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PALEOPROTEROZOIC TECTONICS AND EVOLUTIONARY MODEL OF THE ONEGA SYNCLINORIUM

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ABSTRACT. Consideration is being given to the Onega Paleoproterozoic structure (Onega synclinorium, OS) as a tectonotype of intraplate negative structures, which experience intermittent subsidence over a long period of time. The paper presents a model of the OS and discusses its tectonic evolution. The model is based on the geological and structural data, already published and collected so far by the authors, as well as on the data concerning the OS deep structure, particularly on the interpretation of the 1-EV seismic profile and potential fields. The proposed model illustrates an example of conjectured interaction between different geodynamic factors and explains reasons for the development of the OS throughout the Paleoproterozoic, including the periods of intense subsidence and magmatism, inversions of local basins comprising the Onega trough, and deformations of the Paleoproterozoic strata. An important role in the formation of the OS was played by shear dislocations within an imbricate fan of its controlling Central-Karelian shear zone. The shear dislocations were accompanied by rotation of a large block located to the west of the OS, which led to the rotational-indentational interaction between adjacent blocks and to compensated coexistence among transtensional and transpressional regimes along their separating shear zone. Compensatory dynamic mechanism also manifested itself in crustal layers at the base of the OS. Horizontal flow of the mid-crustal masses and their outflow from the depression were compensated by the development of deep-seated thrust duplexes and uplifts around the depression as well as by the upper crustal extension associated with low-angle dilatant normal faulting. Successive propagation of these faults, dynamically related to shear dislocations within an imbricate fan of the Central Karelia zone, controlled the formation features and southward migration of the OS-contained basins as well as magmatic and syllogenesis-related occurrences. Multilayered subhorizontal flow of low-viscosity rocks at the base and inside the OS section against the background of shear dislocations gave rise to the occurrence of crest-like and diapir-like folding. The processes of OS formation occurred amid the development and localization of active mantle plumes and asthenospheric diapirs. One of the factors of their development and localization were the phenomena of relative decompression within the imbrication fan of the Central Karelian shear zone.

KEYWORDS: Onega Paleoproterozoic structure; intraplate tectonics; geodynamics; shear zone; imbricate fan; detachment; seismic profiling

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1. INTRODUCTION

In the intracontinental areas there are negative structures (syneclises, depressions, basins) which tended to subside over a long period of time. The existing understandings of the factors and mechanisms of formation of such geostructures are rather various and based on different concepts. The development of subsidence is considered in relation to mechanical extension of the Earth's crust, transpression or transtension, magmatic and plume events, phase transitions in the lower crustal levels, and also as a result of the Earth spheroid deformation [Artyushkov, 1993; King, 1967; Kropotkin et al., 1971; Leonov, 2004; Glushanin et al, 2011; Khain, Lomize, 1995].

A well-understood example of a long-existing trough is the Onega Paleoproterozoic structure (synclinorium, OS) whose active development occurred 2.5–1.7 Ga ago [Krats, 1963; Glushanin et al., 2011; Sokolov et al., 1970; Heiskanen, 1990]. This unique geological object of the Baltic Shield, occupying an area of ~40000 km^2 in the south of Karelia, combines the elements of specific sedimentary formations and peculiar tectonic and magmatic features. The most detailed description of the OS geological structure is presented in the collective monograph [Glushanin et al., 2011], which focuses on the modern ideas of its deep-seated structure, obtained as a result of the Onega parametric borehole drilling and related geological-geophysical studies. In many chapters of the monograph, dedicated to some aspects of the OS geology, emphasis is put on a specific group of lithological, tectonic or magmatic manifestations resulting in the generation of numerous, sometimes conflicting evolutionary models of the OS. Most of the authors relate the development of this structure to the plume model, though there are also proposed versions of its formation in conditions of scattered rifting, in transpressional and transtensional regimes, and due to the Earth's spheroid deformation based on the "chord model" [Glushanin et al., 2011].

The ideas of the OS structure involve many aspects including the character of the development of the Paleoproterozoic complexes within the Archean cratons of Fennoscandia. The OS-composing complexes are interpreted as fragments of the epiplatform cover originally lying on the vast areas [Gilyarova, 1974; Krats, 1963; Kharitonov, 1966] or as formations of continental rift grabens and pull-apart basins [Kolodyazhny, 2006; Morozov, 2002b; Svetov, Sviridenko, 1991; Heiskanen, 1990], and also as suture-type sedimentary-volcanic belts having an imbricate thrust structure [Morozov, 2010].

The results of drilling the Onega parametric borehole which penetrated the continuous cross-section of the Paleoproterozoic OS did not show any features of double section or double thrust structures but confirmed the existing ideas of succession, borders and composition of the major Paleoproterozoic stratons in the Karelia region. However, at the base of the OS, there was revealed for the first time a thick Precambrian-aged salt-bearing unit, underwent brittle-ductile deformations, which implies a detachment in the Paleoproterozoic basement [Glushanin et al., 2011].

Understanding of occurrence and long-term development mechanisms of the OS requires a complex analysis of sedimentary, magmatic and structure formation features. The present paper, aimed at evolutionary modeling of the OS, deals with the analysis of our geological-structural data [Kolodyazhny, 1999, 2002, 2006; Leonov et al., 1996, 2003; Poleshchuk, 2006, 2007; Kuznetsov et al., 2023] and with that of published and archive materials [Voitovich, 1971; Galdobina, Mikhailyuk, 1971; Sokolov, 1973, 1987; Gilyarova, 1974; Sharov 2004; Morozov, 2010; Golod et al., 1983; Krats, 1963; Korosov, 1991; Kozhevnikov, 2000; Kulikov et al., 1999, 2017a, 2017b; Makarikhin et al., 1995; Negrutsa, 1984, 2011; Novikova, 1975; Glushanin et al., 2011; Report..., 1991; Polekhovsky, Golubev, 1989; Polekhovsky et al., 1995; Puchtel et al., 1995; Ryazantsev, 2014; Satsuk et al., 1988; Svetov, 1979; Svetov, Sviridenko, 1991; Svetov et al., 2015; Sokolov et al., 1970; Systra, 1991; Kharitonov, 1966; Heiskanen, 1990; Amelin et al., 1995; Melezhik et al., 2013].

2. GENERAL INFORMATION ON GEOLOGICAL STRUCTURE OF THE REGION

The Onega synclinorium (OS) is composed of the Paleoproterozoic volcanogenic-sedimentary complexes, erosively and unconformably overlying the Archean granite-greenstone formations of the Karelian Craton (KC) in the southeastern Baltic Shield (Fig. 1). The synclinorium is located at the south of the exposed portion of the KC which is bordered by the structures of the Svecofennian accretionary orogen in the southwest and by the structures of the Belomorian-Lapland belt in the northeast. The southern parts of the OS and KC are overlain by the sedimentary cover of the East European platform.

The Archean granite-greenstone complexes compose the KC basement unconformably overlain by the protoplatform cover – Paleoproterozoic volcanogenic-sedimentary rocks (Karelian complex, karelides) [Sokolov, 1987; Krats, 1963; Kulikov et al., 2017a, 2017b; Heiskanen, 1990; Melezhik et al., 2013]. The karelides compose the structural level, sharply isolated from the basement and comprising large synclinal structures, narrow squeezed synclines, and fault and fold belts extended primarily northwestward (Fig. 1). In many cases, the Paleoproterozoic synclines, including OS, are spatially compatible with the shear zones along the margins of the KC and in the central part of it (Fig. 1).

In the KC basement structure, there are distinguished three main domains composed of heterochronous granite-greenstone formations – oldest within the Vodlozero and Western Karelia domains (Sm-Nd model ages >3 Ga) and younger (Sm-Nd model ages 2.8–2.7 Ga), comprising the Central Karelia domain [Kozhevnikov, 2000; Kozhevnikov et al., 2006; Kulikov et al., 2017a, 2017b; Levchenkov et al., 1989; Lobach-Zhuchenko et al., 2000]. The domain borders, as well as the KC greenstone belt locations, have submeridionally trending orientation which is sharply discordant with the strike of the Karelia Complex structures and KC-bordering zones elongated northwestward (Fig. 1).

The OS is located near the western margin of the Vodlozero domain and changes along the NW strike to the wedge-shaped Segozero syncline overlying the boundary between the Vodlozero and Central Karelia domains and intersecting it at an acute angle (Fig. 1).

3. STRUCTURAL-MATERIAL COMPLEXES OF THE ONEGA SYNCLINORIUM

There are the following suprahorizons distinguished traditionally in the cross-section of the Paleoproterozoic complexes of the KC: Sumian (2.5–2.4 Ga), Sariolian (2.4–2.3 Ga), Yatulian (2.3–2.1 Ga), Ludicovian (2.10–1.92 Ga), Calevian (1.92–1.80 Ga) and Vepsian (1.80–1.75 Ga) [Sokolov, 1973, 1987; Krats, 1963; Kulikov et al., 2017a, 2017b; Lower Precambrian Stratigraphic Scale..., 2002; Glushanin et al., 2011; Sokolov et al., 1970; Kharitonov, 1966; Heiskanen, 1990; Melezhik et al., 2013].

The most complete and best-studied lithostratigraphic sections of the Paleoproterozoic are located in the OS and in the Segozero trough. Within the OS, there are distinguished the North Onega synclinorium and South Onega synclinal trough. The structure of the North Onega depression is contributed to by the Sumian, Sariolian, Yatulian, Ludicovian and Calevian formations; the South Onega syncline is composed of the Vepsian formations [Kulikov et al., 2017a, 2017b; Negrutsa, 2011; Lower Precambrian Stratigraphic Scale..., 2002; Glushanin et al., 2011] (Fig. 1).

Sumian suprahorizon (2500–2400 Ma) is represented at the base by thin weathering crusts and highly mature silicoclastites. They are overlain by andesibasalts (up to 1.5 km thick), locally occurring as relics of paleorift system [Korosov, 1991]. Intrusive comagmates of these volcanites are represented by dikes and stratified mafite-ultramafite massifs. The largest of them, Burakovsky massif (U-Pb age of 2449±1.1 Ma), is located northeast of the OS [Amelin et al., 1995]. The massif and its related dike swarms comprise a deep-root part of the Sumian paleorift [Glushanin et al., 2011].

Sariolian suprahorizon (2400–2300 Ma) is represented by polymictic conglomerates and mixtite-bearing formations, spatially related to the Sumian rift structures and volcanites [Korosov, 1991]. In the North Onega depression, the Sumian and Sariolian formations are localized in graben-shaped structures. Their fragments are exposed in its western and northwestern flanks of the OS (Kumsa zone) (Fig. 2).

