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Structural–Kinematic Evolution of the Central Belomorian–Lapland Belt in the Paleoproterozoic

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Abstract—A model of the evolution of the central Belomorian–Lapland Granulite–Gneiss Belt is proposed on the basis of analysis of the Paleoproterozoic structural–kinematic assemblages. It is shown that this tectonic zone is a long-lived mobile structural unit that evolved through several stages of tectonic transformation and metamorphism of rocks, including (1) the Reboly stage, which comprises subduction (2.88–2.82 Ga) and collision (2.74–2.53 Ga) substages; (2) the Selet stage of rifting and extension of the continental crust according to the model of simple shear (2.45–2.35 Ga); and (3) the Svecofennian stage, characterized by collision and general transpression (1.94–1.75 Ga). The results of structural–kinematic study indicate that tectonic flow in the Svecofennian time was nonuniform and related to the formation of the Kolvitsa–Umba near-horizontal protrusion. The propagation of this protrusion was caused by transpressional extrusion of plastic lower-crustal masses to the surface as a gently ascending tectonic flow directed to the northwest (in present-day coordinates). Thereby, a thrust–normal-fault kinematic effect was expressed in pushing-out of deep-seated complexes contemporaneously with tectonic erosion of the upper portions of the sequence owing to the development of low-angle normal faults.

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INTRODUCTION

The reconstruction of the tectonic evolution of the lithosphere in the Early Precambrian is one of the most complicated problems of modern geology. The new geophysical, isotopic, and geochemical data allow application of the actualistic approach to geodynamic interpretation of the Archean and Paleoproterozoic events. However, the same initial data are often interpreted from different standpoints based on the theory of plate tectonics, intraplate models of crustal evolution, or the ideas of mantle plume ascent. In this context, the application of the methods that provide additional information for the solution of debatable issues would not be out of place. In particular, the structural–kinematic data on the character and direction of tectonic movements supplement other geological evidence and promote the development of adequate geodynamic models. An attempt to reconstruct the evolution of the central Belomorian–Lapland Belt in the Baltic Shield is made on the basis of the original data obtained with modern structural–kinematic methods.

GEOLOGICAL OUTLINE

The Belomorian–Lapland Belt—one of the most important structural zones of the Baltic Shield—separates the Neoarchean Kola and Karelian massifs. This tectonic province is known in the literature under different names: the Belomorian–Lapland granulite–gneiss belt, the Belomorian geoblock or microcontinent, the Belomorian fold zone or rift system, a belt of tectonothermal reworking, and the Belomorian–Lapland mobile or collision belt. Such a wide range of terms is due to consideration of the origin of this zone from different viewpoints [3–5, 11, 12, 23–25, 27, 36, 40, 44].

The Belomorian–Lapland Belt is composed of granulite–gneiss and amphibolite–gneiss rock associations reworked by granitization to a variable extent. The steady, polycyclic development of high-pressure metamorphism under conditions reaching granulite and eclogite facies is one of the relevant attributes of this belt [11, 12, 17, 36]. In addition, the multiphase folding, doming, migmatization, and ultrametamorphism; abundant minor basic intrusions emplaced at a high pressure (drusites dated at 2.45–2.35 Ga); and rare-metal and muscovite pegmatites (1.90–1.75 Ga) are specific features of this province. As has been shown in several publications, the Belomorian–Lapland Belt is a long-lived mobile structural unit that actively developed in the Neoarchean and Paleoproterozoic and subsequently underwent multifold remobilization in the Riphean, in the Phanerozoic, and recently [7, 11, 12, 23–25]. This region is heterogeneous and consists of two large tectonic units: the Belomorian Amphibolite–Gneiss Belt and the Lapland–Kolvitsa Granulite Belt (Fig. 1).

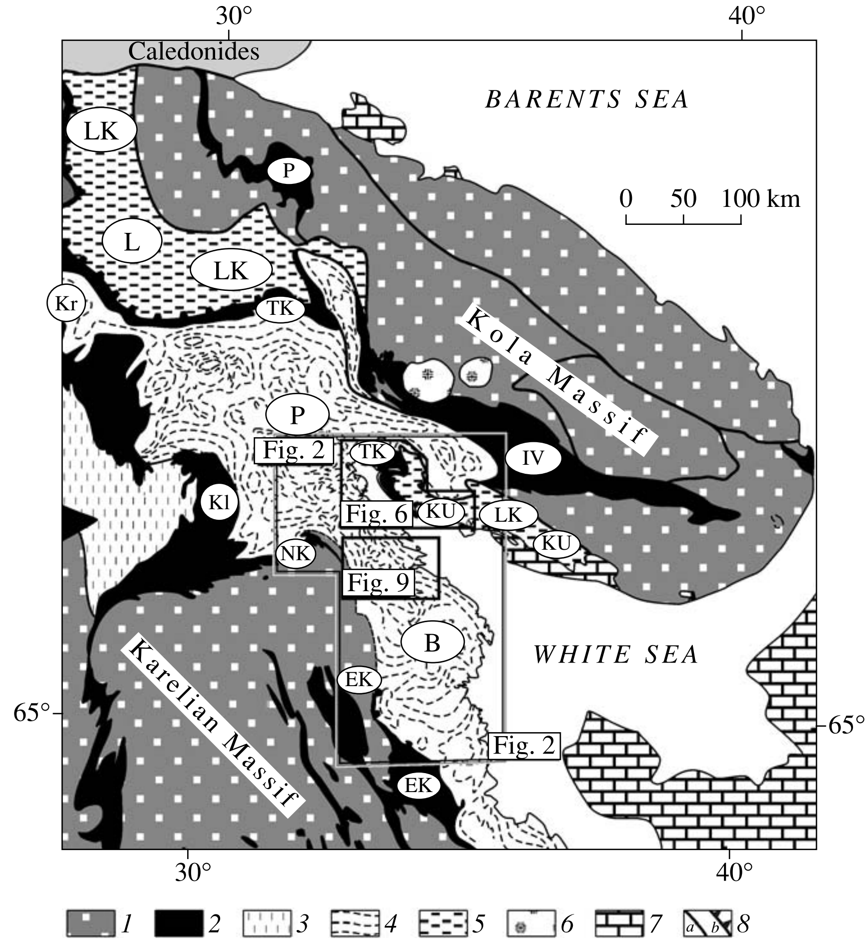


Fig. 1. The main tectonic units in the northeastern Baltic Shield. (*1*) Archean granite–greenstone complexes; (*2, 3*) Paleoproterozoic: (*2*) mainly epicontinental volcanic and sedimentary rift-related complexes, (*3*) sedimentary, volcanic, and intrusive complexes of the Svecofennian accretionary–collision belt; (*4, 5*) Archean–Proterozoic mobile belts: (*4*) Belomorian Amphibolite–Gneiss Belt, (*5*) Lapland–Kolvitsa Granulite Belt; (*6*) Devonian intrusions; (*7*) Riphean sedimentary cover; (*8*) faults: (*a*) steeply and (*b*) gently dipping. Archean–Proterozoic mobile belts (letters in figure): B, Belomorian, LK, Lapland–Kolvitsa Belt and its segments: L, Lapland and KU, Kolvitsa–Umba; Paleoproterozoic volcanic–sedimentary belts: EK, East Karelian; NK, North Karelian; Kl, Kuolojarvi; Kr, Karasjok; P, Pechenga; IV, Imandra–Varzuga; TK, Tanaelv–Kandalaksha.

The Lapland–Kolvitsa Granulite Belt

This belt consists of the Lapland and the Kolvitsa–Umba segments (Fig. 1). According to the geological and geophysical data, the belt has a nappe–thrust structure. The Lapland Nappe in the northwestern part of the belt was displaced for no less than 100 km to the southwest [26, 27, 32]. The time of thrusting is estimated at 1.95–1.91 Ga from the age of synkinematic metamorphism [15, 27, 32, 51, 52]. The belt is composed of mafic and felsic granulites, enderbite, tonalite, and charnockite. As follows from Sm–Nd model ages and U–Pb zircon isochron ages, the protolith of Paleoproterozoic metamorphic rocks was formed 2.28–1.95 Ga ago [8, 46, 51, 52]. The model Sm–Nd age and positive $\varepsilon_{Nd}(t)$ values testify to the predominance of the juvenile component in their composition. This fact, together with the geochemical signature of granulites, indicates that the origin of these rocks was related to the subduction that determined not only the formation of island-arc volcanic and plutonic series but also their erosion and deposition of clastic material in the interarc basins [16, 47, 48, 51, 52].

The large sheets of metamorphosed gabbroanorthosite and the underlying complexes of the Tanaelv–Kandalaksha Zone lie at the base of granulite allochthons (Fig. 1). The isotopic data testify to the long-term evolution of these rocks from 2.5 to 1.90–1.85 Ga [28, 48]. The Neoarchean gneiss and amphibolite of the Belomorian Group occupy a lower structural position.

The retrograde reaction structures in granulites mark (1) decompression and cooling, (2) nearly isobaric cooling, and (3) retrograde hydration [52, 54, 55]. The reactions of nearly isobaric cooling are characteristic only of marginal portions of granulite nappes. The rocks of the Tanaelv–Kandalaksha Zone that underlie granulite nappes demonstrate the inverse metamorphic zoning that follows a clockwise $P–T–t$ path. It is suggested that the rocks of the Tanaelv–Kandalaksha Zone were thrust under granulites, which, having come in contact with cold rocks, underwent isobaric cooling. These events proceeded at 600–700°C at a depth of ~20 km [54, 55].

The Belomorian Belt

This belt is composed largely of Neoarchean rocks that have features similar to granite–greenstone associations of the Karelian Massif [11, 36]. The geological and structural interpretation of the Belomorian Belt remains equivocal. The belt is regarded as a domain of long-term tectonic and metamorphic remobilization and multiphase folding [4, 39], as a system of oval (in plan view) structural elements in the framework of zones of ductile flow [11], as a zone of strike-slip faulting and transpression [30], or as a zone of long-term extension and formation of low-angle normal faults [40]. According to [2, 12, 21–25], the Belomorian Belt consists of a series of intricately deformed tectonic sheets (Fig. 2): (1) the Kovdozero Sheet of biotite tonalitic gneiss, gneissic granite, and volcanics of the Tikshozero greenstone belt; (2) the Chupa Sheet of various aluminous gneisses; (3) the Khetolambina Sheet of amphibole tonalitic gneiss, large orthoamphibolite skialiths, and relict zones of mafic and ultramafic rocks; (4) the Keret Sheet of biotite tonalitic gneiss; (5) the Orijarvi Sheet of biotite–amphibole tonalitic gneiss; and (6) the Riikolatvi Sheet of biotite and amphibole tonalitic gneisses with stratal bodies of orthoamphibolite.

