norites with banded texture) are clearly drawn to the lowest hypsometric relief level, above which they transfer to much better crystallized pyroxene-amphibole gabbro. Such correlations can be explained only by the fact that in this part of the ridge, amphibole microgabbro norites build the lower endocontact.

The bottom of the body of the first-phase hornblende-rich gabbro (marginal series) is built from metamorphized basic rocks. Most completely, the bottom of the marginal series gabbroids is characterized by granitized amphibolites, building the block to the south of the Yuzhnyy Chekogytyn Lakes. Granitization of amphibolites indicates that in the period of metamorphism, these rocks were in the uplifted (hanging) wing of the fault zone, where decompression and free fluid influx took place. Parametamorphic rocks (lower part of the Sbornenskaya Strata), spatially attached to the LS, on the contrary, correspond recrystallization products under higher general pressure by all petrological characteristics. This embarrassed melting but promoted crystallization of barophilic garnet, which is quite rare for the rocks in the northern part of the Pekulney Ridge. This kind of situation is well conformed with geologic and tectonic conditions in the lying wing of the inclined fault zone. The deep melting spot that had produced the Svetlorechensky complex was to the west relative to the crystallization chamber of the LS and connected to it with an inclined conduit while the additional phase was injected by later vertical faults. Only this can explain the spatial separation of the additional phase intrusions and the LS.

Manifestations of “pre-Svetlorechensky” magmatism are fixed to the east of the system faults bordering outcrops of the LS rocks (**Figure 2**). On FGM-200/2 sheets, they are distinguished into the Mid-Jurassic-Early Cretaceous Ostrozubsky complex, uniting bosses and dykes of metadolerites with fissure intrusions of plagiogranites (**Figure 3**); also, the Poperechninsky complex of contiguous dykes of gabbro-metadolerites-plagiogranite-porphyrries, assumedly cutting through the Svetlorechensky complex gabbroids and the Yanranaysky plagiogranites and, thus, dated by the Valanginian [14]. According to our data, neither smaller bodies of the Ostrozubsky complex nor variegated Poperechninsky dykes penetrate Svetlorechensky gabbroids. Misunderstanding here originates from yet another complex of layered gabbroids, older than Ostrozubsky metadolerites (diabases) and fragmentally present in the structure of the eastern slope of the ridge. We first distinguished them on the eastern slope of the ridge to the south of Lake Romb and described them as uralitized gabbro [13]. Mapping showed that uralitized gabbro are widespread in the area as enclosing rock relics (screens) for most of genuine “parallel” dykes (**Figure 2**). The age of uralitized gabbro was originally defined as pre-Cretaceous [13]. At present, we should consider the results of SHRIMP-dating zircons from plagiogranites, which, judging by their description, refer to the Ostrozubsky metadolerite-plagiogranite complex. Zircon dates fall in two domains: Triassic (with individual Late

Permian and Early Jurassic values) and Neoproterozoic-Early Paleozoic [43]. The data on relatively old layered gabbroids (uralitized gabbro complex), present on the eastern slope of the Pekulney Ridge, were a basis for reconstructing the assumed structure of the lying side of the fault-closing tectonic structure enclosing the Svetlorechensky pluton (**Figure 6**).

Thus, the materials in total permit to interpret the Svetlorechensky pluton as a highly asymmetric harpolith localized in the hanging wing of the long-developed horst-anticlinorium. The crystallization chamber must have been located in the presumably Paleozoic basement. The unconformity surface in its sole might have worked as a mechanic and thermal screen, which provided volatiles accumulation at the upper edge of the chamber and slowed its central parts cooling.