Yatulian suprahorizon (2300–2100 Ma) is represented by volcanogenic-sedimentary formations (up to

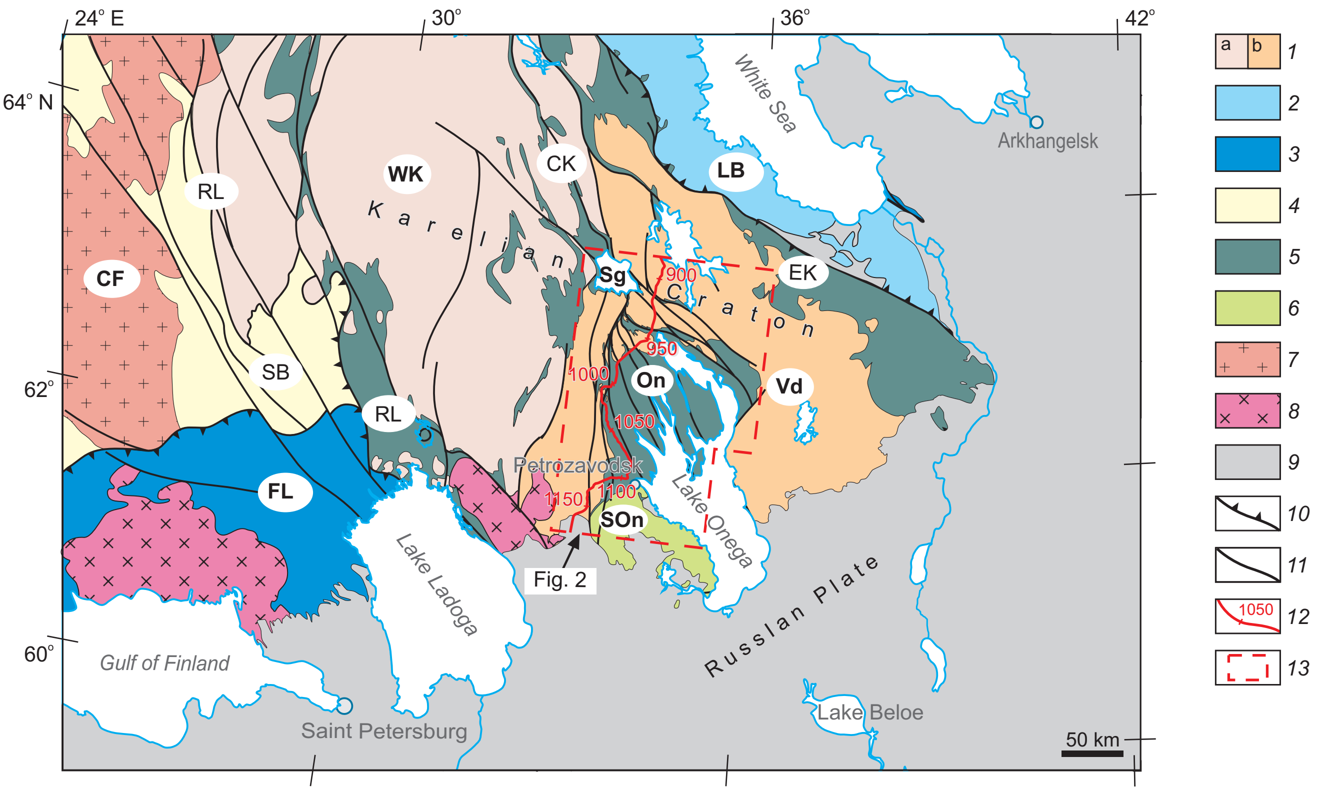

Fig. 1. Scheme of the geological structure of the southeastern Baltic Shield.
1 – Archean granite-greenstone complexes: *a* – West and Central Karelian (WK, CK), *б* – Vodlozersky (Vd) domains; *2* – Archean – Paleoproterozoic granulite-gneiss complexes of the Lapland-White Sea belt (LB); *3–7* – Paleoproterozoic complexes: *3* – metamorphic and igneous of the Southern Finland-Ladoga belt (FL), *4* – volcano-sedimentary and igneous island arc of the Svecofennian belt (SB), *5* – volcano-sedimentary of the Karelian Craton, *6* – terrigenous deposits of the South Onega trough, *7* – granitoids of the Central Finnish massif (CF); *8* – Early Riphean rapakivi granites; *9* – Vend – Phanerozoic cover; *10–11* – faults: *10* – reverse faults and thrusts, *11* – mainly strike-slips; *12* – 1-EV seismic profile; *13* – contours of Fig. 2. Shear zones: RL – Raakhe-Ladoga, CK – Central Karelian, EK – East-Karelian; Sg – Segozersk syncline, On – Onega synclinorium, SOn – South Onega trough.

2 km thick) which form the base of the KC protoplatform cover and overlie the Sumian-Sariolian rift formations or Archean basement with a sharp angular unconformity (Fig. 2). The Yatulian is underlain by areally distributed silicate crusts of chemical weathering. Up to half of the Yatulian consists of basite lavas and sills. The Yatulian sections fall into two parts: Lower Yatulian (Yangozersky and Medvezhyegorsky formations), mostly represented by quartzite sandstone package with sheet-like basaltic bodies and interlayers of basal conglomerates/gravelites, aleurolites and argillites, and Upper Yatulian, represented by carbonate (Tulomozersky formation) and terrigenous-carbonate rock masses – dolomites (partly with stromatolite and oncolite biostromes), argillites, sandstones, and gravelites [Negrutsa, 1984; Makarikhin et al., 1995; Satsuk et al., 1988; Glushanin et al., 2011; Melezhik et al., 2013].

The Onega parametric well in the western OS at the base of the Yatulian, overlying the basement rocks, penetrated evaporites: about 200 m thick halite stratum overlain by a 300-m anhydrite-magnesite stratum underlying the dolomites [Glushanin et al., 2011]. The evaporite occurrences are also found on the eastern slope of the North Onega synclinorium [Trofimov, Loginov, 2005]. In the salt-bearing section, there are numerous fragments of the altered Lower Yatulian volcanites and sandstones. The absence of sedimentogenic and the presence of brecciated textures, as well as s lepido-granoblastic structure of the halite stratum, indicate its complete recrystallization under brittle-ductile flow conditions. The age of the halite stratum corresponds to the Upper Yatulian which is confirmed by Rb/Sr isochron dating (2216±68 Ma) [Glushanin et al., 2011].

Lithosedimentary features of the Yatulian rocks meet the conditions of a shallow-water epicontinental sea basin and its coastal areas [Krats, 1963; Makarikhin et al., 1995; Negrutsa, 1984; Sokolov et al., 1970; Kharitonov, 1966; Heiskanen, 1990]. Sedimentation conditions varied from a fluviolacustrine plain in the Lower Yatulin to playa lakes and, throughout the hypersaline environment of sabkha, to shallow sea water in the Upper Yatulian [Glushanin et al., 2011; Sokolov et al., 1970]. In the early Yatulian time OS was an area prone to erosion and lacustrine-alluvial deposition. There subsequently occurred the marine transgression from north to south, and in the late Yatulian time isolation of the North Onega depression bordered by a swell-like uplift – an area of eroded land [Glushanin et al., 2011; Sokolov et al., 1970].

The Yatulian volcanites are represented primarily by toleitic platobasalts of the trappean formation occurred in the intracontinental platform environment [Svetov, 1979; Svetov et al., 2015; Negrutsa, 1984; Sharkov, 1984; Sharkov et al., 2000]. The lavas released from fissure volcanoes in shallow-water basins or on land [Svetov, 1979].

Ludicovian suprahorizon (2100–1920 Ma) is represented by the Zaonega (lower) and Suisar (upper) formations [Sokolov, 1987]. The Zaonega formation (up to 1.3 km thick) is composed of substantially carbonaceous rocks (shungites, shungite-containing tuffoaleurolites and argillites), silicites, limestones and dolomites, hosting numerous gabbro-dolerite sills. The Suisar formation (up to 700 m thick) consists of pyroxene-, plagioclase- and picrite-basalt tuffs and lavas [Kulikov et al., 1999]. These volcanites comprise the cores of small synclinal structures in the central and southern parts of the North Onega synclinorium (Fig. 2). Together with their underlying Koncheozero sill (a feeder, 1974±27 Ma), the volcanites form the volcanic-plutonic association of platobasalts [Glushanin et al., 2011].

Carbonaceous sediments of the Zaonega formation were deposited in the basin with hydrogen sulfide contamination and low sedimentation rate against the background of synchronous basaltic volcanism. The petrochemical data show that magma sources of the Suisar picrobasalts originated in the asthenospheric mantle plume and, moving towards the surface, underwent fractional crystallization and mixing with the material of the lithospheric mantle and host rocks of the continental crust [Kulikov et al., 1999; Glushanin et al., 2011; Puchtel et al., 1995, 1999].

Kalevian suprahorizon (1920–1800 Ma) is represented by a monotonous rhythmic alternation of arkose and quartz sandstones, aleurolites and clay schists, with a limited distribution of silicites, gritstones, and conglomerates. The Kalevian (up to 550 m thick) is exposed in small synclinal cores in the southern and central North Onega syneclise (Fig. 2). The Kalevian formations correspond to shallow-water-basin and continental molassoid sediments accumulated in a period of declining magmatic activity. The Kalevian is characterized by facial zonality which manifests itself in the occurrence of coarse-grained rocks in the sections of the northern segments of synclinal structures whereas fine-grained terrigenous rocks start to prevail towards the south [Glushanin et al., 2011]. Such asymmetric lithofacial profile of the basin and the presence of the Ludicovian rock fragments in the Kalevian formations testify to inversion of the northern Onega basin, its transformation into erosion-prone area, and migration of the residual depression towards the south. The area of occurrence of conglomerates and gravelites obviously marks a relatively steep-sided coastal zone which can be compared with a tectonic scarp of normal faulting origin.

Vepsian suprahorizon (1800–1750 Ma) combines the Petrozavodsk (lower) and Shoksha (upper) formations [Galdobina, Mikhailyuk, 1971; Sokolov, 1987]. The Petrozavodsk formation (thickness <300 m) is primarily composed of gray arkose sandstones with interlayered aleurolites, gritstones, and conglomerates. The cross-section shows the interlayers of sedimentary breccias with fragments of the Ludicovian shungite schists and volcanites. The Shoksha formation (no less than 1000 m in thickness), with unconformity and conglomerate lenses at the base of the cross-section, overlies the Petrozavodsk formation and is represented by red-colored, often cross-bedded sandstones and quartzite sandstones with conglomerate lenses. The Vepsian formations compose the South Onega syncline, lie unconformably over all Paleoproterozoic complexes and, unlike those, are weakly dislocated.