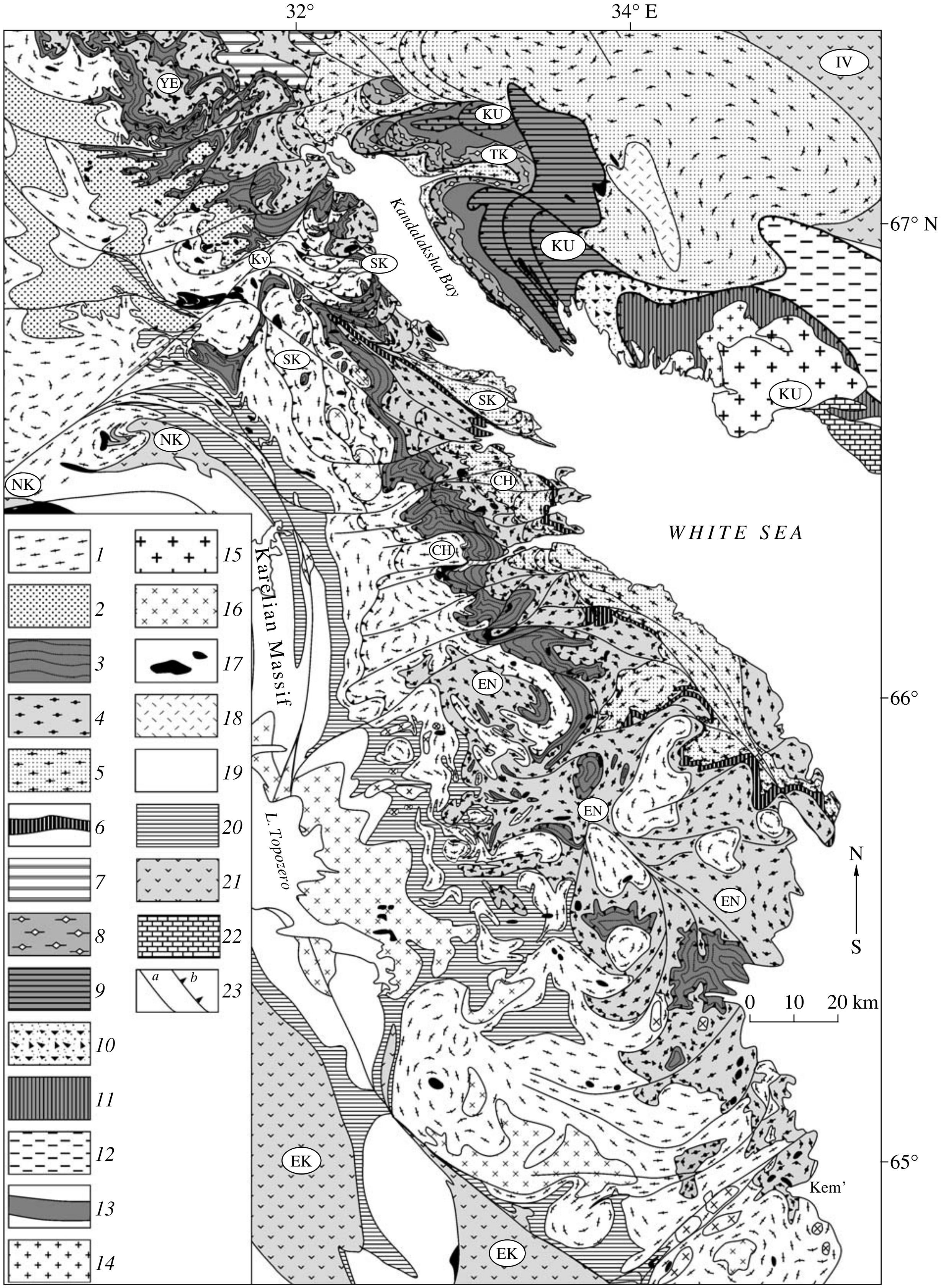
A subduction–collision model of the evolution of Belomorides in the Neoarchean is based on structural, lithologic, geochemical, and isotopic evidence [24]. At the subduction stage, the oceanic plate (Khetolambina Complex) and the overlying sedimentary rocks (Chupa Gneiss) were subducted beneath the Karelian granite–greenstone domain (Kovdozero Complex). The time of subduction is estimated at 2.88–2.82 Ga from the age of island-arc complexes of the Tikshozero greenstone belt and early metamorphism [9, 45]. The subsequent collision resulted in overturning of systems of the older nappes and their obduction upon the margin of the Karelian accretionary region, phenomena that were accompanied by high-pressure metamorphism and formation of the younger tonalite 2.74–2.69 Ga ago [12, 20, 21]. The collision was completed with development of variously oriented folds and migmatite–granite domes. As a result, the collisional orogen that welded the Karelian and Kola cratons formed by the end of the Archean.

The early Paleoproterozoic igneous rocks in the eastern part of the Baltic Shield make up a vertical column as follows (from top to bottom): (1) Sumian volcanic rocks, including mafic–ultramafic layered intrusions; (2) drusite complex; and (3) gabbroanorthosite. The drusite complex (lherzolite, gabbronorite, diorite, gabbroanorthosite) and genetically related charnockite are known in the Belomorian–Lapland Belt as minor intrusions dated at 2.45–2.35 Ga [11, 37, 38, 40, 50]. The corona (drusite) textures resulting from melt crystallization at P = 6–12 kbar and the subsequent high-pressure metamorphism are typical of these rocks [11, 37, 38, 50, 53]. In terms of geochemistry, these rocks are similar to the coeval volcanics that fill rift troughs and the layered intrusions from marginal parts of the Karelian and Kola massifs [37, 38, 42, 43]. The drusite complex includes gabbroanorthosites that occur in layered plutons and as isolated sheetlike intrusive bodies. According to [40], these rocks indicate the extensional setting and development of low-angle normal faults.

In general, the association of the early Paleoproterozoic igneous rocks of the Belomorian–Lapland Belt is a bimodal series of mafic–ultramafic mantle-derived rocks and lower-crustal granitoid rocks that characterize the tectonic setting of intracontinental rifting. This magmatism was related to the ascent of a mantle diapir whose axis was projected on the Belomorian Belt [35, 37, 40, 42, 53].

Metamorphism. With allowance for the data published in [11, 12, 21, 31], the following sequence of tec-

Fig. 2. Geological sketch map of the central Belomorian–Lapland Belt. Compiled after [4, 11, 12, 18, 21–23, 31, 40, 44]. (*1–7*) Neoarchean rocks of the Belomorian Belt: (*1*) Kovdozero Nappe (mainly biotite and less abundant biotite–amphibole tonalitic gneisses and gneissic granite), (*2*) Orijarvi Nappe (biotite–amphibole tonalitic gneiss), (*3*) Chupa Nappe (aluminous garnet biotite, kyanite–garnet–biotite, kyanite–garnet–biotite–muscovite, and biotite–muscovite gneisses), (*4*) Khetolambina Nappe (mainly amphibole and biotite–amphibole tonalitic gneisses, trondhjemite, granodiorite, and skialiths of ortho- and paraamphibolites), (*5*) Keret Nappe (mainly biotite tonalitic gneiss), (*6*) mafic zones (granitized metamorphosed mafic and ultramafic rocks), (*7*) Riikolatvi Nappe (biotite and amphibole tonalitic gneisses with stratal orthoamphibolite bodies; (*8–15*) Paleoproterozoic rocks of the Kolvitsa–Umba segment (belt) of the Lapland–Kolvitsa Belt: (*8*) Kandalaksha Complex of the Tanaelv–Kandalaksha Zone (garnet amphibolite, amphibole gneiss, and basal metaconglomerate), (*9*) Por'ya Guba Complex (basic granulite, two-pyroxene crystalline schist, and less abundant intermediate and felsic granulites), (*10*) zone of tectonic melange, (*11*) Umba Complex (mainly felsic garnet–sillimanite granulite), (*12*) Tersky Complex (biotite–amphibole gneiss), (*13*) gabbroanorthosite (2.46–2.45 Ga), (*14*) enderbite and charnockite (1944–1912 Ma), (*15*) porphyritic granite; (*16–18*) intrusive rocks of the Belomorian Belt: (*16*) Neoarchean enderbite and charnockite (2.4 Ga), (*17*) mafic and ultramafic drusites (2.45–2.35 Ga), (*18*) subalkali granite (2.3–1.9? Ga); (*19, 20*) Neoarchean rocks in basement of the Karelian Massif: (*19*) granite gneiss, (*20*) greenstone complexes; (*21*) Paleoproterozoic volcanic–sedimentary rocks; (*22*) Riphean sedimentary cover; (*23*) faults: (*a*) steeply and (*b*) gently dipping. Structural units of the Lapland–Kolvitsa Belt (letters in figure): KU, Kolvitsa Umba segment (belt); TK, Tanaelv–Kandalaksha Zone; segments of the Belomorian Belt: SK, Seryak–Kovdozero; CH, Chupa; EN, Engozero; YE, Yena; Kv, Kovdozero Strike-Slip Fault; Paleoproterozoic volcanic–sedimentary belts: EK, East Karelian; NK, North Karelian; IV, Imandra–Varzuga.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tonic and metamorphic events may be outlined: (1) the Reboly stage with subduction (2.88–2.82 Ga) and collision (2.74–2.53 Ga) substages, (2) the Selet rifting stage (2.45–2.35 Ga), and (3) the Svecofennian stage (1.94–1.75 Ga).

The Reboly stage predetermined the main features of the Belomorian metamorphic complexes and their zoning that is reflected in the northeastward increase in the metamorphic grade with an increase in the distance from the margin of the Karelian Massif [12].

The Selet rifting is characterized by syn- and postmagmatic mineral reactions in rocks of the drusite complex (2.45–2.35 Ga). The early metamorphism is marked by ortho- and clinopyroxene rims at olivine–plagioclase boundaries as a result of the subsolidus reaction Ol + Pl = Opx + Cpx ± Sp at $P > 8$ kbar and $T = 700–800$°C. Garnet-bearing and amphibole rims appeared later [37, 38]. The mineral assemblages formed at $P = 7–9$ and 11–12 kbar and at $T = 570–620$°C and 700–710°C were identified in drusites [50].

The Svecofennian collisional stage was accompanied by tectonic transformation and metamorphism that locally developed along zones of ductile deformation and under conditions of kyanite–muscovite subfacies of almandine–amphibolite facies ($T = 590–630$°C and 620–720°C; $P = 5.8–7.5$ kbar) [11, 12, 18, 19, 33, 34]. The intensity of metamorphism increases toward the allochthonous Lapland–Kolvitsa granulites; inverse metamorphic zoning has locally developed in their framework. The retrograde Svecofennian metamorphism proceeded against the background of falling temperature and a fall in pressure from 7.5 to 3.6 kbar [11, 31]. Several areas with different U–Pb ages of titanite are recognized within the Belomorian–Lapland Belt: (1) an area of uniform metamorphism that embraces granulite allochthons and underlying rocks (1.94–1.87 Ga), (2) an area of discrete metamorphism in the central zone of the Belomorian Belt (1.87–1.815 Ga), and (3) an area of zonal metamorphism along the boundary between the Karelian Massif and Belomorides (1780–1750 Ma) [49]. Taking into account that the U–Pb age of titanite characterizes the time of closure of its isotopic system at <600°C, one may suggest that the metamorphic complexes were exhumed to the low-temperature levels of the crust in the following sequence: (1) the Lapland–Kolvitsa granulite and complexes of the (2) central and (3) marginal zones of the Belomorian Belt. If this sequence is considered with respect to the thrusting, it appears that the tectonic sheets were pushed out in unusual sequence, beginning with the upper sheets and progressively shifting downward (see below).