On the geodynamic nature of the Svetlorechensky gabbro complex: Materials of our Pekulney Ridge research were broadly discussed in the interested professional community. Our conclusion that there are no outcrops of Archean “granulite-basites,” identical to the oldest complexes in the crystalline basement of the Siberian Platform and Omolon Massif, raised no objection. As to the Early Cretaceous age of all gabbroid variations, presented in the northern part of the ridge, at that time, this opinion was not taken unanimously. The discussion on the possibility of extrapolating our data on Early Cretaceous deposits hornfelsing by amphibole gabbro of the Svetlorechensky pluton additional phase has been completed by the results of new works in the southern part of the Pekulney Ridge [14]. These facts are more than enough to see that the whole volume of the Svetlorechensky gabbro complex had formed in the interval between the accumulation of deposits of the Tithonian-Valanginian Gruntovskaya Strata and the invasion of granitoid intrusions of the Early Cretaceous Yanranaysky complex. Today’s isotopic dating results unequivocally confirm the Early Cretaceous establishing of the Svetlorechensky complex. Three quantitative $^{40}\text{Ar}/^{39}\text{Ar}$ dates of amphibole from the Svetlorechensky complex rocks [44] appear equally important. Two samples characterize the main (layered) phase; one more, the additional. The plateau calculation showed the same age, consistent with the Hauterivian and Barremian border by the International Chart (about 129.4 Ma). Thus, this result completely correlates with the conclusion made on a purely geological basis. It is especially interesting for the purpose of interpreting the geodynamical nature of the Svetlorechensky gabbro complex.

The Hauterivian age is brightly distinguished by the manifestation of facially varied basite-ultrabasite magmatism. The paleontologically characterized (remains of ammonites) Hauterivian mass (lavas, hyaloclastites, tuffs of picrites, picrobasalts, basalts; at the top, thin interbeds of tuffaceous-sedimentary rocks, limestones, ash tuffs of rhyolites) is a component of the Ostantsovogorsky volcanic-plutonic association. The latter unites two complexes of the same name: picrite-basalt-metadolerite and peridotite-gabbro-metadolerite. [14]. The comprehensive research of the rare variation of the Svetlorechensky pluton rocks, orbicular allivalite, resulted in a series of petrological arguments for the genetic kinship of the Svetlorechensky pluton and Hauterivian basite-ultrabasites in the southern part of the Pekulney Ridge, offered by Gelman (1930–2017), a prominent expert in magmatism and metamorphism of Russia’s North-East. In the then absence of data on intrusions of the Svetlorechensky gabbro complex of the ridge southern part, Gelman assumed that the Svetlorechensky pluton was an intrusive analog to the picrite-basalt association, whose development band seems to continue gabbroid outcrops to the south [1]. The current picture of spatial relations between intrusives of the Svetlorechensky and of both Ostantsovogorsky complexes looks somewhat different at the first glance (**Figure 3**), but in fact does not contradict

the described model. Mapping showed that the absence of near-surface basite-ultrabasites in the northern part of the Pekulney Ridge is determined by its intensive neotectonic uplift.