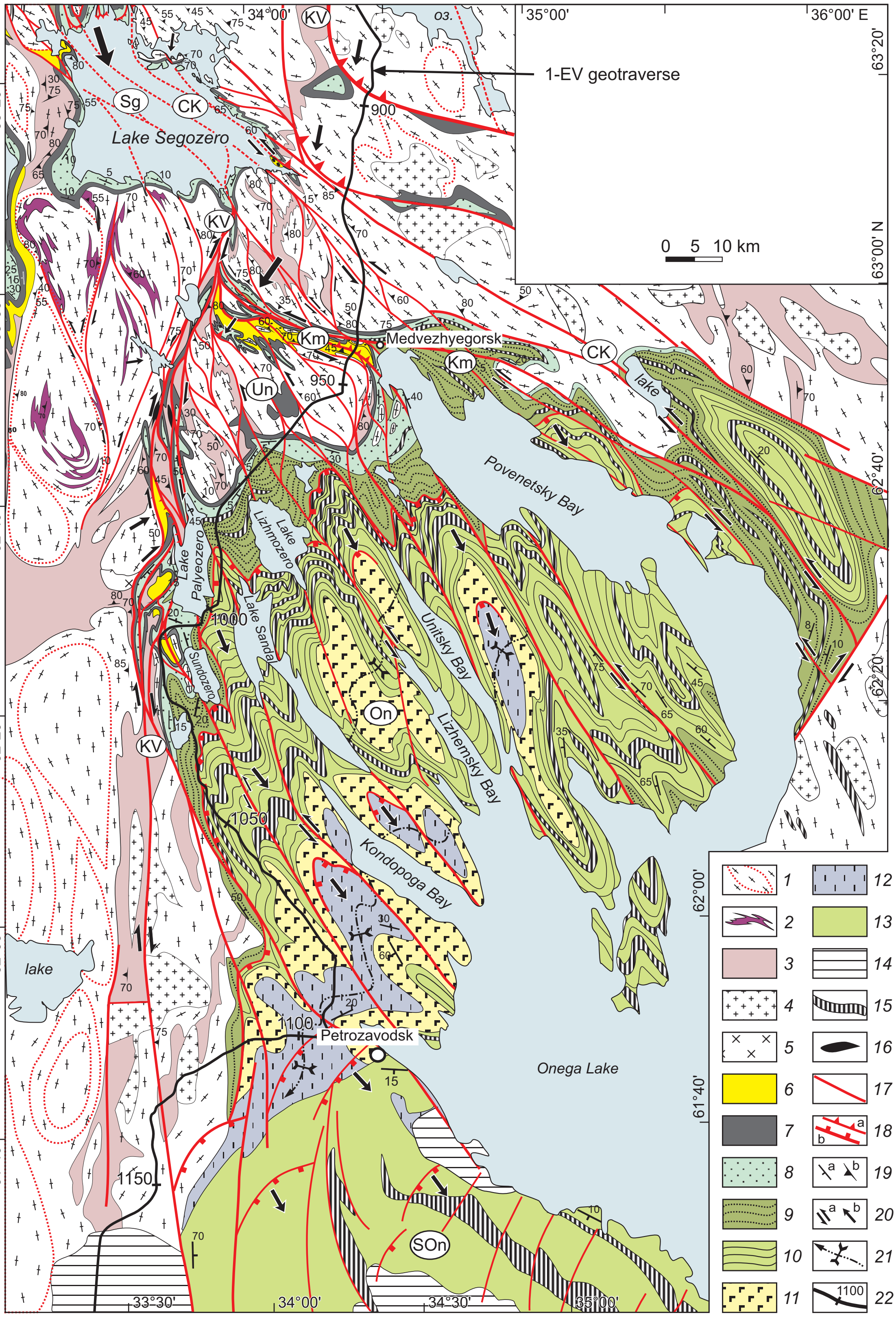

Fig. 2. Geological and structural scheme of the Onega synclinorium (after [Morozov, 2010; Kolodyazhny, 2006; Kulikov et al., 2017b]). *1–5* – Archean complexes: *1* – gneissic granites, *2* – gneisses, *3* – greenstone formations, *4* – plagiomicrocline granites, *5* – diorites; *6–13* – Paleoproterozoic complexes: *6* – Sumian –Sariolian, *7–8* – Lower Yatulian, *9* – Upper Yatulian, *10* – Lower Ludicovian, *11* – Upper Ludicovian, *12* – Kalevian, *13* – Vepsian; *14* – Vend; *15* – gabbro-dolerite dikes and sills; *16* – ultrabasic rocks; *17* – strike-slip faults and reverse slips; *18* – thrusts (a) and normal faults (b); *19* – dip and strike in rock strata (a) and gneissic banding/schistosity (b); *20* – directions of displacement: a – strike-slip, b – horizontal; *21* – axial planes of early-stage folds; *22* – seismic profile 1-EV. Paleoproterozoic synclinal structures: On – North Onega, SOn – South Onega, Sg – Segozero; shear zones: CK – Central Karelian, Km – Kumsa, KV – Koikary-Vygozero; Un – Units dome.

The Vepsian terrigenous sediments were deposited in the continental alluvial-lacustrine environment under arid climate conditions [Galdobina, Mikhailyuk, 1971; Sokolov, 1987]. The orientation of cross-beds and ripple marks and detrital zircon ages imply that the detrital material was transported primarily from the areas located immediately north of the Vepsian basin [Kuznetsov et al., 2023].

Volcanogenic-sedimentary complexes of the OS are paragenetically related to contrastively differentiated intrusive series. All these magmatic formations occurred in intraplate rifting environments accompanying the development of plumes whose maximum activity is confined to time intervals of 2.53–2.42 and 2.1–1.95 Ga [Sokolov, 1987; Morozov, 2010; Kulikov et al., 2017a, 2017b; Mints, Eriksson, 2016].

Gabbro-dolerite and less often ultrabasic sills lie at several levels of the Yatulian, Ludicovian and Vepsian sections and take up substantial OS volumes (Fig. 2). The location of sill feeders has not yet been reliably determined. They are supposed to be located in high permeability areas of the central and marginal parts of the OS [Kulikov et al., 1999; Novikova, 1975; Svetov, 1979].

The sills form sublayered and sublayered-crosscutting bodies gradually or abruptly moving to higher levels of the OS section [Kulikov et al., 1999; Poleshchuk, 2006]. An abrupt transition between the levels occurs due to stepped (ramp-bent) sill-like bodies increasing in thickness at the turns. Sill contacts along the ramp steps sharply crosscut host rock stratification, produce an exocontact influence, and are accompanied by slickensides (Fig. 3).

The OS sills show their relationship with the sublayered fault zones and often lie among dinamoschists and other tectonites which underwent an exocontact effect of intrusions. Tectonic nature of the sublayered zones of sill intrusions is clearly defined in the Upper Yatulian formations. These zones are confined to basite-cemented carbonate breccias and ductile-flow structures enclosed by sills [Glushanin et al., 2011; Sokolov et al., 1970]. The peperites, found at the contacts between host rocks and sills, testify to the emplacement of sills into wet sediments [Biske et al., 2004; Poleshchuk, 2007]. A spatial relationship between sills and tectonites and the seismic profiling data (see below) suggest that the OS sills heal the sublayered and step faults called normal faults.

The Proterozoic volcanogenic-sedimentary complexes within the OS have an irregular spatial distribution: their sectional structure changes significantly in the lateral, primarily meridional direction. The Lower Yatulian formations occur mostly in the Segozero basin and northern part of the North Onega synclinorium (see Fig. 2), gradually pinching out towards the south and southeast. The wells in the central OS at the base of the Proterozoic cross-section penetrated the Upper Yatulian carbonate-terrigenous and evaporite formations [Glushanin et al., 2011; Report..., 1991; Satsuk et al., 1988]. The Ludicovian and Kalevian only occur in the central and southern North Onega synclinorium. Towards the south, the unconformable pre-Vepsian strata are overlain by the Vepsian rocks comprising the isolated South Onega syncline. Such lateral change of the Paleoproterozoic cross-sections suggests a gradual southern migration of the Onega paleobasin depocenter during the Yatulian-Vepsian time.

4. TECTONICS OF THE ONEGA SYNCLINORIUM

The North Onega synclinorium has a deltaic shape in plan and is built up by the NW-elongated oval South Onega syncline on the south. The western termination of the OS is the submeridional Koikary-Vygozero shear zone which in the north joins the adjacent Kumsa zone developed along the northeast side of the North Onega synclinorium (see Fig. 1, 2).

The North Onega synclinorium of size 120×150 km is located in the area of fan-shaped virgation (a horsetail structure, an imbricate fan) of the Central Karelia shear zone whose branches frame the OS and complicate its inner structure [Kolodyazhny, 2002, 2006; Glushanin et al., 2011] (see Fig. 2). The Archean basement rocks, which frame this depression, form different-rank dome-shaped and lenticular structures comprising a half-closed belt of tectonic uplifts.

The earliest folded structures of the synclinorium are gentle folds of the N-NE orientation. A large syncline of such a kind has been reconstructed from the location pattern of the Kalevian formations (see Fig. 2). Similar smaller consedimentary folds (typical changes in sediment thickness on the syncline slopes) were found in the west of the North Onega structure [Voitovich, 1971]. These folds are complicated by the imposed shear zones and northwest-striking folds [Kolodyazhny, 2006; Systra, 1991].

The northwest-oriented structures prevail and mainly form a tectonic style of the North Onega synclinorium. This style is represented by the alternation of wide trough-shaped synclines and narrow crest-like anticlines localized in the shear zones (Fig. 4). The synclines have wide (6–12 km), weakly dislocated bottoms and short steep wings. The anticlines are crest-like compressed and isoclinal folds, sometimes squeezed mushroom-shaped and

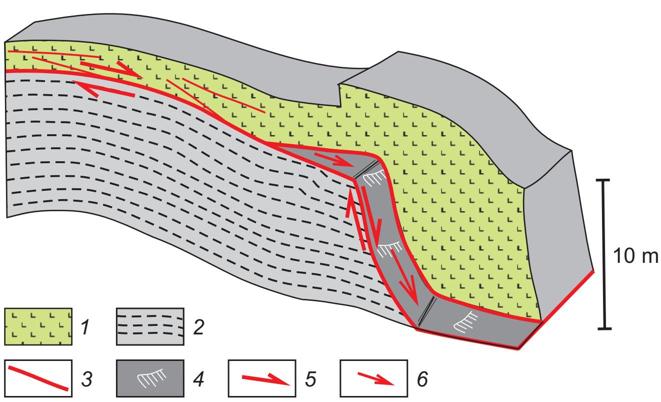

Fig. 3. A model of an outcrop with a stepped segment of the Koncheozero sill.
1 – gabbro-dolerite sill; *2* – shales of the Zaonega formation; *3* – sublayer detachment; *4* – slickensides; *5–6* – directions of displacements along the fault (*5*) and the fault plane (*6*).

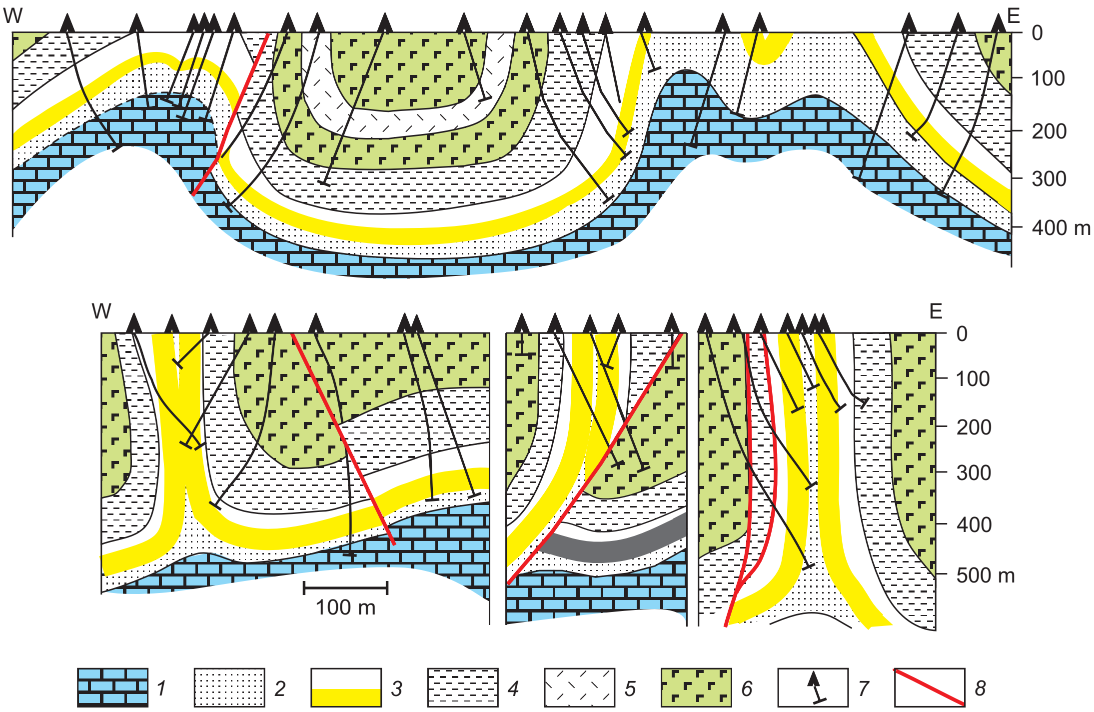

Fig. 4. Drilling profiles through crest-like and diapire-like anticlinal structures of the North Onega synclinorium [Report..., 1991]. *1–3* – deposits of the Upper Yatulian: *1* – carbonate–terrigenous, *2* – sandstones, *3* – shales, siltstones, limestones; *4–5* – Ludicovian shungite-bearing deposits (Zaonega formation): *4* – terrigenous, *5* – carbonate-terrigenous; *6* – gabbro-dolerite sills; *7* – boreholes; *8* – faults.

diapir-like structures resembling open flowers. These anticlines are complicated by parasitic folds, oblique reverse faults, and thrusts. A significant strike-slip component of the faults is emphasized by en echelon parasitic folding and elongated basite bodies which indicate the localization of crest-like anticlines in shear zones [Kolodyazhny, 2006; Report..., 1991]. The structure of some "antiform" shear zones is very similar to transpressional flower-like structures.