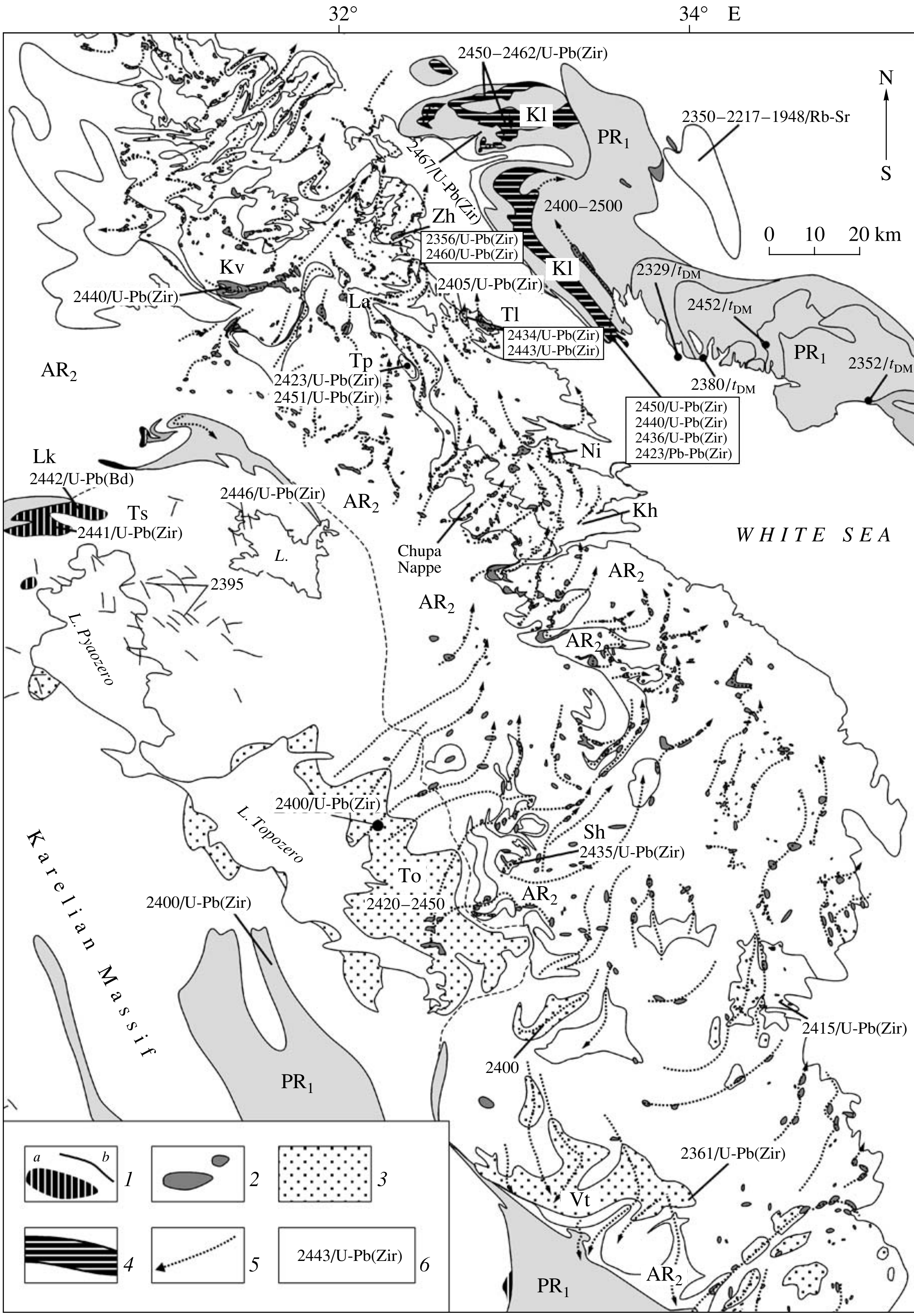
PALEOPROTEROZOIC STRUCTURAL–KINEMATIC ASSEMBLAGES

The structural–kinematic study of the Belomorian–Lapland Belt was focused on the Paleoproterozoic tectonites and related structural assemblages of the Selet and Svecofennian stages of tectonic transformation and metamorphism of rocks. These assemblages were superimposed on the nappe-and-thrust assemblages of the Reboly stage as a result of subduction and collision in the Neoarchean. According to [12, 21, 23, 24], by the early Neoproterozoic, the tectonic style of the study region was predetermined by recumbent folds and intensely developed tectonic delamination and metamorphic banding. The superimposed, largely upright folds striking in the northwestern direction, as well as the domal structural elements, were formed at the final stage of collision. The thermobarometric estimates [37, 38, 50] indicate that, by the early Paleoproterozoic, the Belomorian complexes were localized under the conditions of the lower and middle crust.

Structural–kinematic assemblages of the Selet stage are recognized from their relationships with synkinematic drusite and granitoid intrusions (2.45–2.35 Ga). The previously identified fold systems of the Selet age are oriented across the Reboly structural grain [22]. The drusite complexes make up chains and tortuous zones (Fig. 3) and mark the axial planes of the Selet folds and related faults. The Paleoproterozoic granitoid bodies follow the same style of localization. In the southern part of the study area, chains of such plutons are located at the extension of the Selet folds that complicate the marginal zone of the Karelian Massif. The larger Topozero and Vitozero intrusions are complicated by offsets controlled by these folds (Fig. 3). In most cases, the zones of Selet folding strike in the northeastern and near-meridional directions; however, while approaching the granulite nappes of the Lapland–Kolvitsa Belt, they gradually turn to the northwest (Fig. 3) against a background of increasing intensity of the superimposed Svecofennian tectonic and metamorphic effects.

In a sketch form, the localization of the Selet intrusions is displayed in a block diagram that exemplifies synkinematic formation of drusites in low-angle normal fault zones and in fold hinges as boudins elongated along the fold axes and as magmatic duplexes (Fig. 4A).

Fig. 3. Tectonic localization and isotopic age of igneous complexes of the Selet stage (2.50–2.35 Ga). Compiled after [6, 8, 35, 37, 38, 40, 46, 50, 53, etc.]. (*1–4*) Rift-related igneous rocks (2.50–2.35 Ga): (*1a*) layered mafic–ultramafic plutons localized in the upper crust and (*1b*) basic dikes; (*2*) lherzolite, gabbronorite, diorite, etc. (drusites), localized in the middle crust; (*3*) charnockitic rocks and porphyritic granite localized in the middle crust; (*4*) gabbroanorthosite localized in the lower crust; (*5*) fold axes and fold and fault zones of the Selet stage; (*6*) age, Ma/method (mineral). Intrusive bodies (letters in figure): Lk, Lukulaisvaara; Ts, Tsipringa; To, Topozero; Sh, Shobozero; Vt, Vitozero; Zh, Zhemchuzhny; Kv, Kovdozero; Tp, Tupaya Guba; Tl, Cape Tolstik; Kl, Kolvitsa; minor intrusions in the areas of Nil'moguba (Ni), Khetolambina (Kh), and Lyagkomina (La).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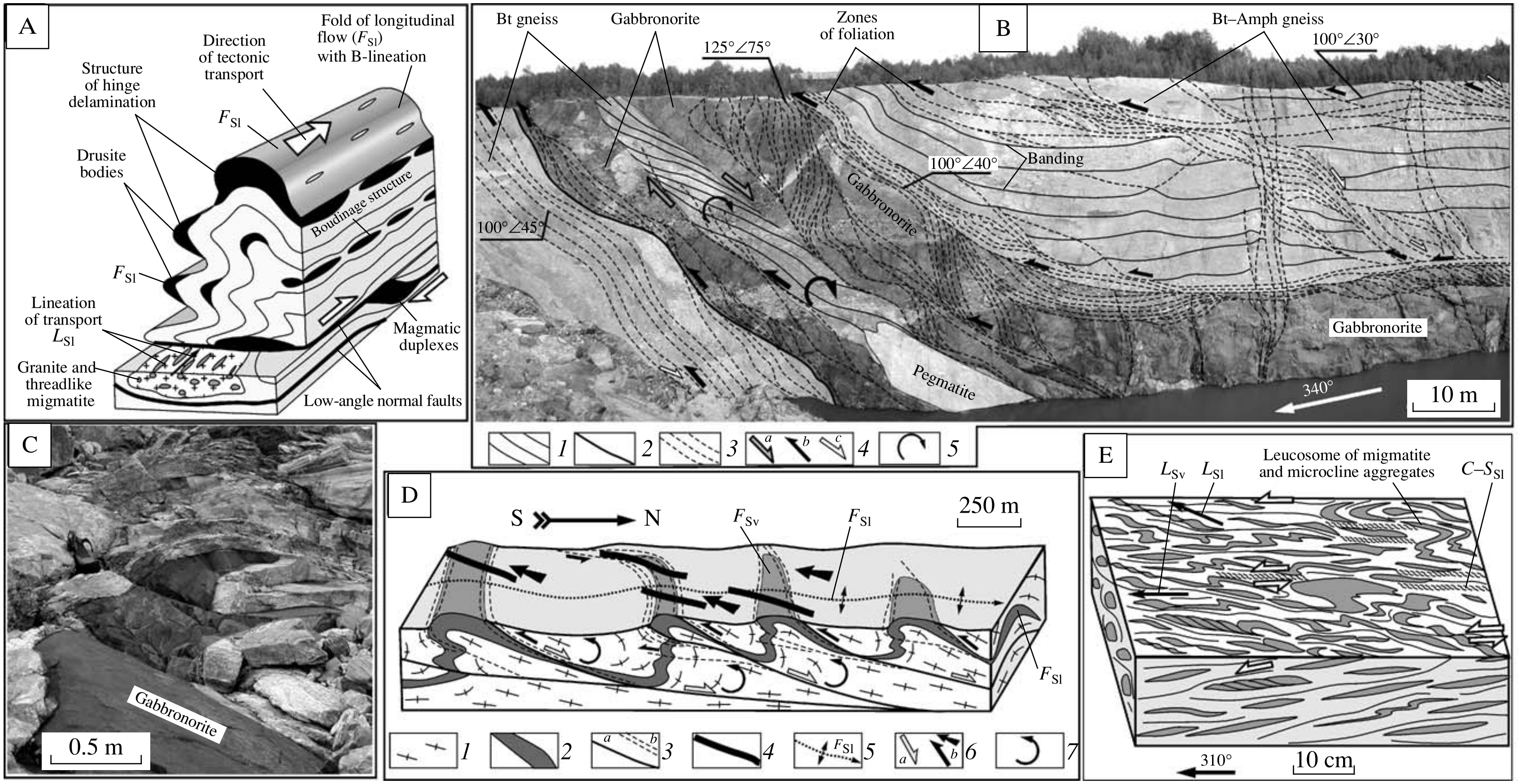

Fig. 4. Structural–kinematic assemblages of the Selet stage. (A) Integral diagram illustrating localization of synkinematic intrusions (2.45–2.35 Ga), (B–E) occurrence and structure of intrusions of the Selet stage in the areas of (B) Khetolambina, (C) Lyagkomina, (D) Nil'moguba, and (E) Cape Tolstik. See Fig. 3 for area location. (B) Geological structural section (photopanorama) of the eastern wall of an abandoned quarry. See text for explanation. (*1*) Banding in gneiss; (*2*) low-angle fault; (*3*) zones of foliation and C–S-structures; (*4*) direction of displacement at the (*a*) Selet and (*b*, *c*) Svecofennian stages, according to first- and second-generation structures of dynamodiaphtorites generations, respectively; (*5*) direction of rotation of structural units at the Selet stage. (C) Photograph of a lenticular gabbronorite body in the hinge of the Selet fold with a horizontal axial plane. (D) Block diagram illustrating the occurrence of gabbronorite in the delaminated hinge of the Selet anticline (F_{Sl}) disturbed by Svecofennian thrust faults and folds (F_{Sv}). (*1*) Biotite gneiss, (*2*) gabbronorite, (*3a*) thrust faults and (*3b*) zones of foliation and C–S structures, (*4*) muscovite pegmatite, (*5*) track of the axial surface of the Selet anticline; (*6*) direction of displacements at the (*a*) Selet and (*b*) early Svecofennian stages, (*7*) direction of rotation. (E) Block diagram illustrating relationships of structural assemblages of the Selet and Svecofennian stages in Paleoproterozoic migmatite-granites, see text for explanation. Structural elements (letters in figure): F_{Sl} and F_{Sv} are folds of the Selet and Svecofennian stages, respectively; L_{Sl} and L_{Sv} are lineations of the Selet and Svecofennian stages, respectively.

In many cases, the sill-like drusite intrusions are controlled by the low-angle Selet normal faults that inherit the surfaces of the Reboly thrust faults (Fig. 4B). In the wall of a quarry shown in Fig. 4B, one can see two closely spaced gabbronorite sills that mark listric faults. In the central portions of these intrusive bodies, the mafic rocks undergo only slight alteration and retain ophitic and drusitic textures, whereas in contact zones they become strongly foliated. The stratal body of biotite gneiss sandwiched between the sills experienced a thermal effect and became partly recrystallized and amphibolized. The foliation of gneiss that developed synchronously with the emplacement of drusites indicates the normal faulting (Fig. 4B).