The inner structure reconstruction for the Svetlorechensky pluton (**Figure 6**) permitted to conclude that its establishment took place in the hanging wing of a long-developed anticlinorium. Here, the beginning of basalt magmatism is fixed by small metamorphized bedded bodies of gabbro-norites localized in the lower parts of the conventionally Paleozoic, possibly older (particularly Precambrian, considering the latest zirconometric data [43]) paragneiss-amphibolite Sbornensky Strata. In the actualistic view, the reconstructed structure can be interpreted as an island arc uplift. However, the question of the time of its appearance is still open. The problem of relations of the complexes building the western and the eastern slopes of the ridge also seems debatable. Their interpretation as autochthon and allochthon, respectively and widely acknowledged, is far from indisputable. The thick tectonic suture of the northeastern extent, dividing structures of the western and the eastern slope, comprehensively researched, turned out to be not serpentinite mélange marking the fault sole [5] but the zone controlling the Hauterivian basite-ultrabasite magmatism. According to our data, in the current structure, this suture is reconstructed as a large and, probably, sufficiently old shift, dislocated in the course of later tectonic movements. In the preserved pull-apart structures, there are erratic blocks of deep complexes on the current erosion section, including, according to our observations [10], fragments of at least three geologically independent complexes: (1) deep-seated magmatic ultramafics, uniting the magnesia-calcium (dunites, wehrlites, and clinopyroxenites) and the aluminous-ferruginous (garnet-spinel clinopyroxenites, containing orthopyroxene, pargasite, and magnetite) series; (2) fragments of the frame of aluminous-ferruginous ultramafics, represented by texturally heterogeneous eclogite-like feldspar-free hornblende-rich rocks (stratigraphically equivalent to Lower Archean amphibole eclogites of the Omolon Massif basement [47]); (3) structurally and facially various diaphthorites by rocks of the regional metamorphism granulite facies, analogous to supracrustal Lower Archean formations building the crystalline basement offsets in Verkchoyansk-Chukotka Mesozoids. The purposeful study of garnet-spinel clinopyroxenites, participating in building ultramafic massifs in the southern part of the Pekulney Ridge (Middle Jurassic-Early Cretaceous Pekulneysky dunite-peridotite-gabbro complex [14]), would greatly contribute to developing the geological aspect of the nature of the Svetlorechensky layered gabbroids. By their chemical composition (low SiO_2 , high Al_2O_3 and MgO), those feldspar-free rocks with clear signs of magmatic crystallization are analogous to leucocratic troctolites of the Svetlorechensky pluton [10]. It is natural to assume that they represent the deepest seated facies of the Svetlorechensky gabbro complex.

5. Conclusions

1. The study of the northern part of the Pekulney Ridge started with the aim to identify finely grained thin-banded amphibole-two-pyroxene rocks in the Pekulneyveem River basin with Archean crystalline schists of the analogous mineral composition, brought the author to an absolutely different range of problems. Our research showed that the rocks of disputable genesis are amphibole microgabbro-norites included in the composition of a large intrusive massif. It belongs to a special type, never distinguished in the region before, which has features of layered plutons and multiphase intrusions. The first (main) phase

consists of two different facies, the marginal and the layered; externally, they are sharply different. Amphibole microgabbroites, whose nature served as a subject for discussion, are a typical component of the marginal series. Their petrographic peculiarities that make them externally similar to amphibole-two-pyroxene crystalline schists are determined by the high velocity of crystallization in the anisotropic substance of the intrusive chamber exterior. The main volume of the intrusive is the layered series differentiated from plagioclase peridotites and troctolites to olivine-amphibole gabbroites. According to the data obtained, the parent magmatic melt was alumina-rich and alkali-poor. By the principal parameters of its chemical composition, it corresponds to the typical basalt of the tholeiite series of island arcs. The second (additional) intrusive phase is built by amphibole and biotite-amphibole gabbro. It is accompanied by a vein series of amphibole plagiogranites.

2. The researched intrusion was named the Svetlorechensky-layered pluton and is considered a petrotype of the intrusive gabbro complex of the same name. The pluton area exposed on its current section is no less than 200 km². By the present, the Svetlorechensky gabbro complex intrusions have been also mapped on the eastern slope of the southern part of the ridge, but here they are significantly smaller in size. Critical consideration of geological and geochronological data available today permits to conclude that the most probable time of establishing the Svetlorechensky gabbro complex was the Hauterivian. Some petrological and geological indicators support the previously published hypothesis of genetic kinship of the Svetlorechensky gabbro complex with the Ostantsovogorsky volcanic-plutonic basite-ultrabasite association, whose Hauterivian age has been paleontologically confirmed.
3. The deep structure reconstruction of the Svetlorechensky layered pluton, based on geological mapping materials, permitted to interpret it as a heavily asymmetric harpolith localized in the hanging side of a long-developed horst-anticlinorium (ancient island arc uplift). The determinant of its evolution was the system of long-lasting deep faults inclined under the Paleoasian Continent¹.

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