The structure of crest-like and diapiric anticlines is contributed to by the Yatulian low-viscosity carbonate-terrigenous and evaporite formations, Ludicovian shungites, and Archean granite-gneisses of the basement. The thickness of the Yatulian and Ludicovian strata increases significantly (2–4 times) in the anticlinal cores as compared to the cores of adjacent anticlines. This testifies to a layered ductile flow of low-viscosity rocks into anticlinal cores. The cross-section of the North Onega depression reveals no less than three horizons, prone to brittle-ductile flow, which resulted in their structural disharmony relative to adjacent formations. These are Yatulian evaporites and carbonate-terrigenous formations, and Ludicovian shungite schists. Disharmonic structural patterns of layered-complex packets of the OS are separated by detachments [Glushanin et al., 2011].

The degree of structural-material reworking of the rocks in "antiform" shear-zone structures is extremely high. Smaller-size folds, schistosity, cataclase and brecciation manifested therein are sometimes accompanied by metasomatic albite-carbonate-mica mineralization whose K/Ar ages are grouped into ranges of 1900–1700, 1100–900 and 150–100 Ma [Polekhovsky et al., 1995].

The South Onega syncline of size 60×120 km is composed of the Vepsian formations, resting with angular unconformity on the folded and faulted structures in the North Onega depression (see Fig. 2). The South Onega depression has relatively simple and asymmetric cross-sectional structure. On the northwest limb of the anticline the rocks show a gentle dip (10–12°, rarely 20–25°) which is steeper and reaches 70° in the near-fault zones on the southwestern limb. The rocks lie almost horizontally in the central part of the depression. The South Onega syncline is complicated by small-amplitude faults, predominantly normal faults and oblique normal faults of the submeridional, northwestern and northeastern strike. Parasitic folds are usually gentle and rather few. More common are small (0.5–3.0 m) asymmetric subaqueous slump folds [Kuznetsov et al., 2023].

The formation of the South Onega depression is related to final episodes of the Karelia tectonic era when there was a transition from the Svecofennian folded deformations (1.90–1.87 Ga) to a relatively quiet platform tectonic regime [Systra, 1991].

5. SHEAR ZONES IN THE MARGINAL PARTS OF THE ONEGA STRUCTURE

The OS-bordering shear zones are the main branches of the Central Karelia zone in the area of its fan-shaped virgation. These are Koikary-Vygozero and Kumsa shear zones (see Fig. 2).

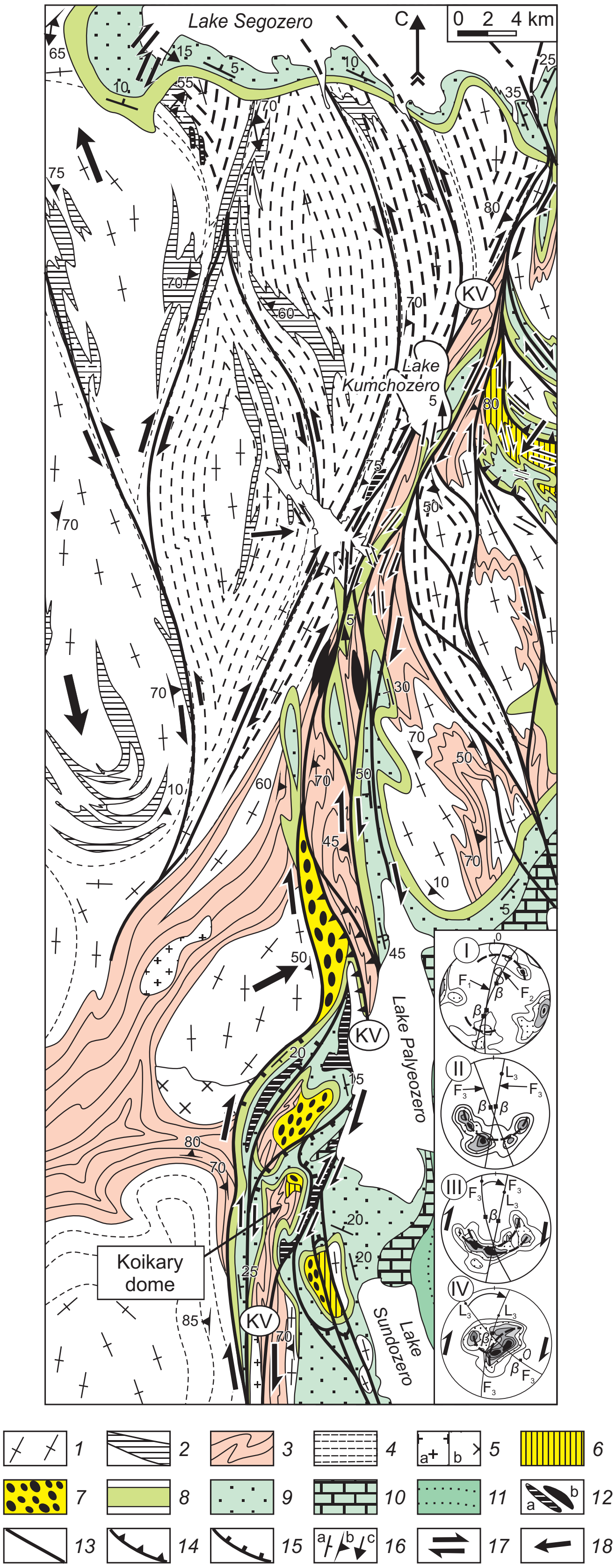

Fig. 5. Geological and structural scheme of the Koikary-Vygozero shear zone (modified based on [Voitovich, 1971; Kolodyazhny, 1999; Systra, 1991; Kharitonov, 1966]).
Stereographic equal–area projections on the lower planisphere of the poles of schistosity and bedding: I – schistosity of the Archean greenstone complexes (128 measurements, isolines 3-5-10-18-20 %), II – Sumian rock bedding (48 measurements, isolines 2-4-6-10-15 %), III – Sariolian rock bedding (46 measurements, isolines 1-5-12-15 %), IV – Yatulian rock bedding (143 measurements, isolines 1-2-5-7-10-15 %). F_1, F_2 and F_3 – fold axial surfaces of the first, second and third generations, L – their geometric hinges, β – fold axes. *1–5* – Archean complexes: *1* – gneissic granites, *2* – gneisses, *3* – greenstone, *4* – migmatite granites, *5* – granites (a) and diorites (b); *6–12* – Paleoproterozoic complexes: *6* – Sumian, *7* – Sariolian, *8–9* – Lower Yatulian, *10* – Upper Yatulian, *11* – Ludicovian, *12* – gabbro-dolerite (a) and ultrabasic (b) dikes; *13–15* – faults: *13* – strike-slips, reverse-slips, *14* – thrusts, *15* – normal faults; *16* – dip and strike in rock strata (a), shistosity/gneissic banding (b), linearity (c); *17–18* – directions of the Svecofennian movements: strike-slip (*17*) and horizontal (*18*) for large volumes of rocks.

The Koikary-Vygozero shear zone about 5–10 km wide is submeridionally traced for more than 100 km along the western margin of the OS (Fig. 5). Its structure is contributed to by the Archean granite-greenstone complexes and Paleoproterozoic volcanogenic-sedimentary formations. The zone has a lenticular shape structure caused by a combination of high-order conformal and diagonal faults. The tectonic lenses are often sigmoidal. There are elements of en echelon lenticular bodies, fold axial surfaces and secondary faults represented by oblique (with strike-slip component) reverse faults and thrusts. The position of diagonal structures – Paleoproterozoic folds, normal faults, thrusts and reverse faults – indicates the right-lateral displacements along the zone (Fig. 5).

The lenticular structures in the planar bending segments of the Koikary-Vygozero zone form the systems of decompressional or compressional shear duplexes depending on the step configurations. A well-defined right-stepped structure to the west of Lake Palyeozero forms a decompressional shear duplex at the right-lateral displacement along the zone. It is composed of diagonal strike-slip (with normal fault component) faults and dome-shaped structures. The left-step bending further north is marked by diagonal reverse-thrust structures (Fig. 5). The sheeted protocover complexes in the northern Koikary-Vygozero zone form narrow, compressed synclines oriented diagonally or conformally to the zone strike.

The inner structure of the decompressional shear duplex near Lake Palyeozero is complicated by a series of dome-shaped anticlines, whose cores expose the basement rocks and Sumian-Sariolian formations. One of them is the Koikary dome-shaped structure, drop-shaped in plan (Fig. 5). The geological-structural studies within the Koikary dome made it possible to identify kinematic stages of its development [Kolodyazhny, 1999, 2006]. By the end of the Neoarchean, in the greenstone belt there occurred a system of linear compressed and isoclinal cylindrical F_1 folds with N/NE-oriented fold axes (Fig. 5, I).

The subsequent left-lateral displacements gave rise to the formation of strike-slip faults and F_2 conical folds with steeply dipping hinges and planar left-lateral asymmetry (Fig. 5, I). The Sumian-Sariolian rift-structure formation was accompanied by the development of the Sariolian mixtite-bearing formations marking the normal-fault scarps on the graben slopes. After the deposition of the Yatulian protocover, as a result of the Svecofennian deformations there was an inherited basement faulting under the right-lateral strike-slip displacement conditions. There were formed narrow blastomylonite and cataclasite zones, major and secondary (R, R', P) fault systems, ruptures (T), kink-zones, and F_3 shear zone-related right-lateral planar asymmetric folds. In the Sumian and Sariolian rocks there are two systems of F_3 conjugated conical folds with axial planes making a sharp angle (Fig. 5, II and III). In the Yatulian rocks there is a dome-shaped structure and its two complicating systems of conjugated conical folds oriented conformally and diagonally to the main zone strike (Fig. 5, IV). The orientation of diagonal northwest-striking folds indicates the right-lateral strike-slip displacement along the Koikary-Vygozero zone (Fig. 5).

Therefore, within the Koikary-Vygozeto zone, there were identified strike-slip displacements which were left-lateral at an early stage (Late Archean) and right-lateral at a late one (Paleoproterozoic, Svecofennian).