The drusite intrusions are often located in hinges of folds with vertical and horizontal axial planes (Figs. 4A, 4C). A typical exposure was studied near the settlement of Nil'moguba. A series of isolated lherzolite and gabbronorite bodies are clustered here as extended chains. Initially, this was a common linear body related to the hinge of the Selet fold (Fig. 4D). The systems of low-angle normal faults developed at the late magmatic stage and were marked by narrow zones of migmatization provided a certain fragmentation of this body. The Svecofennian deformations were expressed in thrusting and the associated overturned folds. The thrusting developed along the initial strike of the intrusive body and resulted in further fragmentation and formation of asymmetric transverse folds. In many cases, such structural transformation led to the fragmentation of drusite intrusions into the chains that extend for many kilometers.

Granites associated with drusites are characterized by formation of aggregates of potassium feldspar that reveal synkinematic B-lineation oriented along the axes of the Selet folds (Figs. 4A, 4E). Granitic rocks grade into the thread-like migmatites with a similar lineation. As follows from observations, the linear structure of granitic rocks is related to their synkinematic crystallization and autometamorphism under conditions of ductile flow in the near horizontal plane, when the extensional lineation is oriented in the direction of tectonic transport.

The available data show that the igneous rocks of the Selet stage were formed at a depth of more than 20 km under conditions of the near-horizontal ductile flow. The paths of the rock transport are recorded in the orientation of B-lineation and linear zones of folding that strike in the northeastern and near-meridional directions (Fig. 3).

Structural–kinematic assemblages of the Svecofennian stage were formed in the tectonically anisotropic medium created at the preceding stages and partly inherited in the newly formed structural features. These circumstances make it quite difficult to identify the high-rank folds and faults on the basis of their geometric characteristics. At the same time, the Svecofennian transformations on the meso- and microscales are expressed contrastingly. Their main indicator is the formation of tectonites, i.e., the products of retrograde dynamometamorphism.

In a generalized form, the Svecofennian structural elements as kinematic indicators are shown in Fig. 5A. They make up an assemblage consisting of small-scale asymmetric and sheath folds, asymmetric boudins, duplexes of compression and extension, and asymmetric veins. C–S structures, mineral lineation, δ- and σ-shaped porphyroblasts, en echelon arranged orientations of mineral aggregates, and various rotation structures are elements of this assemblage. To reveal the direction of movements, these structural elements were studied in different sections of hand specimens and outcrops. The particular displacements established in this way were used further for reconstruction of the resultant vector of local tectonic transport. In the case of low-angle structural elements, the obtained vector indicates the direction of displacement of the hanging lithon (block) relative to the footwall.

The C–S structures are immediately related to the retrograde metamorphism of the Svecofennian stage and composed of mineral assemblages that are defined as Svecofennian dynamodiaphtorites (Fig. 5B). The phyllosilicates (Bt, Mu, Chl) are localized along microshears C, thereby marking sigmoid bent surfaces S, which show a shear component. The retrograde character of these assemblages is expressed in the consecutive replacements: dark brown Bt $\longrightarrow$ green Bt $\longrightarrow$ Chl + Mu + Ru, Grt $\longrightarrow$ Bt + Qtz $\longrightarrow$ Chl + Bi + Qtz, and Hbl $\longrightarrow$ Act + Chl. Blastocataclasites with C–S structures that characterize brittle–ductile stage of deformation are often formed at the late stages of retrograde metamorphism. The crosscutting relations allow recognition of several generations of C–S structures. The timing of C–S structures is based on their relationships with muscovite pegmatites (1.90–1.85 Ga) that reveal indications of multistage formation. The early generations of veins (pegmatite 1) bear distinct C–S structures, whereas the late generations (pegmatite 2) are almost completely devoid of these structures and crosscut the early veins (Fig. 5C). Thus, C–S-structures are nearly coeval with muscovite pegmatites. Furthermore, these structures are superimposed on igneous rocks of the Selet stage (2.45–2.35 Ga) (Fig. 4B, 4E). Pressure shadows and clastic rims of porphyroblasts likewise are often composed of minerals related to the retrograde stage, so that the structural elements formed by these minerals are clear kinematic indicators (Fig. 5D). Other structures of this assemblage are identified by their spatial relations to the Svecofennian dynamodiaphtorites. For example, the zones of the Svecofennian blastomylonites (dynamodiaphtorites) are often conjugated with asymmetric and sheath folds that reveal kinematic commonness with C–S structures (Figs. 5A, 5E). The zones of the Svecofennian blastomylonites often demonstrate the retrograde sequence of ductile to ductile–brittle and brittle deformations and the respective sequence of mineral assemblages that are indicative of different

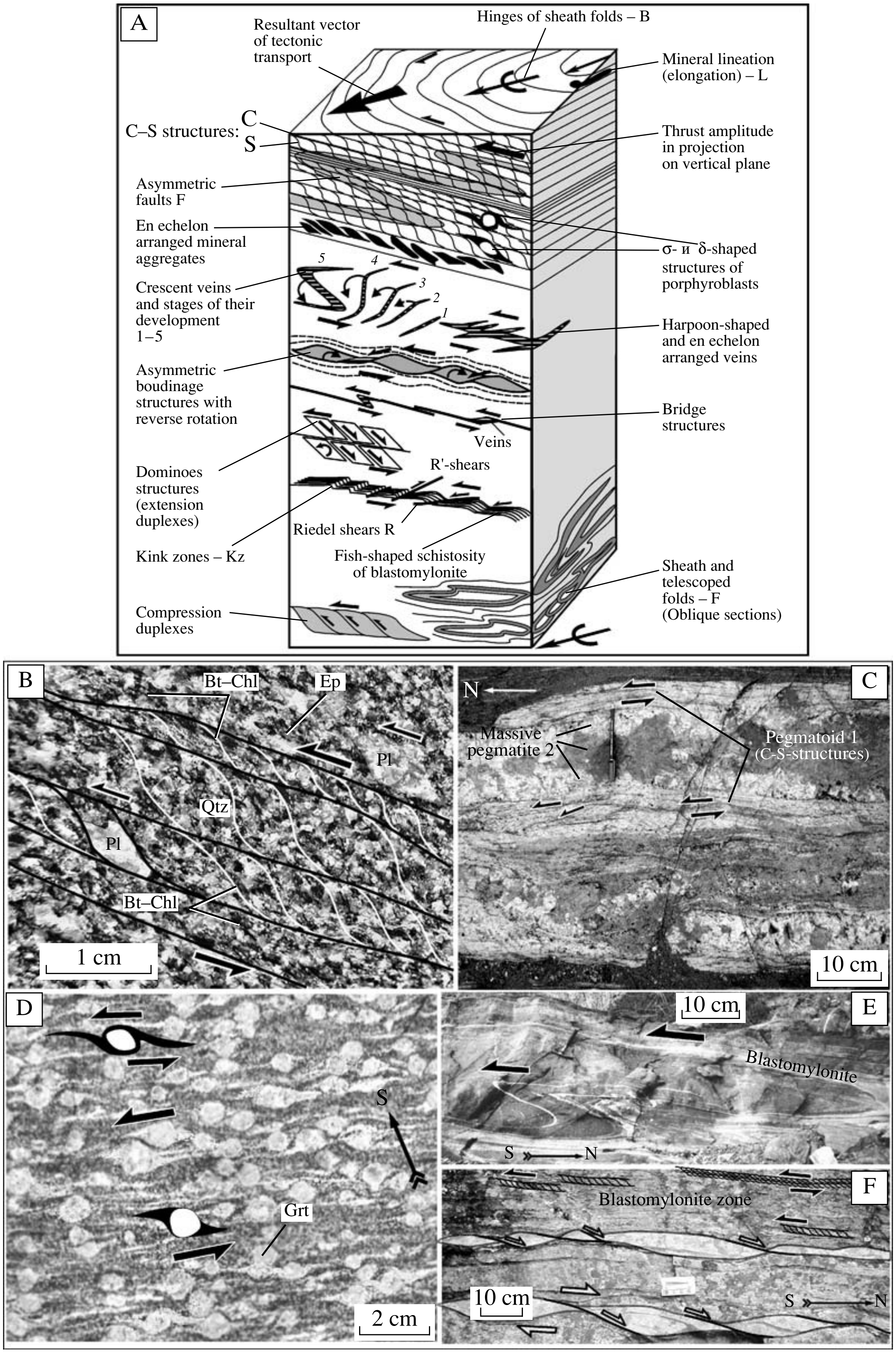

Fig. 5. Structural–kinematic assemblages of the Svecofennian stage. (A) Integral scheme (view in oblique sections), (B–F) photographs. (B) C–S structures in biotite–muscovite gneiss of the Chupa Sequence. (C) Svecofennian synkinematic pegmatoids (1) and postkinematic pegmatites (2) make up a common vein. (D) δ- and σ-shaped structures of garnet porphyroblasts in amphibolite of the Kandalaksha Sequence. (E) Asymmetric recumbent fold in blastomylonite zone of the Kandalaksha Sequence. (F) Kinematic inversion in blastomylonite zone: older C–S structures of the stage of ductile deformation are changed by younger structures of brittle–ductile deformation in the course of formation of asymmetric boudins in gneiss of the Chupa Sequence. Black and white arrows indicate directions of older and younger displacements, respectively. See text for explanation.

stages of retrograde metamorphism. As is judged from the structures related to specific tectonites, the kinematic inversion is not a rare phenomenon (Fig. 5F).

The considered structural and metamorphic assemblage developed in all Archean and Paleoproterozoic complexes of the Belomorian–Lapland Belt, so that the kinematics of tectonic processes in this province may be reconstructed on the basis of the observations that cover wide areas.

STRUCTURE OF DIFFERENT SEGMENTS OF THE BELOMORIAN–LAPLAND BELT

The Belomorian–Lapland Belt reveals transverse and longitudinal structural and compositional zoning and consists of several segments with specific tectonic features. The Lapland–Kolvitsa Granulite Belt consists of the Lapland and Kolvitsa–Umba segments (particular belts), while the Belomorian Belt comprises the Yena, Seryak–Kovdozero, Chupa, and Engozero segments (Fig. 2).

The Kolvitsa–Umba Belt is well studied with respect to its geology [4, 10, 15, 32, 41, 46, 52]. The belt is composed largely of Paleoproterozoic complexes separated by a basal detachment from gneiss of the Belomorian Group (Fig. 6). These complexes form a system of tectonic sheets that form the following vertical succession (from bottom to top): (1) garnet and monomineral amphibolites of the Tanaelv–Kandalaksha Belt (2.50–2.46 Ga) that correspond to tholeiitic basalt and basaltic andesite in chemical composition, (2) a sheetlike body of tectonized gabbroanorthosite of the Kolvitsa massif (2.45–2.46 Ga), (3) two-pyroxene and garnet–pyroxene basic granulites of the Por'ya Guba Group (metatholeiite and metaandesite (2.5–2.4 Ga)), (4) a zone of tectonic melange that consists of fragments belonging to the adjacent complexes, and (5) felsic garnet–sillimanite granulites of the Umba Complex (metaterrigenous rocks deposited no earlier than 2.1 Ga ago) [52]. The felsic granulites of the Umba Complex are cut through by granitoid intrusions of the Umba plutonic complex that consists of three intrusive phases: enderbite (1944 Ma), charnockite (1912 Ma), and late porphyritic granite [15, 52]. The base of the tectonic sheet of the Umba granulites (melange zone) bears indications of isobaric cooling, while the central portion of this sheet underwent decompression and cooling. These settings coexisted at the early stage of Svecofennian collision (1.95–1.91 Ga) [1, 41, 52]. Anatectic melting and dynamometamorphism are somewhat younger processes.

The Svecofennian mega- and mesoscopic structural–kinematic assemblages are systems of large tectonic nappes and imbricate thrust sheets that have a horseshoelike form and demonstrate a festooned general structural pattern in plan view (Fig. 6). The tectonic sheets make up the separate Kolvitsa and Umba synforms and gently plunge in the eastern bearings. Their vertical succession is characterized by inverse metamorphic zoning and blastomylonitic and melange zones at the centroclinal closures, which are accompanied by thrust faulting, whereas strike-slip faults are localized at synform limbs (Fig. 6). The structures of tectonic pumping (systems of fold–thrust hummocking) oriented transversely to the general trend of the belt developed in frontal horseshoe-shaped thrust-fault zones. Several generations of folds are recognized; the recumbent and overturned folds grading into thrust faults are the oldest (Fig. 5E). The younger fold systems have various orientations and exhibit cylindrical and conical morphology (Fig. 6, II). The hinges of small folds and mineral lineation disperse along the arc of a great circle, thus indicating their rotation around a near-vertical axis (Fig. 6, I, III).

The Svecofennian meso- and microscopic structural–kinematic assemblages make up a successive retrograde series: (1) structures of bedding-plane and pervasive ductile deformation that are synchronous with amphibolite- and granulite-facies metamorphism, (2) structures of ductile deformation that are related to the formation of the first-generation dynamodiaphtorites that took place under conditions of epidote-amphibolite facies, and (3) structures of brittle–ductile deformation that contain second-generation dynamodiaphtorites that formed under conditions of greenschist facies. The first structures are little informative in kinematic terms because they are devoid of symmetry and strongly obscured by subsequent deformations. The second and third structural elements commonly have distinct monoclinic symmetry and may be regarded as the respective generations of the structural–kinematic assemblages. The first-generation pervasive assemblages comprise C–S structures, structures resulting from rotation of porphyroblasts, en echelon arranged mineral aggregates, transport lineation, etc. (Fig. 5A). The relationships of these structures with granitoids of the Umba Complex indicate that these structures formed at the late magmatic stage of charnockite crystallization (1912 Ma) before emplacement of porphyritic granite. The second-generation structures developed locally and are superimposed on the younger granites.

The Kolvitsa Synform strikes in the latitudinal direction and closes near the town of Kandalaksha, while slightly widening owing to the gradual plunging of its hinge to the east. In the section, this is an upright symmetric fold consisting of tectonic sheets and slices (Fig. 7A). At the northern limb of the synform, the most representative section is exposed in the rocky valley of Lake Sredny Luven'ga (Fig. 7B), where the strongly tectonized gabbroanorthosite of the Kolvitsa massif transformed into blastomylonite is thrust over amphibolite of the Kandalaksha Group. The first-generation structures crosscut and deform structural elements of the older tectonic and metamorphic delamination: the thin lenticular banding expressed in alternation of plagioclase and garnet–pyroxene–amphibole laminas,

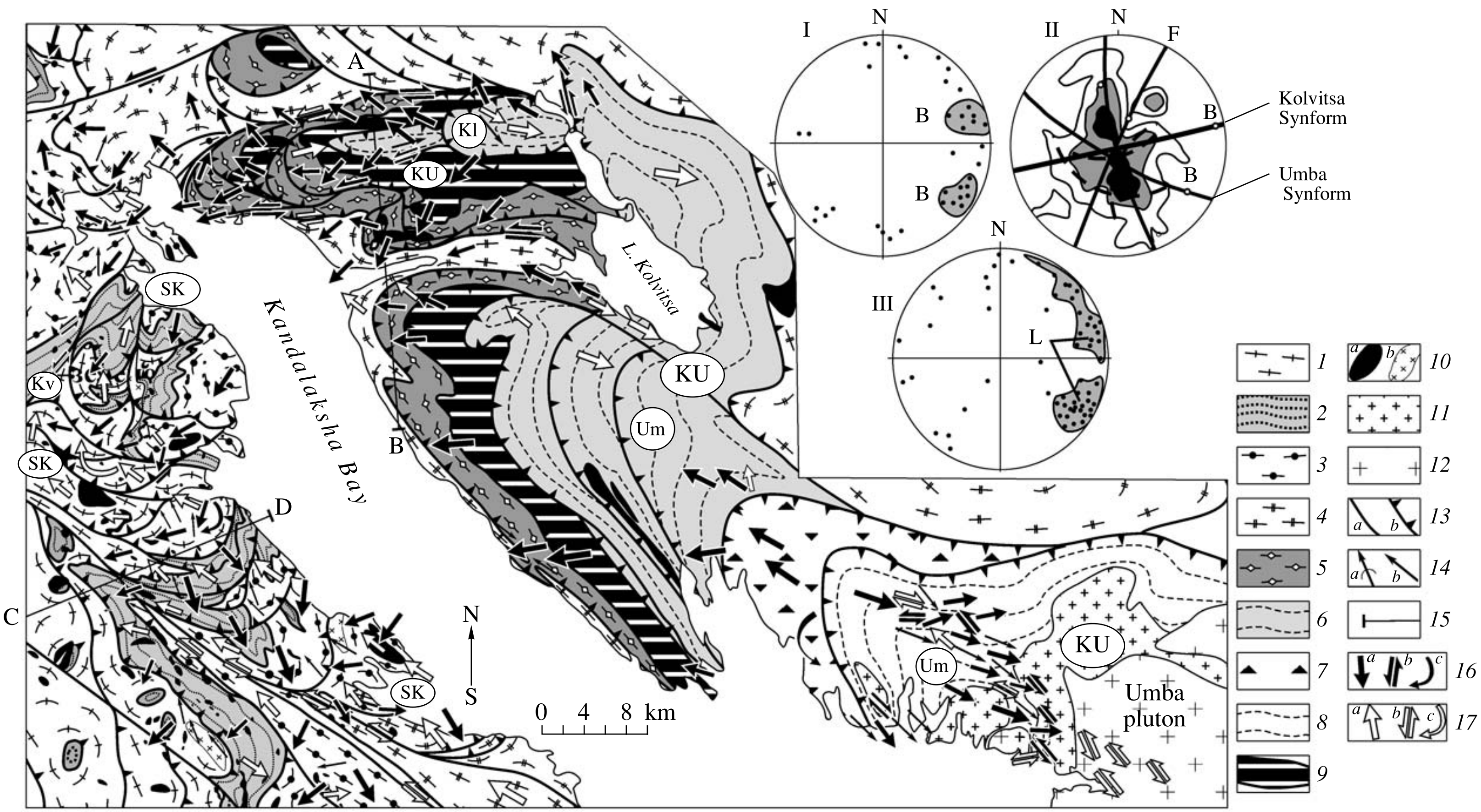

Fig. 6. Structural–kinematic sketch map of the Kolvitsa–Umba Belt. Compiled after [4, 31, 40, 51, 52]. (*1–4*) Neoarchean structural units of the Belomorian Belt: (*1*) Kovdozero Complex (Nappe), (*2*) Chupa Nappe, (*3*) Khetolambina Nappe, (*4*) Keret Nappe; (*5–9*) Paleoproterozoic structural units of the Lapland–Kolvitsa Belt: (*5*) Kandalaksha Complex (Tanaelv–Kandalaksha Zone), (*6*) Por'ya Guba Complex, (*7*) zone of tectonic melange, (*8*) Umba Complex, (*9*) gabbroanorthosite (2.46–2.45 Ga); (*10*) minor intrusions 2.45–2.35 Ga in age: (*a*) mafic and ultramafic drusites and (*b*) granitoids; (*11, 12*) granitoids of the Umba Complex: (*11*) enderbite and charnockite (1944–1912 Ma), (*12*) porphyritic granite; (*13*) faults: (*a*) steeply and (*b*) gently dipping; (*14a*) anticline hinges and (*14b*) aggregative mineral lineation; (*15*) section line; (*16*) directions of (*a*) thrusting, (*b*) strike-slip faulting, and (*c*) rotation at the Svecofennian stage along zones of first-generation dynamodiaphtorites; (*17*) directions of (*a*) thrusting, (*b*) strike-slip faulting, and (*c*) rotation at the Svecofennian stage along zones of second-generation dynamodiaphtorites. Structural units (letters in figure): KU, Kolvitsa–Umba Belt; Kl and Um, Kolvitsa and Umba synforms; SK, Seryak–Kovdozero segment of the Belomorian Belt; Kv, Kovdozero Strike-Slip Fault. Stereographic projections of the orientation of structural elements on the lower hemisphere: (I) fold hinges, (II) poles of tectonic delamination and metamorphic banding (260 measurements, contour lines are spaced at 5, 3, and 1%), (III) aggregative mineral lineation. See Fig. 5A for the letters on projections.

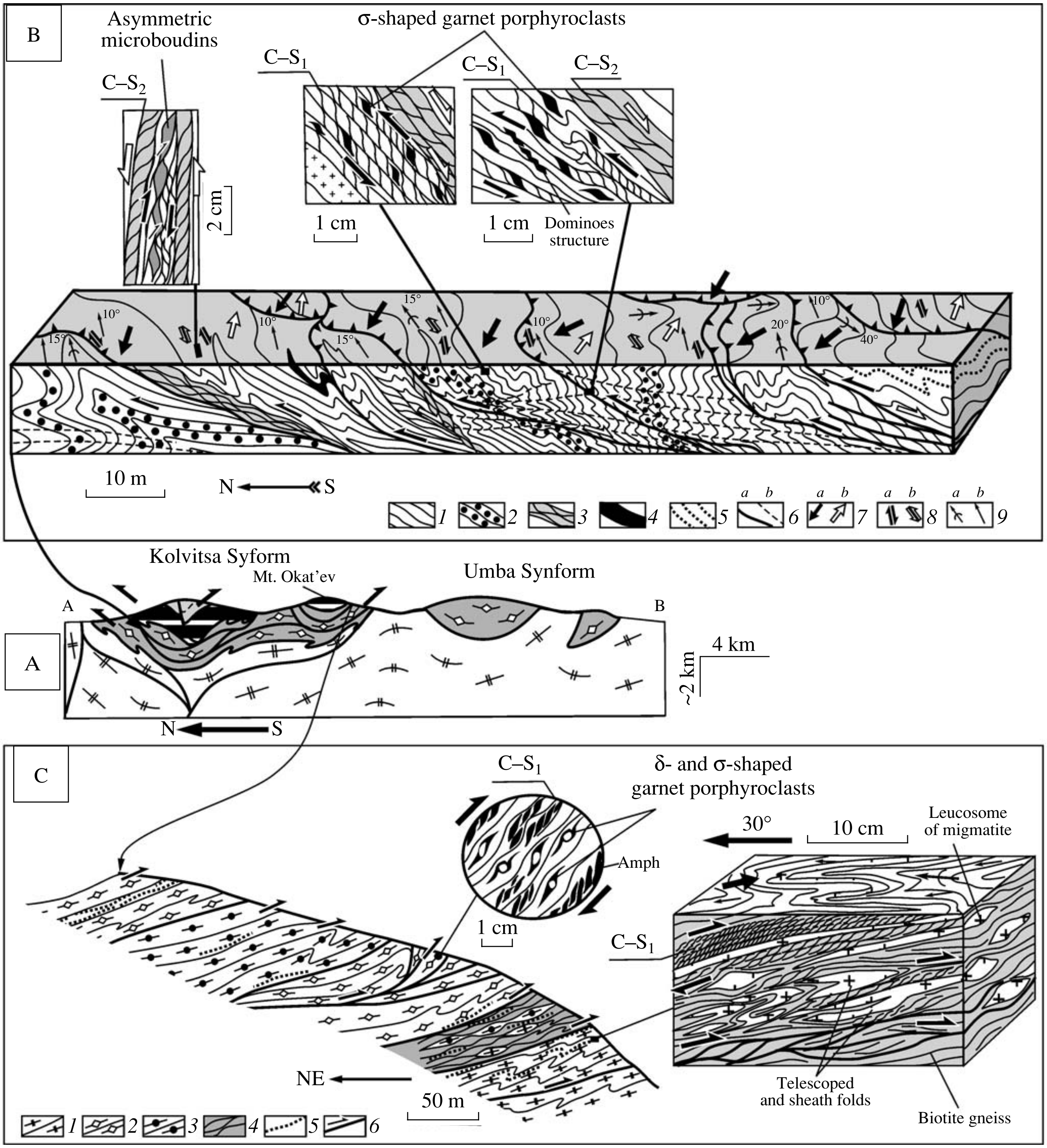

Fig. 7. (A) Sketch geological section of the Kolvitsa Synform along line AB (see Fig. 6A for line location and legend) and geological structural sections of (B) northern and (C) southern limbs of the Kolvitsa Synform. Panel B: (*1*) thin-banded garnet-bearing blastomylonites after gabbroanorthosite, (*2*) lenticular banded garnet blastomylonite after gabbroanorthosite, (*3*) zones of tectonic dislensing and melange, (*4*) metapyroxenite and metagabbroid rocks, (*5*) intermediate granulite affected by retrograde metamorphism, (*6a*) faults and (*6b*) foliation zones, (*7*) vectors of tectonic transport based on measurements of Svecofennian dynamodiaphtorite structures of (*a*) first and (*b*) second generations, (*8*) directions of strike-slip based on measurements of Svecofennian dynamodiaphtorite structures of (*a*) first and (*b*) second generations, (*9*) orientation of (*a*) fold hinges and (*b*) aggregative mineral lineation. Panel C: (*1*) biotite gneiss of the Belomorian Group, (*2*) garnet amphibolite of the Kandalaksha Sequence, (*3*) biotite–amphibole gneiss of the Kandalaksha Sequence, (*4*) zone of tectonic melange, (*5*) zone of intense migmatization, (*6*) faults and direction of displacement.