The Kumsa shear zone is developed along the northeast slope of the OS and comprises the southeastern branch of the Central Karelian zone in the area of its fan-shaped virgation (see Fig. 2). The northwestern segment of the zone is separated from the centrocline of the North Onega synclinorium by the Units granite-gneissic dome. This area has a synclinal structure and is 5–10 km wide [Kolodyazhny, 2002, 2006; Korosov, 1991; Krats, 1963]. The Kumsa syncline is an asymmetric structure complicated by parasitic folds, longitudinal and diagonal shears, oblique reverse faults, and thrusts. Its northern limb is steep, sometimes tilted to the south; the southern limb is relatively gentle, complicated by sub-layered thrusts of the southwestern vergence. The Sumian-Sariolian formations compose the main syncline and, together with the basement rocks, are unconformably overlain by the Yatulian formations which compose the secondary synclines located on the limbs of the main-syncline diagonally to its strike (Fig. 6).

In the near-axial part of the Kumsa zone, the Sumian-Sariolian formations are steeply bedded and broken through by small (0.1–3.0 km) diapir-like bodies (domes) of the Neoarchean gneissic granites [Kolodyazhny et al., 2000;

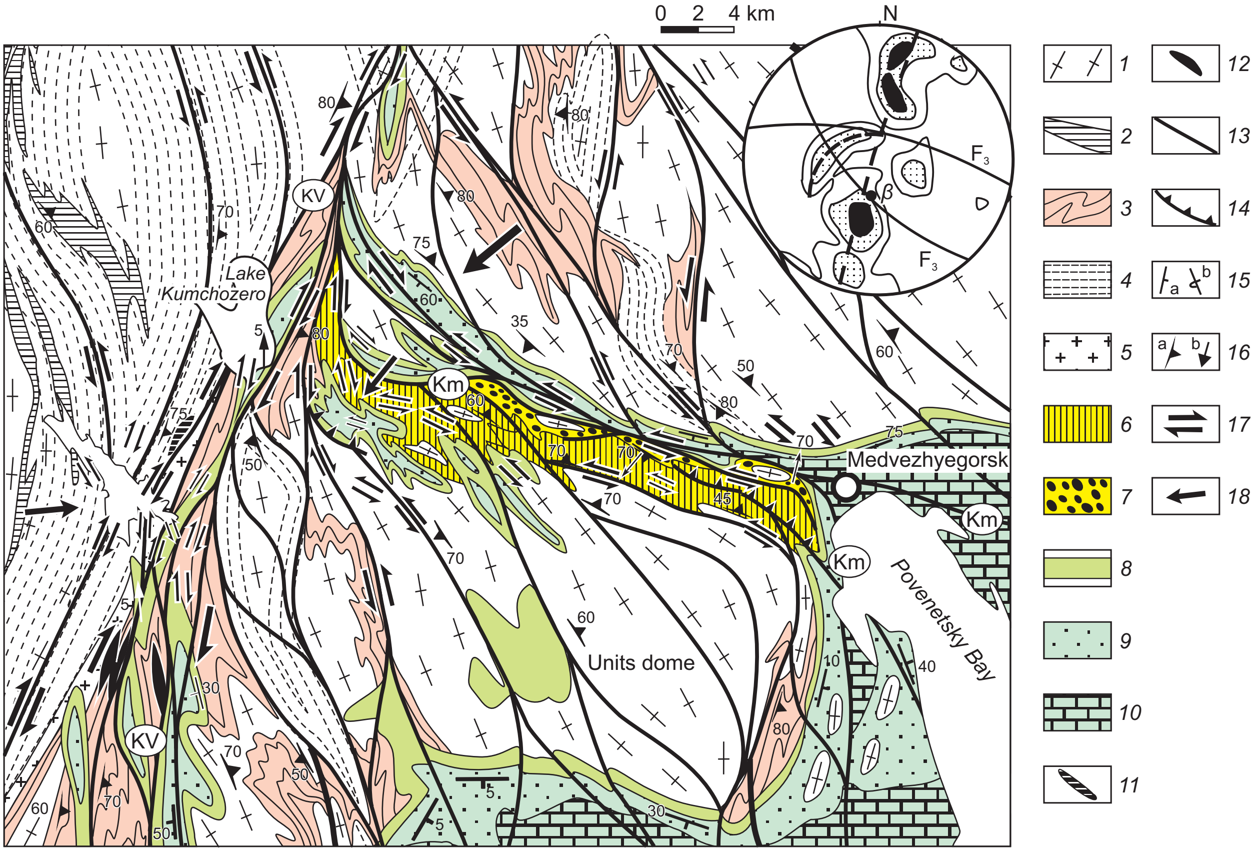

Fig. 6. Geological and structural scheme of the Kumsa shear zone (after ([Voitovich, 1971; Kolodyazhny, 2006; Korosov, 1991; Systra, 1991; Kharitonov, 1966]).
Stereographic projection of the stratification poles of the Sumian-Yatulian rocks (141 measurements, isolines 1-4-8 %). F3 are the axial planes of the third-generation folds of the third generation, β is an axis of folding. *1–5* – Archaean complexes: *1* – gneissic granites, *2* – gneisses, *3* – greenstone, *4* – migmatite granites, *5* – granites; *6–12* – Paleoproterozoic complexes: *6* – Sumian, *7* – Sariolian, *8–9* – Lower Yatulian, *10* – Upper Yatulian, *11* – gabbro-dolerites, *12* –ultrabasic rocks; *13–14* – faults: *13* – strike-slips and reverse-slips, *14* – thrusts; *15–16* – dip and strike: *15* – normal (a) and inverted layering (b), *16* – schistosity (a) and linearity (b); *17–18* –directions for the Svecofennian movements: *17* – strike-slip, *18* – horizontal.

Korosov, 1991; Krats, 1963; Leonov et al., 1996]. The granitoid cores of the domes are lens-shaped in plan and form chains along the strike of the zone. The domes are surrounded by mixtite-bearing formations and Sariolian conglomerates formed during the dome growth in the Sariolian time. The geochronological data obtained using the blastomylonite samples from the granitoid rocks of the domal structures yielded the following ages: K/Ar – 1830 ±10 Ma; Rb/Sr – 1670±60 Ma [Kolodyazhny, 2006]. These data imply a long (Sariolian–Svecofennian) period of the dome-shaped structure development.

Statistical analysis of dip and strike in the Paleoproterozoic rock strata of the Kumsa syncline testifies to the presence of two systems of folds: south-tilted cylindrical and conical structures which are probably subsynchronous and correspond to associated F_3 folds of the Koikary-Vygozero zone (Fig. 6, a stereogram). The synclines composed of the Yatulian rocks are located diagonally to the general strike of the Kumsa zone and form left-stepping en echelon systems indicating the left-lateral strike-slip displacements (Fig. 6). The northwest-striking left-lateral strike-slip faults intersect the Kumsa structure as well as the more southern Units dome and penetrate into the Paleoproterozoic complexes of the North Onega synclinorium [Kolodyazhnyi, 2002, 2006].

In the Late Paleoproterozoic, at the Svecofennian deformation stage, the development of the Kumsa left-lateral shear zone was associated with the Koikary-Vygozero right-lateral shear. The right-lateral displacement along the latter was dynamically related to the southwestward moving of the basement block, located north of the Kumsa zone, as a result of which this synform zone was squeezed between the northern block and the Units dome south of it (Fig. 6). The considered northwestern segment of the Kumsa zone was isolated in the Svecofennian; at earlier stages (in the Lower Yatulian) there existed a single Segozero-Onega sedimentary basin [Kolodyazhny, 2002, 2006; Makarikhin et al., 1995].

6. GEOPHYSICAL RESEARCH MATERIALS

Analysis of potential fields gives an indication of the OS deep structure [Sharov, 2004; Morozov, 2010; Golod et al., 1983; Glushanin et al., 2011]. The gravimetric data show that the OS basement is presented by granitoids and gneissic granites with a density of 2.65–2.68 g/cm^3, which only affect the general level of the gravity field. The occurrence depth of the Archaean basement at the OS base is estimated at about 3 km which is in agreement with the drilling data [Glushanin et al., 2011]. In the regional gravimetry field, the North Onega structure corresponds to a weak positive anomaly complicated by higher-order anomalies. Intensive positive anomalies were identified within the South Onega syncline, central part of Lake Onega, and along the OS western limb. The local narrow gravity anomalies reflect the structure of the Paleoproterozoic OS formations. Shear zones and their related anticlines correspond to negative narrow gravity anomalies that may be due to decompaction of rocks in tectonic disintegration zones and to composition of rocks in the anticlinal cores (carbonate-terrigenous and salt-bearing formations). Positive gravity anomalies correspond to trough-like synclines, in which large volumes of basic volcanites and sills are concentrated.

The strike of the axes of the magnetic anomalies coincides with the predominantly northwestern orientation of the OS tectonic elements. Positive magnetic anomalies are concentrated along the axes of "antiform" shear zones, thus implying the presence of ore bodies or strongly magnetic basic rocks. DTa anomalies show that magnetic bodies in the anticlinal cores form en echelon systems emphasizing the strike-slip displacement component [Kolodyazhny, 2006; Report..., 1991].

Magnetic and gravity anomalies, identified in the central South Onega depression, correspond to a large, Vepsian sediment-buried basic intrusion localized in the northeast-oriented zone on the continuation of the Burakovsky-Kozhozero rifting structure [Glushanin et al., 2011; Ryazantsev, 2014].

The 1-EV/RWM-CDP seismic profile crosses the northwestern centrocline and runs along the southwestern limb of the North Onega synclinorium (see Fig. 2). The seismic image of the Earth's crust shows four isolated layers with different structure and reflection intensity (Fig. 7, a). North of the OS, the lower crustal layer (4) with intense reflection therein lies subhorizontally, and its bottom marks the Moho at depths of 40–43 km. The Moho at the base of the OS undergoes multiple interruptions and general subsidence towards the southern part of the structure to depths of about 50 m. The lower crustal layer (4) also undergoes subsidence therewith and is broken into a series of jugged blocks (Fig. 7, a, interval 1000–1150 km). Somewhat further south, the layer (4) forms a single body, represented at the base of the accretionary Svecofennian orogen by a series of wedge-shaped slabs plunging into the mantle or forming scaly-thrust structure (Fig. 7, a, 1160–1200 km). A combination of the upper crustal structures of the Svecoffenides thrusted over the KC, and the lower crustal slabs represents a "crocodile's jaw"-type structure [Morozov, 2010].

The overlying homogenous layer (3) at the base of the southern OS, with low-intensity reflection, includes a seismically transparent "massif" surrounded by an exocontact zone of highly reflective rocks (Fig. 7, a, 1070–1150 km). This structure may correspond to the marginal part of the mantle diapir (basic intrusion) whose central part is located further southeast and characterized by gravity anomaly in the center of Lake Onega.

The mid-crustal layer (2) at the base of the northern OS, with intense reflection, is composed of a set of tectonic slabs and slices which provide tectonic thickening by clustering and thrusting northwards (Fig. 7, a, 1100–940 km). On the contrary, in the cross-section interval of 1070–1150 km, corresponding to the inferred supra-diapir area of the southern OS, the considered layer is much thinner and complicated by deep-seated thrust faults oppositely directed from the mantle diapir axis. The upper crustal layer (1) at the base of the OS, with low intensity reflection, is dissected by faults which dip gently to the south, merge with the mid-crustal thrusts and are interpreted as normal faults (see below).