migmatite veinlets, and anatectic lenses. The recumbent and asymmetric folds are overturned in the northern bearings (Fig. 7B). The planar first-generation structures occasionally develop along the older banding but more frequently cross the banding at different angles, in particular, in hinges of folds. These thin (1–2 mm) C–S structures of blastomylonites (dynamodiaphtorites) pervaded throughout the rocks and accompanied by the deformation and replacement of older garnet porphyroblasts and pyroxene–amphibole aggregates as well as by the recrystallization of plagioclase. The mineral assemblages of epidote-amphibolite facies oriented in line with the morphology of C–S structures developed as a result of retrograde dynamometamorphism. The deformed garnet grains are transformed in σ- and δ-shaped porphyroclasts rimmed by clastic tails (Fig. 7B, close-ups). The older porphyroblasts often pull apart and make up a pencil-type lineation, which in some sections looks like a dominoes microstructure (Fig. 7B, close-ups). The segregation laminas that make up the early banding are often transformed into asymmetric microboudins. The pencil-type lineation of transport develops as retrograde chlorite–amphibole aggregates. The study of kinematic indicators in different sections of outcrops allowed reconstruction of displacement directions of the hanging lithons that correspond to the obliquely oriented paths of tectonic flow in the northwestern direction (Figs. 6, 7B). Some zones reveal a predominance of right-lateral displacements along with poorly developed thrust kinematics. The second-generation structural forms are local, thin cataclastic zones with relatively rough C–S structures accentuated by stringers of the youngest minerals of retrograde metamorphism (Ep, Chl, Qtz, Ab, Cal), which cut the older C–S structures at various angles and partly rearrange them (Fig. 7B, close-ups). The reconstruction of displacement vectors pertaining to this generation of structures indicates the eastward tectonic transport; the left-lateral dislocations are noted as well.

Quite another kinematic situation is noted at the southern limb of the Kolvitsa Synform. Along the southern slope of Mount Okat'ev, biotite gneiss of the Belomorian Group is overthrust by amphibolite of the Kandalaksha Group (Fig. 7C). The planar and linear structures of the first-generation kinematic assemblage have the same orientation in both sequences. A slight disharmony is revealed in the character of folding, which is more intense and complex in the Belomorian Gneiss and less distinct in amphibolites. The folded migmatite veinlets are seen in biotite gneiss. As a rule, these are small asymmetric and recumbent folds–boudins; fragments of hinges; and sheath and telescoped folds, whose hinges are parallel to the mineral aggregative lineation (Fig. 7C, block diagram). The Belomorian Gneiss is pervaded by a conformable system of first-generation C–S structures (Fig. 7C, block diagram). These structural elements consist of sigmoid aggregates of plagioclase and quartz and flakes of chloritized biotite. The vectors of tectonic transport obtained for these structural features coincide in orientation with lineation and axes of sheath folds. The intensity of migmatization in gneiss gradually increases toward its thrust-fault contact with the Kandalaksha Group. The contact is accompanied by a foliated zone of tectonic melange up to 50 m thick. The lenses of biotite and biotite–amphibole gneisses are incorporated into the matrix of amphibole–biotite blastomylonites; boudinage structures, small asymmetric folds, and narrow migmatite zones are observed. The structural–kinematic situation is similar to that in the underlying complexes. The overlying garnet amphibolite and amphibole gneiss make up a gently dipping homocline. The metamorphic banding and schistosity are conformably pervaded by C–S structures of first-generation dynamodiaphtorites. The en echelon arranged lines of recrystallized hornblende grains replaced with low-temperature amphibole and chlorite (Fig. 7C, close-up) are widespread. Small garnet porphyroclasts affected by retrograde metamorphism are accompanied by pressure shadows and δ- and σ-shaped clastic tails. In general, the first-generation kinematic assemblages indicate thrusting in the WSW direction; this situation is substantially different from the kinematic situation at the northern limb of the Kolvitsa Synform (Fig. 6). The poorly developed subsequent deformations have remained unestimated. A similar situation was observed along almost the entire southern limb of the Kolvitsa Synform.

Based on the consideration of structural–kinematic assemblages, the vectors of tectonic movements in different parts of the Kolvitsa and Umba synforms have been obtained and plotted on the structural geological scheme (Fig. 6). At the limbs of synforms, the vectors of tectonic transport are divergent and symmetric relative to the synform axes and characteristic of oblique strike-slip and thrust displacements partly resembling the displacements that develop during formation of the transpressional palm-tree structures. The first-generation structures indicate NW-directed general tectonic transport and the resultant formation of telescoped systems of tectonic sheets. Thus, the indications of transpressional setting (divergent squeezing-out of rocks toward the limbs of synforms) are combined with still more distinct kinematic attributes of longitudinal tectonic flow and thrusting. This circumstance makes it possible to consider the Kolvitsa–Umba Belt as a whole as a near horizontal protrusion that formed under transpression and underwent transport to the upper crust as a system of telescoped thrust sheets verging largely to the northwest. At the same time, the structure of first-generation dynamodiaphtorites in the upper sheet of the Umba granulites in the east of the Umba Synform is related to the relative displacement in the opposite direction relative to the underlying nappes (Fig. 6). Hence, the under- and overthrusting developed nonuniformly and the sheet of the Umba granulite moved toward the surface at a lower velocity relative to that of the underlying complexes. A similar tendency

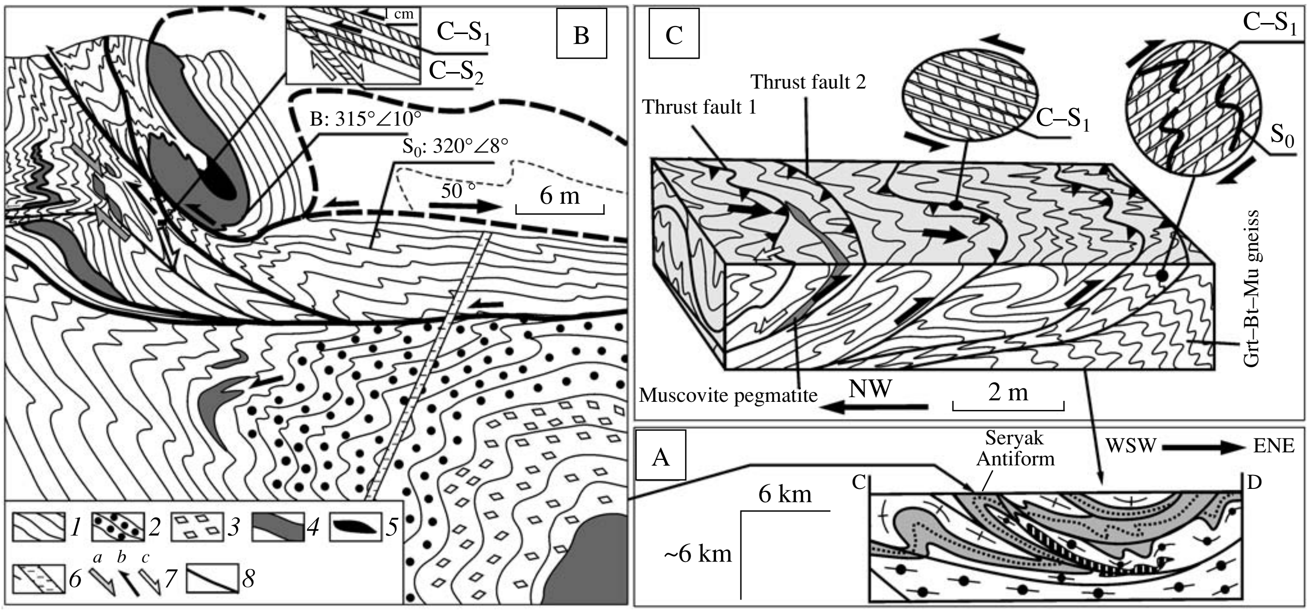

Fig. 8. (A) Sketch geological section of the Seryak Antiform along line CD (see Fig. 6A for line location and legend); (B) structure of the hinge of the Seryak Anticline near the settlement of Lyagkomina (Fig. 3), in section view; and (C) block diagram illustrating relationships of low-angle faults of different generations with folding. (*1*) Biotite–amphibole and biotite gneisses, (*2*) garnet–biotite–muscovite gneiss, (*3*) feldspathized gneiss, (*4*) Paleoproterozoic gabbronorite, (*5*) pyroxenite, (*6*) Riphean or Paleozoic (?) lamproite, (*7*) direction of displacements at the (*a*) Selet and (*b, c*) Svecofennian stages as determined from structures of dynamodiaphtorites of the first (*b*) and second (*c*) generations, (*8*) fault. In B: thrust fault 1 is deformed into upright folds, whereas fault 2 cuts off older structural elements and is transformed afterward into a low-angle normal fault.

was recorded in the second-generation structural–kinematic assemblages. The overall northwestward tectonic transport was in progress, but the belt was doubled. The region of pumping was separated in the frontal zone as the Kolvitsa Synform with structural features of lateral squeezing of rock masses under the effect of wedging provided by protrusion of the Umba Synform (Fig. 6).

The central Belomorian Belt consists of the Seryak–Kovdozero, Chupa, and Engozero segments.

The Seryak–Kovdozero segment is situated along the southwestern coast of Kandalaksha Bay and embraces the drainage basins of lakes Kovdozero and Seryak. In the northwest, this segment is bounded by the Kovdozero Strike-Slip Fault, while in the southeast, it is built on by the Chupa segment, which is separated from the Seryak–Kovdozero segment by a near-latitudinal fault zone (Fig. 2). The results of the previous detailed geological and structural investigations in this district were published in [4, 12, 21–25]. The Belomorian complexes make up the Neoarchean Kovdozero, Chupa, Khetolambina, and Keret nappes (Fig. 6). In the central part of the Seryak–Kovdozero segment, these nappes are complicated by the Seryak Antiform, whose hinge gently plunges to the northwest. In the cross section, the antiform looks like an asymmetric isoclinal fold overturned to the southwest (Figs. 6, 8A). The fold abruptly widens southeastward, and its axial surface is lost within the conformable transpressional shear zone that is traced along the entire axis of the antiform. The rocks that compose the antiform are severely deformed as a result of numerous low-angle detachments that either are folded conformably to the general structure of the antiform or discordantly cut this structure (Fig. 8B). As is judged from the development of tectonites, the discordant detachments are systems of the Svecofennian thrust faults. The surfaces of detachments deformed into folds are often healed by drusite intrusions and most likely are of the Selet age. Several generations of C–S structures are observed in zones of the Svecofennian dislocations providing evidence for the kinematic inversion: the older thrusting giving way to the younger normal faulting (Fig. 8B, close-up). These observations lead to the suggestion that the Seryak Antiform is Svecofennian in age; however, it cannot be ruled out that this structural element began to form during the Selet stage.