The 1-EV/DSM seismic profile based on the differential summation method, was used for a detailed characteristic of the upper crustal and mid-crustal structures at the base of the OS (Fig. 7, b, c) [Sharov, 2004]. In the cross-section interval of 940–960 km (Kumsa zone and Units dome) within the mid-crustal layer, there is an identified system of thrust duplexes of the northern vergence, forming a thick lens-shaped body – a compression structure, surfacialy manifested by the Units dome uplift (Fig. 7, b, 940–960 km). Further south, at the back of deep-seated thrust duplexes in the upper crust, there are identified gently south-dipping normal faults with typical near-fault reflection bends indicative of normal-fault displacements (Fig. 7, b, c, 965–1090 km). The upper-crustal normal faults often have listric and stepped configuration, are traced underneath the entire OS, and penetrate into its composing Paleoproterozoic formations.

In many areas, there is a concentration of short reflecting segments forming an interferential pattern of intersecting stepped and gently sloped surfaces (Fig. 7, c, 1060–1090 km). These megastructures are morphologically similar to C-S-structures (Fig. 7, d).

The frequent step-shaped reflectance bands (S-surfaces) are exposed in the areas where the OS basite sills are concentrated. This suggests that mafite intrusions occurred along the low-angle step normal faults, which is confirmed by direct geological observations over step-like morphology of sills and development of tectonites along their contacts (see Fig. 3). The dynamics of normal-fault displacements along the stepped surfaces with flats and

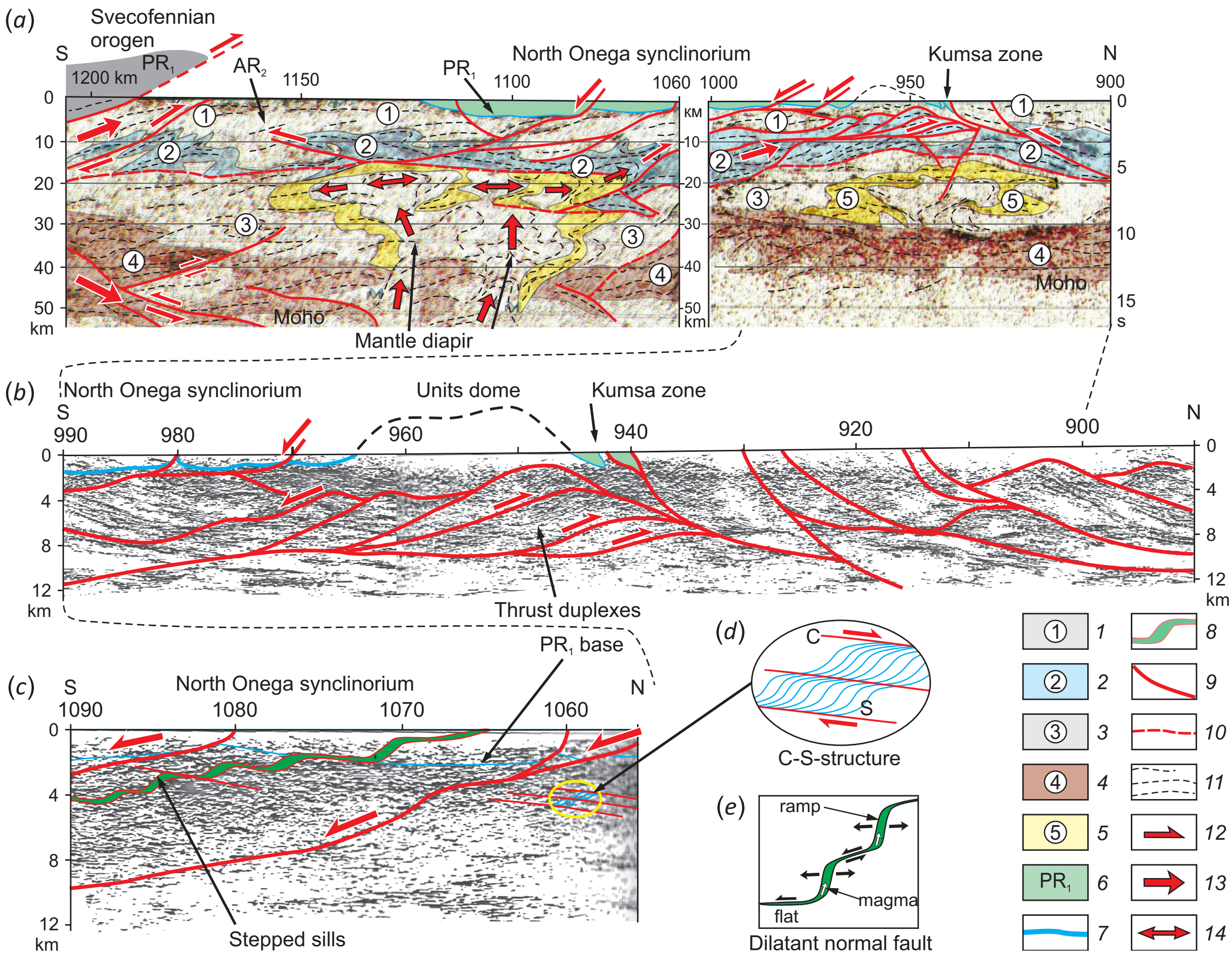

Fig. 7. Interpretation of the segment of the 1-EV seismic profile crossing the North Onega synclinorium (after [Sharov, 2004; Morozov, 2010] with changes).
(*a*) – 1–EV/RWM-CDP seismic profile; (*b*, *c*) – 1–EV/DSM seismic profile based on the differential summation method; (*d*) – structural pattern of the C-S structure-type reflections; (*e*) – morphology of a stepped sill embedded along the dilatational normal fault. *1* – upper crustal layer with medium-to- low intensity reflections; *2* – mid-crustal layer with high intensity reflections; *3* – mid-to-lower crustal seismically "transparent" layer; *4* – lower crustal layer with high intensity reflections; *5* – volumes of rocks with reflections of varying intensity in layer 3 (exocontact zones of intrusions); *6* – Paleoproterozoic volcano-sedimentary complexes; *7* – Proterozoic base; *8* – basic rock sills; *9* – faults; *10* – detachments; *11* – reflection systems; *12–13* – directions of movement: *12* – along the faults, *13* – of bulk mass flow; *14* – extension directions.

ramps implies the opening of decompression cavities of magma absorption within the ramp bends and the associated occurrence of low-angle slip zones – flats (melt-squeezing segments), which joined the decompression ramp "traps" together (Fig. 7, e).

7. DISCUSSION AND ANALYSIS

The above-considered materials on the geological structure of the OS allow its evolutionary modeling. The following data were selected as the priority for geodynamic reconstructions.

1. The sedimentary series of the OS are usually separated by stratigraphic unconformities and composed of shallow marine, lagoon and continental deposits. Their amount is contributed to by lava flows and subvolcanic bodies (sills, dikes) corresponding to the formations of continental traps and volcanic plateaus. Over more than 500 Ma-long (Yatulian – Vepsian) evolution of the OS, there were accumulated about 5000 m of sediments. Spatiotemporal patterns of the distribution of the volcanogenic-sedimentary series indicate a long-term periodical subsidence of the Onega basin which gradually migrated southward during the Yatulian – Vepsian. Massive volcanic eruptions and the Yatulian-to-Suisar increase in the amount of volcanites, as well as the change in composition from tholeitic basalts to high-magnesia picrobasalts, are indicative of a long-term extensional regime and high crustal permeability, with the mantle matter transported to the Earth's surface [Polekhovsky et al., 1995]. The OS was formed in the intracontinental environment without dissection of the continental crust [Glushanin et al., 2011] whose high permeability was due to dissipative extension (ductile spreading after [Khain, Bozhko, 1988]).

2. The Central Karelia shear zone and the OS, together with the syncline-complicating systems of marginal and inner dislocations, constitute a single, dynamically linked structural ensemble. The OS faults form an imbricate fan in the area of virgation and attenuation of this shear zone. Spatial combinations of shears and basins of different types are rather common. As analogues could be the relationships between the southern Paleozoic Illinois basin and the area of virgation of the New Madrid shear zone [McBride, 1998; McBride, Nelson, 1999], and graben-like basins in the area of virgation of the Eastern California shear zone [Sims et al., 1999]. The largest shear zones (Levantian, North Anatolian, Mukur-Chaman and others) in discontinuous areas form herringbone or horsetail patterns and transform into the normal-fault or thrust systems located on the principle of dynamic pairs [Kopp, 1997; Lukyanov, 1991].

3. The Central Karelia zone is characterized by a gradual decrease in the intensity of deformations and transverse northwest-to-southeast flattening of the structures [Kolodyazhny, 2002, 2006]. It is also evident from a planar configuration of the zone-marking Paleoproterozoic synclinal structures which gradually flatten out and open towards the southeast (see Fig. 1). Generally, the shear zone is segmented into high (northwest) and relatively low (southeast, near the OS) compression areas.

The trends observed therein are typical of the dislocation zones occurring due to indentational or rotational scissor-like movements of blocks located on the sides of shear zones [Kopp, 1997; Allerton, 1998; Carey, 1955]. The rotation of rock massifs including the segments of shear zones is often related to the change in direction of movement there on. There was identified a kinematic inversion of the Koikary-Vygozero zone which can be attributed to its rotation in the stationary stress field from the sector favorable for early-stage left-lateral displacements to the position preferable for the right-lateral shear development. These trends can be explained based on the version of clockwise rotation of the Western Karelia block and its adjacent structures of the OS western margin which is considered in detail in [Kolodyazhny, 2006].

4. The North Onega synclinorium is characterized by thin-skinned tectonics, with the cross-section represented by alternating narrow crest-like anticlines and wide, weakly dislocated trough-like synclines (see Fig. 4). There deformations are concentrated along separate "antiform" transpressive shear zones with flower-shaped morphology. The formation mechanism of such structure of the synclinorium is not confined to volumetric tangentional compression. The fact of flow of low-viscosity rocks from synclinal areas into antiform structures shows that the factor of tectonic load transmission lies in the processes of horizontal flow of ductile horizons and development of detachments along the boundary of rheologically contrasting layers.

Discrete folding and its associated disharmonic detachment at the basement/cover boundary are rather typical of thin-skinned tectonics. Crest-like/diapiric folding is primarily caused by the processes of horizontal flow in ductile layers [Harris, Koyi, 2003; Koyi, Skelton, 2001; Schultz-Ela, Walsh, 2002; Sims et al., 1999]. This conclusion is confirmed by a series of analogue experiments modeling the processes of flow and formation of diapiric folds in the evaporites of the Paradox formation of the Canyonlands National Park [Schultz-Ela, Walsh, 2002]. Similar models are represented for pull-apart basins. They show that in the presence of a ductile layer at the base of these structures under shear conditions there occur diapiric folds as a result of horizontal flow of substance and squeezing it out of ductile substrate interface into the near-shear destruction (discharge) zones of the upper model layers [Sims et al., 1999].

5. The seismic profiling data show that the Onega depression subsidence was related to horizontal flow and deep-set geomass outflow from beneath the basin area (Fig. 7, a). The mid-crustal layer (2) at the base of the OS underwent extension/thinning as a result of a centrifugal mass horizontal flow which was compensated by the formation of intralayer thrust-related compression duplexes and their associated OS-surrounded dome-shaped uplifts (Fig. 7, b, Units dome). At the back of the thrust duplexes, the upper crustal layer (1) underwent extension/subsidence due to the formation of gently dipping and listric normal faults associated with shear zones. The displacements along the listric normal faults are usually related to

an antithetical rotation of hanging-wall blocks, which gives rise to the formation of asymmetric depressions [Kopp, 2005]. The amplitudes of normal-fault displacements in the OS were small (a few tens of meters) but sufficient for the formation of normal-fault scarps and their-related asymmetric basins. Normal faulting was dynamically associated with the OS boundary boards shears: right-lateral along the Koikary-Vygozero zone and left-lateral along the Kumsin zone (see Fig. 2). A consistent southward propagation of shears associated with normal faulting controlled the corresponding migration of the Onega basin depocenter.