A system of higher order tight folds that complicates the limbs of a large gentle synform is observed to the northeast of the Seryak Antiform. This region is severely imbricated as a result of the development of horseshoelike and festooned (in plan view) thrust sheets oriented across the northwestern trend of folds (Fig. 6). The thrust faults cut off the folds and, at the same time, participate in younger folding. The study of thrust faults in outcrops has shown that their surfaces actually are complexly built imbricate zones accompanied by Svecofennian dynamodiaphtorites with clearly expressed C–S structures (Fig. 8C). Some fault surfaces of older generations are deformed into folds and discordantly cut only by slightly deformed younger thrust

Fig. 9. Structural–kinematic model of the Chupa segment. Compiled after [13, 14, 21]. (*1*, *2*) Neoarchean basement rocks of the Karelian Massif: (*1*) granite gneiss, (*2*) greenstone complex. See Fig. 6 for other symbols.

zones as a result of multiple thrusting and folding of longitudinal flow with the fold axes oriented in the direction of tectonic transport. The same structural assemblage of festooned thrust faults and folds is traceable to the north within a wide tract that gradually turns to the northeast and conjugates beneath Kandalaksha Bay with the Kolvitsa–Umba Belt, similar in structure in many respects (Fig. 6).

These data show that this segment was affected by the front of the Kolvitsa–Umba protrusion and may be regarded as a continuation of the system of the telescoped Svecofennian nappes of the Kolvitsa Synform that are spread over the Archean complexes of the Belomorides (Fig. 6). At the early stages, these dislocations developed as thrust faults and afterward became partly reactivated as normal faults, as is recorded in the structure of tectonites.

The Chupa segment of the Belomorian Belt is situated between the Seryak–Kovdozero and Engozero segments at the flank of the Kolvitsa–Umba protrusion. This region differs from the adjacent territories largely in the style and spatial orientation of the Paleoproterozoic structural assemblages that mainly strike in the near-latitudinal direction (Fig. 9). The Chupa segment is composed of the rocks belonging to the Kovdozero, Chupa, Khetolambina, and Keret complexes that make up a system of overturned tectonic sheets in the hanging wall of the large recumbent synform [21] (Fig. 10A). The substantial role of the Paleoproterozoic tectonic and metamorphic processes in the formation of the structural assemblages of this territory has been pointed out in many publications [11, 13, 14, 33, 34, 39, 40]. The Svecofennian transformation resulted in the appearance of wide fields of dynamodiaphtorites that control localization of muscovite pegmatites. The near-latitudinal right-lateral and more frequent left-lateral strike-slip fault zones are marked by dynamodiaphtorites and metasomatic rocks of the Svecofennian age. The conjugate thrust and low-angle normal faults, which are located between these zones, often inherit the surfaces of the Reboly nappes. These low-angle faults commonly cut the folds and, in turn, participated in the younger folding.

The Svecofennian thrust faults are often accompanied by tectonic melange zones up to a few meters in thickness (Fig. 10B) that consist of lenses and boudins diverse in lithology, fragments of detached fold hinges, sheets of discordantly folded gneisses, blastomylonites, dynamodiaphtorites, and metasomatic rocks of various compositions. The dynamodiaphtorites, greisen-like metasomatic rocks, and related lenses of muscovite pegmatoids indicate that these structural elements are Svecofennian in age. The asymmetric shape, rotation structures of garnet and feldspar porphyroblasts, and C–S structures are consistent with the thrust kinematics of these zones. Relict fragments of the older metamorphic banding deformed into the folds with horizontal

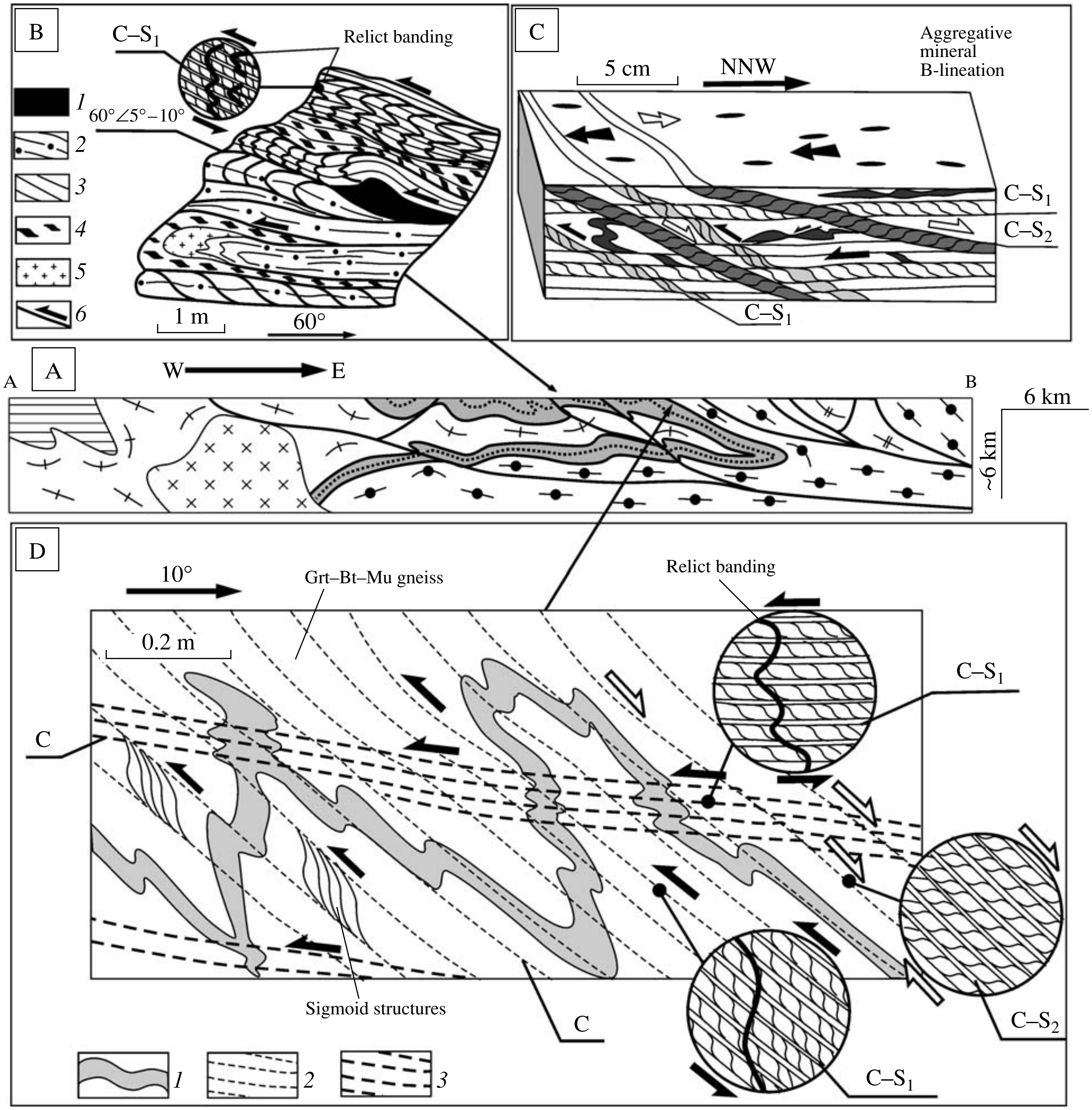

Fig. 10. Structural–kinematic assemblages in the Svecofennian thrust fault zones: (A) sketch geological section along line AB (see Fig. 9 for line location and Fig. 6 for legend), (B) section of tectonic melange in zone of the Svecofennian thrust fault, (C) block diagram illustrating relationships of C–S structures of different generations, (D) relationships of Svecofennian C–S structures of various kinematic pulses and generations in section view. Panel B: (*1*) serpentinite, (*2*) garnet orthoamphibolite affected by retrograde metamorphism, (*3*) kyanite–garnet–muscovite gneiss, (*4*) greisenized porphyroclastic gneiss, (*5*) muscovite pegmatite, (*6*) tectonic surfaces and displacements along them. Panel D: (*1*) leucosome of migmatite, (*2, 3*) foliation planes of different generations in tectonized gneiss.

axial planes are retained in the strongly tectonized rocks (Fig. 10B, close-up). The Svecofennian dislocations closely pervade the Archean complexes of the Belomorides as lenticular–loop shear and blastomylonite zones (Fig. 4B). The dispersed C–S structures that embrace considerable volumes of rocks develop in the areas adjacent to the zones of thrusting. In the structural style and grade of metamorphism, two generations of C–S structures are recognized: an older generation of dynamodiaphtorites that formed under conditions of epidote-amphibolite facies and younger blastocataclasites of greenschist facies (Figs. 10C, 10D). Several kinematic pulses expressed in differently oriented C–S structures of the older generation are noted. The character of crosscutting relations and superposition shows that the tectonic movements periodically resumed, while following the weakened surfaces oriented in either direction. The older generation of C–S structures commonly mark thrust and strike-slip displacements. As a rule, the second-generation structures are related to the normal faulting (Figs. 10C, 10D).

In general, the Chupa segment is characterized by a system of Svecofennian low-angle faulting that progressively developed from thrusting to normal faulting. This system was combined with near-latitudinal strike-slip faults and variously oriented folds. The C–S structures in near-latitudinal steeply dipping fault zones indicate both right-lateral and left-lateral (more frequent) displacements. The eventual structural assemblage may be defined as being the result of strike-slip–thrust and strike-slip–normal faulting. This assemblage consists of large sliding domains bounded by strike-slip faults (Fig. 9). The faulting most likely was controlled by the longitudinal transport of the Kolvitsa–Umba protrusion.

The Engozero segment may be regard as a flank or a back region with respect to the Kolvitsa–Umba protrusion (Fig. 2). A large vortex structure that formed here in the Svecofennian time requires further investigation. Its evolution likely was caused by rotation of rock masses around a vertical axis under the effect of lateral longitudinal tectonic flow.

DISCUSSION

The present-day structure of the Belomorian–Lapland Belt exhibits the final result of the multistage deformation that reached a peak of intensity at the early stage of the Svecofennian cycle and gradually waned afterward. Because of this circumstance, the obtained kinematic data mainly pertain to the retrograde Svecofennian tectonic processes. The older structural assemblages were obliterated to a great extent and retained only as relicts. The data presented above show that the evolution of the Belomorian–Lapland Belt is a series of three consecutive tectonic and metamorphic events related to the Reboly stage (2.88–2.53 Ga), Selet stage (2.45–2.35 Ga), and Svecofennian stage (1.94–1.75 Ga).

The Reboly stage of the evolution of the Belomorides in the Neoarchean was considered in [12, 21, 24, 25, 36] in terms of the subduction–collision model of the formation of the Belomorian Belt. As follows from the above-cited publications, a collisional orogen was formed by the end of Archean and the Belomorian complexes proper were localized at its base.