Analogous compensatory structural parageneses (deep-seated thrusts – near-surface normal faults) were largely found in the thrust-nappe structures of the Apennines [Scisciani et al., 2002; Cello, Mazzoli, 1996]. Such combinations of thrusts and normal faults are also found within the White Sea belt which is considered as a result of "inverse kinematic effect" [Morozov, 2002a].

The mechanisms of sill intrusions into the OS areas can be related to the formation of step normal faults, in the ramp segments of which there occurred an opening of the decompression cavities of magma absorption (Fig. 7, e). Tectono-magmatic occurrences of such a type correspond in many respects to the pull-apart structures and magmatic duplexes (after [Tevelev Al.V., Tevelev Ark.V., 1997]). In the literature analogous structures are referred to as dilatant normal faults which, according to the modeling results, can control the fluid and melt movement due to dilatant effects in the step fault plane [Ferrill, Morris, 2003].

6. The results of structural-paragenetic analysis and isotopic dating of tectonites testify to a long-term (Neoarchean – Paleoproterozoic) development of shear zones in the Central Karelia [Kolodyazhny, 2006]. In the Sumian-Sariolian time they controled the development of dome-shaped structures and pull-apart basins. In the Upper Yatulian, in the area of an imbricate fan, there occurred an isolated Onega depression which then migrated consistently southwards. In the second half of the Ludicovian, synchronously with the picrobasaltic lava flow within the OS, the more northern segments of the Central Karelia zone were under transpression conditions, which is evidenced by the tectonites whose Rb/Sr isochronous age is 2010±80 Ma [Kolodyazhny, 2006]. The southward migration of the basins also continued in the Kalevian – Vepsian. In relation to this migration, there was a consistent southward expansion of the transpression area which is confirmed by the Rb/Sr and K/Ar isochronous ages of tectonites at the south of Lake Segozero (1870±90 Ma), in the Kumsa zone (1830 ±10 Ma), and in the central North Onega basin (about 1800–1700 Ma) [Kolodyazhny, 2006; Polekhovsky et al., 1995]. Therefore, dynamically related transpression (north) and transtension (south) environments within the Central Karelia zone underwent an associated southward migration. Their corresponding areas, experiencing inversion or subsidence, also underwent an associated migration to the south. The early-stage normal-fault surfaces in the northern part of the OS gradually became obsolete and underwent transpressional deformations including folding. Further south, there occurred new gently dipping normal-fault systems and their corresponding basins which were in the same conditions as their predecessors during the lateral migration of the transpression/inversion sedimentary basin area.

The development of shears and their associated "faulting and faulting" systems is typical of the geomass lateral extrusion zone. "Faulting and faulting" mechanism was examined in a study on the Alpine orogeny [Mancktelow, Pavlis, 1994]. The Lepontine dome, in the core of which

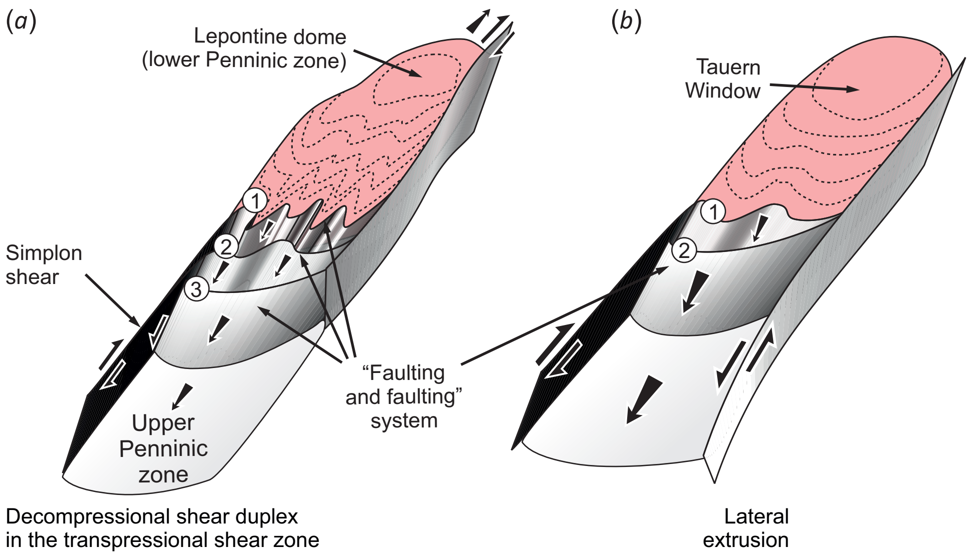

Fig. 8. Block-diagrams illustrating mechanisms of the formation of domes and tectonic windows of the Alpine belt due to co-development of shears and systems of "faulting and faulting" systems.
(*a*) – Lepontine dome – mechanism of transtensional bending in the transpressional shear zone; (*b*) – Tauern tectonic window – mechanism of geomass lateral extrusion. Numbers in diagrams show the sequence of development of low-angle normal faults (after [Frisch et al., 2000; Mancktelow, Pavlis, 1994]).

there are exhumed lower Penninic nappes, occurred in the area of decompressional shear duplex of the Simplon transpressional shear zone due to repeated faulting and subsequent fault-related folding (Fig. 8, a). A similar mechanism can be proposed for the dome-shaped structures of the Koikary-Vygozero zone on the western OS limb (see Fig. 5, Koikary dome etc.). It is also impossible to exclude the dome-shaped structure occurrence due to the interference of differently oriented fold systems found in the Yatulian formations (after [Morozov, Gaft, 1985]).

A similar reconstruction was proposed for the Tauern Window (Eastern Alps) whose development was related to lateral extrusion of geomasses between two shears with an opposite shifting character [Frisch et al., 2000; Mancktelow, Pavlis, 1994]. The "faulting and faulting"mechanism served as the base for the inter-shear formation of gently dipping normal faults that cause tectonic erosion of the upper slabs and exhumation of the lower Penninic nappes in the tectonic window (Fig. 8, b). This model corresponds best to the OS tectonic elements as a whole and can be compared with a system of Units dome – OS normal faults – shear zones on the OS limbs (see Fig. 2). Lateral extrusion phenomena are usually caused by the effect of rigid indentors/oroclines or rotational-indentational movements of large blocks [Kopp, 1997; Carey, 1955].

7. An important role in the Onega basin development was played by mantle plumes, with their maximum activity confined to time intervals of 2.53–2.42 and 2.1–1.95 Ga [Morozov, 2010; Glushanin et al., 2011]. A local effect of the asthenospheric diapir caused the mid-crustal mass outflow from beneath the depression area. Evidence of occurrence of diapir could be seen on the 1-EV seismic profile at the base of the OS (see Fig. 7, a). It is possible to note the following chronological sequence of tectono-magmatic events in the region considered: 1) Late Archean shear-zone formation; 2) supra-plume rifting against the background of transtension (Sumian-Sariolian); 3) rotational-indentational movements of geomasses and segmentation of the Central Karelia shear zone into the areas of intense compression and relative decompression with an isolation of an imbricate fan and its related Onega supra-plume basin therein (Yatulian – Ludicovian); 4) attenuation of first magmatic and then tectonic regimes. The deformation processes in this sequence precede and finish magmatic supra-plume activity. It is supposed that the localization of asthenospheric diapir in the OS area was a result of discrete deformations of the Earth's crust in accordance with the passive rifting principles. The processes of crustal extension in an imbricate fan area were an attractor of diapirism.

The above features of the OS tectonics reflect a variety of synchronous and spatially combined complementary temporally alternating geodynamic regimes.

8. EVOLUTIONARY MODEL OF THE ONEGA SYNCLINORIUM

We consider the OS evolutionary model which is represented by a series of paleotectonic sections and block-diagrams characterizing the main stages of the OS development and spatial relationships between its tectonic elements (Fig. 9, 10).

In the Neoarchean, 2.68 Ga ago, there was completed the formation of the subduction accretionary system including the Vedlozero-Segozero greenstone belt developed along the western convergent margin of the Vodlozero block [Svetov, 2005]. The collision events gave rise to the formation of a thick continental crust. At the late collisional stage of the Upper Archean there were initiated shear zones which partially inherited the Archean suture zones; in particular, along the Vedlozero-Segozero greenstone belt the Koikary-Vygozero shear zone was formed.

In the Sumian time (2.5–2.4 Ga), under continental rifting and transtention conditions, there was a formation of mafite-ultramafite intrusions and an outflow of andesibasaltic lava filling the local grabens and pull-apart basins (see Fig. 9). At that time, the OS area and a large part of the KC underwent uplift and intense erosion with formation of weathering crusts [Korosov, 1991]. The domal uplift was caused by the initiation of the Windy Belt mantle plume whose dimensions were comparable with the eastern Baltic shield [Kulikov et al., 2005].

In the Sariolian time (2.4–2.3 Ga), the magmatic activity stopped, whereas shear displacements under transtention conditions continued and controlled the formation of grabens and pull-apart basins wherein conglomerates and mixtite-like formations accumulated.

In the Yatulian time (2.3–2.1 Ga), within the KC there formed a protoplatform sedimentary cover and occurred a trappean basaltic magmatism related to the Yatulian supra-plume [Glushanin et al., 2011]. In the Lower Yatulian, the OS represented an area of erosion, and the basin sediment deposition occurred further north (see Fig. 9, a). In the Upper Yatulian time, the subsidence migrated southwards, and there began a formation of the North Onega basin with a shallow-water evaporite and carbonate-terrigenous sedimentation (see Fig. 9, b). The depression subsidence and migration processes were associated with development of gently dipping stepwise normal faults along which there occurred an intrusion of basite melts (sills), aided by the opening of decompression cavities of magma absorption in the areas of bent-ramp fault planes (see Fig. 9, b, a fragment). Active sillogenesis related to the development of such dilatant normal faults also took place later.

In the Ludicovian time (2.10–1.92 Ga), within the North Onega depression, during the activation of mantle diapirism there occurred local mafite-ultramafite magmatism. In the Lower Ludicovian, there accumulated shungite-containing sediments with subordinate basaltic and basaltic tuff flows (Zaonega formation). In the second half of the Ludicovian, there occurred an outflow of picrobasalts (Suisar formation) which formed a volcanic plateau. It is likely that at this stage, due to localization of mantle diapir at the base of the OS, there started an occurrence of deep horizontal flow processes which caused an outflow of the mid-crustal masses from the depression area towards it edges. This gave rise to the formation of the mid-crustal "blind" thrusts and compression/uplift zones in the form of OS-surrounded thrust duplexes (see Fig. 9, c). Complementary to the deep-seated thrusts, in the upper crust there formed the extension structures – gently dipping dilatant normal faults, associated with shear zones. The northern segments of the Central Karelia zone were under transpression conditions synchronously with the Ludicovian depression development. The transpression zone gradually migrated southwards which caused a partial basin inversion and corresponding displacement of the Onega basin depocenter.