The Selet stage was manifested in extensive occurrence of Paleoproterozoic bimodal igneous complexes (2.50–2.35 Ma) that characterize the setting of epicontinental rifting. The Belomorian complexes that occurred at that time in the middle and lower crust under a pressure of 8–12 kbar were pervaded by dispersed drusite and granite intrusions emplaced under synkinematic conditions throughout the crust. It is suggested that these processes were related to the ascent of a mantle diapir [35, 37, 40]. The structural assemblages of the Selet stage comprise low-angle normal faults and zones of near-horizontal flow, folds of longitudinal flow with vertical and low-angle axial planes, B-type aggregative mineral lineation, boudinage structures, and magmatic duplexes (Fig. 4). Most these structures controlled localization of intrusions. The available data indicate that the igneous rocks of the Selet stage were formed deeper than 20 km under conditions of near-horizontal ductile flow. The paths of rock motion were recorded in the orientation of B-lineation and fold zones oriented in the northeastern and near-meridional directions (in present-day coordinates) (Fig. 3). It may be supposed that near-horizontal flow was accompanied by tectonic delamination and partial exhumation of deep-seated masses due to extension and sliding down of the upper crustal sheets along gently dipping normal faults (model of simple shear [56]). In many respects, this scenario is consonant with the ideas stated by Terekhov [40], who considers the simple shear to be the pivotal mechanism of the evolution of the Belomorian–Lapland Belt in the Paleoproterozoic, including the Svecofennian stage. However, the data discussed above constrain the period characterized by the tectonics of this style by the Selet time.

The Svecofennian stage of the evolution of the study region is characterized most completely in structural and kinematic terms. The results obtained are summarized in the scheme that demonstrates the directions of tectonic movements of this stage and the character of the dynamic segmentation of the central Belomorian–Lapland Belt (Fig. 11). The consideration of this scheme leads to the following conclusions. The Svecofennian structural–kinematic assemblages of the given region have a complex spatial configuration that reflects nonuniform, at first glance, chaotic tectonic flows. The analysis of the vector field and general structural pattern makes it possible to explain these flows and the character of segmentation of the studied area in terms of the formation of the near-horizontal Kolvitsa–Umba protrusion. In plan view, this protrusion is mushroom shaped. The back decompression region that controls the Umba granitoid pluton, the zone of the main protrusion with telescoped thrust systems, the frontal zone of tectonic pumping and indentor action of the protrusion, and its flank segments with thrust and strike-slip or rotation–vortex displacements are recognized (Fig. 11).

The protrusion was formed as a result of tectonic pushing-out of granulite complexes from the lower crustal levels to the upper levels in the form of a low-angle ascending tectonic flow accompanied by tectonic and retrograde metamorphic processes in the course of progressive exhumation of high-grade metamorphic rocks. The relatively narrow subthrust zones of granulite allochthons are the only exceptions. In particular, the clockwise *P–T–t* paths of the rocks of the Tanaelv–Kandalaksha Belt probably illustrate their underthrust-

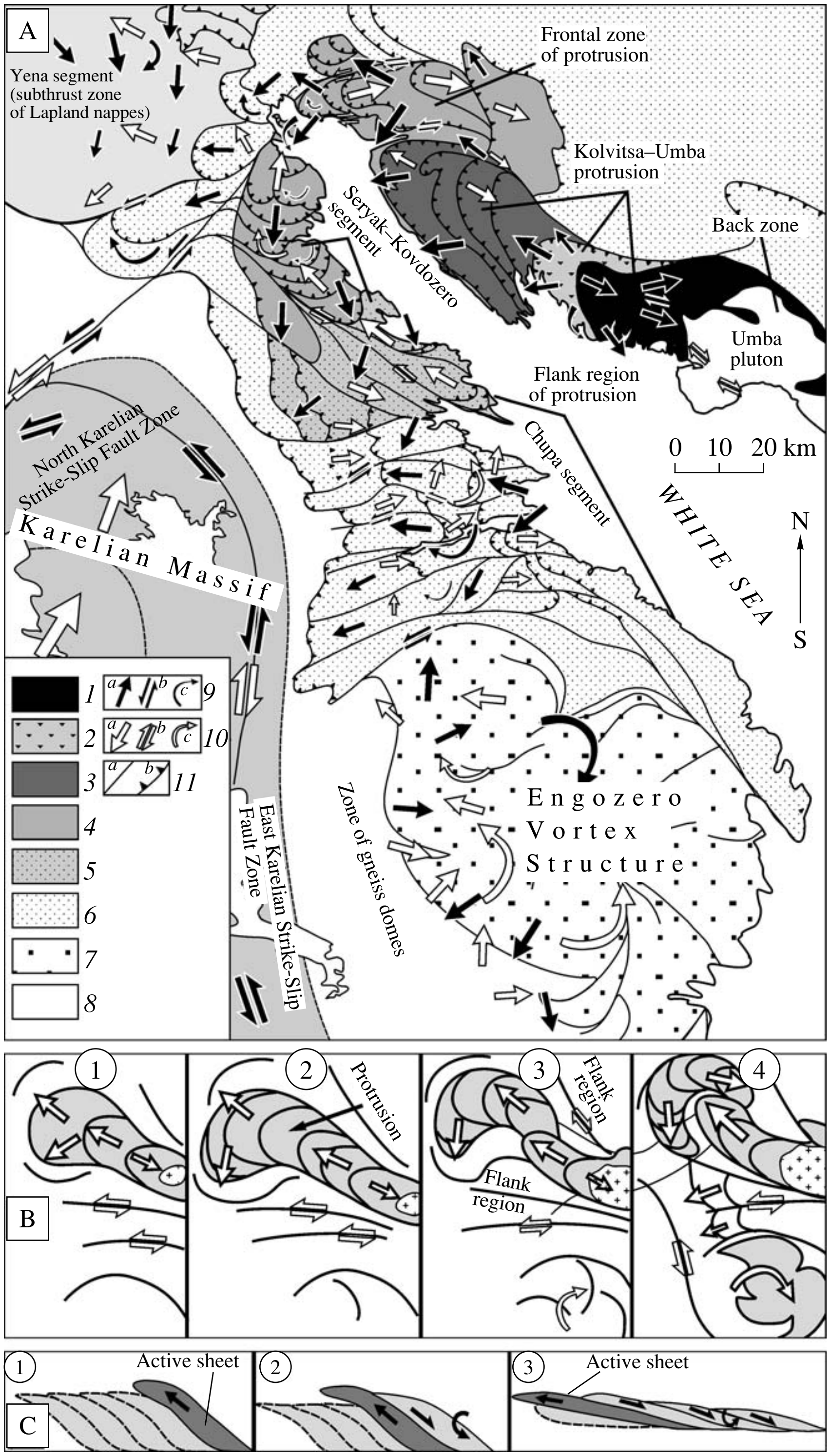

Fig. 11. (A) Structural–kinematic scheme of the central Belomorian–Lapland Belt and Kolvitsa–Umba near-horizontal protrusion (Svecofennian stage); (B) consecutive stages of the formation of the Kolvitsa–Umba near-horizontal protrusion in the process of tectonic telescoping (1–4) in plan view and (C) formation of a packet of tectonic slices in the process of pushing-out of active sheet and normal faulting in its back part (1–3), according to the model developed in [29], in section view. (*1–3*) Central portion of protrusion; (*4*) frontal zone of protrusion; (*5, 6*) flank regions of protrusion; (*7*) Engozero vortex structure; (*8*) zone of gneiss domes; (*9*) direction of (*a*) thrusting, (*b*) strike-slip faulting, and (*c*) rotation at the Svecofennian stage based on structures of first-generation dynamodiaphtorites; (*10*) direction of (*a*) thrusting, (*b*) strike-slip faulting, and (*c*) rotation at the Svecofennian stage based on structures of first-generation dynamodiaphtorites; (*11*) faults: (*a*) steeply and (*b*) gently dipping.

ing and the subsequent emergence. In marginal parts of granulite massifs, the underthrusting is confirmed by their isobaric cooling.

The central portion of the protrusion has a synform structure and indications of the divergent (outward) squeezing-out of rock masses, as occurs during the formation of the transpressional palm-tree structural elements. Thus, the protrusion likely was formed under transpressional conditions. At the same time, according to the reconstruction, the predominant longitudinal tectonic flow was oriented in the northwestern direction and resulted in multifold tectonic telescoping (Fig. 11B). At the early stages, the protrusion developed in the form of a unilateral northwestward flow that gave rise to the formation of tectonic slices and sheets that were festooned and enclosed into one another (Fig. 11B, stages 1–2). As follows from the tectonic doubling of the Kolvitsa–Umba Belt, a region of pumping and tectonic telescoping of a higher rank arose at the front of the protrusion as a result of the progressive displacement (Fig. 11B, stages 3–4). While the protrusion continued to wedge-in to the northwest, the rock masses tectonically spread from the frontal zone of pumping (Fig. 11B, stage 4). The uppermost tectonic sheet of the Umba granulites in the back zone of protrusion moved with a lower velocity relative to that of the underlying complexes. As a result, a system of gentle dipping normal faults developed in the back zone under the conditions of decompression that promoted emplacement of the Umba granitic pluton.

As was mentioned above, the variation of U–Pb titanite ages corresponds to the following succession of transportation of high-grade metamorphic complexes into the upper crust: (1) Lapland–Kolvitsa granulites and complexes of the (2) central and (3) marginal parts of the Belomorian Complex. Thus, an anomalous succession of pushed-out tectonic sheets (from upper to lower) is suggested for the formation of protrusion. This succession is consistent with the structural–kinematic data that show the progressive superposition of normal faults upon the older thrust faults. In line with this evidence, the development of the low-angle faults of the Belomorian–Lapland Belt may be interpreted as follows. The thrusting started in the axial zone of protrusion and progressively spread over its frontal zone and flanks; as a result, the activated fold–thrust region gradually expanded. In the course of pushing-out, the metamorphic rocks reached the upper crust and underwent decompression and cooling (Fig. 11C, stage 1). The next generation of thrust sheets was squeezed out from under the older sheets and also reached the conditions of retrograde metamorphism (Fig. 11C, stage 2). A system of low-angle normal faults conjugated with thrust faults developed in the back zone of the pushed-out active sheet; thereby, the normal faults partly inherited the surfaces of the older thrust faults. The development of normal faults predetermined the tectonic exhumation of deep-seated rocks that was due to sliding away of the upper tectonic sheets. The progressive development of the thrusting and normal faulting in diametrically opposite directions gave rise to the formation of the general dominoes-type structure. As a result, the tectonic sheets rotated around the horizontal axis and flattened; the vertical thickness of the tectonic packet diminished (Fig 11C, stage 3). Such a mechanism of pushing-out of tectonic sheets from under the previously formed nappe assembly was proposed by Morozov [29] on the basis of experimental data and field observations.

Many questions concerning the genesis of granulite complexes and the geodynamic settings that preceded their exhumation, as well as the causes of tectonic squeezing of these metamorphic complexes toward the surface, remain beyond the scope of this paper. The available data indicate that the formation of the Kolvitsa–Umba protrusion proceeded under conditions of general transpression that served as a background for the local longitudinal lateral flow, pumping, compression, and decompression. However, this general statement requires further development in terms of the specific geodynamic model.

CONCLUSIONS

(1) The Belomorian–Lapland Belt is a long-lived mobile zone that developed in different geodynamic settings. Its evolution was related to a series of tectonic and metamorphic events: (1) the Reboly stage that comprises the subduction (2.88–2.82 Ga) and collision (2.74–2.53 Ga) substages, (2) the Selet stage of the epicontinental rifting (2.45–2.35 Ga), and (3) the Svecofennian stage characterized by collision and general transpression (1.94–1.75 Ga).

(2) At the Selet stage, the early Paleoproterozoic structural and metamorphic complexes of the Belomorian Belt occurred at the lower and middle levels of the continental crust that experienced extension related to simple shearing. The rifting in the upper crust was combined with tectonic delamination and pervasive tectonic flow, structural lineation, folding of longitudinal flow, and low-angle normal faulting that controlled localization of synkinematic intrusions deeper in the crust.

(3) At the Svecofennian time, the deep-seated metamorphic complexes of the central Belomorian–Lapland Belt underwent tectonic exhumation under transpressional conditions as a result of emplacement of the near-horizontal Kolvitsa–Umba protrusion. The propagation of this protrusion was accompanied by multiple telescoping of tectonic slices and related to the transpressional squeezing-out of high-grade metamorphic rocks into the upper crust in the form of a low-angle ascending tectonic flow moving in the northwestern direction (in present-day coordinates).

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