In the Kalevian (1.92–1.80 Ga), the North Onega molassoid basin become more localized and moved towards the south (see Fig. 9, d). This stage corresponded to the major stage of the Svecofennian collisional events occurred primarily at the boundary between the KC and the Svecofennian accretionary-collisional orogen. Within the OS, there was a continued development of kinematic situation identified for the Ludicovian time. The northern segments of the Onega depression underwent inversion and uplift, as a result of which the older-rock fragments were transported from the northern OS to be deposited in the basin. The basin was asymmetric, with coarse deposits accumulated along its northern side at the base of the normal-fault scarps and finer-grained terrigenous sediments on its southern gently sloping side (see Fig. 9, d).

At this and the next, Vepsian, stage the basin subsidence was still caused by compensatory mechanism related to the mid-crustal mass outflow towards the basin margins and its associated upper-crustal gently dipping normal faulting. Within the borders of the depression there formed deep-seated thrust-related compression duplexes and the associated dome-shaped uplifts (Units and others) (see

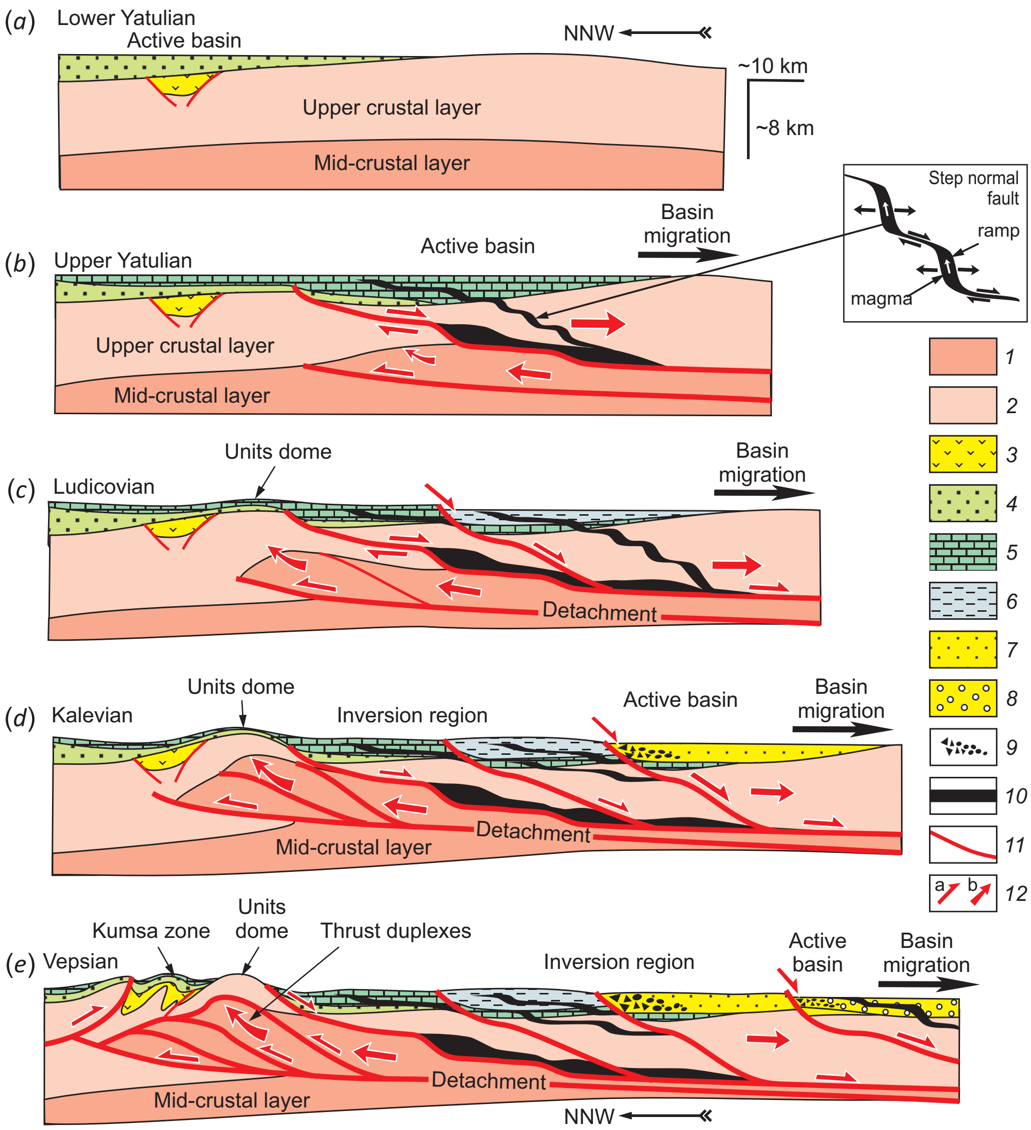

Fig. 9. Paleotectonic sections reflecting the stages of formation of the Onega depression.
1–2 – Archean continental crust of the middle (*1*) and upper (*2*) levels; *3–8* – Paleoproterozoic complexes: *3* – Sumian-Sariolian, *4* – Lower Yatulian, *5* – Upper Yatulian, *6* – Ludickovian, *7* – Kalevian, *8* – Vepsian; *9* – coarse-grained deposits; *10* – basic massifs and sills; *11* – faults; *12* – directions of movement along the faults (a) and volumetric redistribution of geomasses (b).

Fig. 9, d). In the absence of plume activity, these phenomena were probably caused by the existence of low-viscosity rocks, heated in the area of the mantle diapir cooling and flowing towards cooler areas.

In the Vepsian time (1.80–1.75 Ga), against the background of the Svecofennian attenuating shear and normal-fault displacements, there formed the South Onega basin whose occurrence stopped an active development of the OS (see Fig. 9, e). In the basin there were accumulated molassoid and red-colored terrigenous sediments, with the detrital material transported by the braided sediment-carrying stream draining the more northern KC parts [Kuznetsov et al., 2023].

General views on spatial and dynamic relationships between the OS tectonic elements are presented in the block-diagram (Fig. 10). The main role in the development of this ensemble of structures was played by shear displacements along the Central Karelia zone which were accompanied by a clockwise rotation of its more western rock massif. As a result of the rotational-indentational effect of this massif, the Central Karelia zone became segmented into dynamically conjugated transpressional (NNW) and transtensional (SSE) deformation zones and experienced lateral extrusion phenomena. Within a transtensional imbricate fan there was a consistent development of the OS subsidence. A progressive clockwise rotation of the western block favored the SSE expansion and migration of the transpression zone, and the corresponding retreat of the transtension zone in the same direction. Sedimentary basins in the northern OS, which were under transpression conditions, underwent inversion, and the transtension and active subsidence zone retreated southwards.

The crustal extension conditions in an imbricate fan area were conducive to the isolation of mantle plume heads – asthenospheric diapirs, which were related to magmatism occurrence in the OS. Thermal and volumetric effects of magmatism caused a radial flow in the mid-crustal masses from the depression zone to its margins where there were compression structures – deep-seated thrust duplexes and the associated dome-shaped uplifts (Fig. 10). These movements were compensated by the upper crustal extension due to the formation of gently dipping dilatant normal faults (magma conduits). The displacements along the gently dipping normal faults near the OS were associated with the right-lateral shear displacements in the Koikary-Vygozero zone and the left-lateral ones along the Kumsa area (Fig. 10). The destructive processes of gently dipping normal faulting, according to the mechanism of simple shear [Sklyarov et al., 1997; Wernicke, 1985], provided relaxation to significant extensional loads without destruction of the continental crust. The early-stage normal-fault surfaces in the northern part of the OS gradually became obsolete and underwent transpressional deformations as the transpression zone expanded towards the south. Further south there were initiated new gently dipping normal fault systems and related basins.

The presence of low-viscosity horizons within the OS was conducive to multilayer horizontal flow of rocks. Along

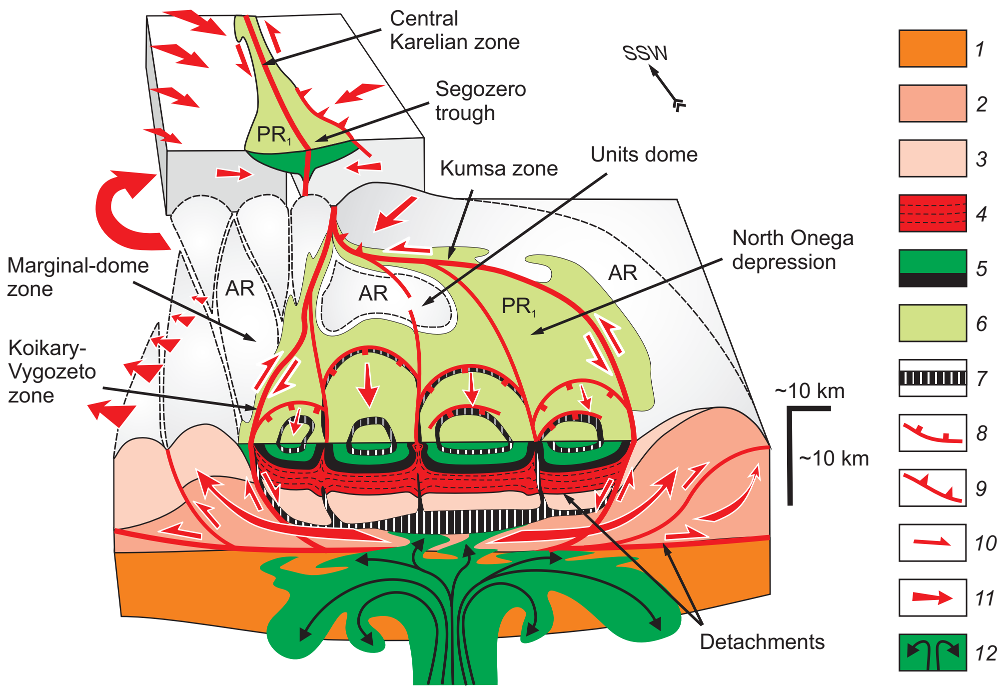

Fig. 10. Volumetric model of the Onega synclinorium illustrating spatial and dynamic relationships between various geological and structural elements.
1–3 – Archean continental crust of the lower (*1*), middle (*2*) and upper (*3*) levels; *4–7* – Paleoproterozoic complexes of the Onega depression: *4* – lower ductile horizons that have experienced tectonic flow, *5–6* – upper competent horizons, *7* – basic/ultrabasic sills and intrusions; *8* – low-angle normal faults; *9* – thrusts; *10–11* – directions of movement along the faults (*10*) and volumetric redistribution of geomasses (*11*); *12* – asthenospheric diapir.

the rheological boundaries there formed detachments localized at the crustal-layer boundaries, on the basement/protocover contact, and within the OS volcanogenic-sedimentary prism. The shear zones in an imbricate fan area of the Central Karelia zone controlled the processes of ductile rock squeezing towards the surface, which gave rise to the formation of crest-like and diapir-like folds (Fig. 10).

9. CONCLUSION

The considered model explains the reasons for the OS long-term formation throughout the entire Paleoproterozoic in result of an associated interaction between different geodynamic factors. The processes of the crustal destruction near the OS contributed to the occurrence of certain forms of plume tectonics. The primary energy factor of the OS development is asthenosheric diapirism (plume-formed apophyses), although the spatial localization of diapirs and their developmental features were related to tectono-dynamic factors. The conditions for an active manifestation of shear tectonics and related discrete deformations in the southern KC gave rise to a variety of compensational phenomena.

Shear displacements in the Central Karelian zone, coupled with the rotation of a large block of the KC, as a result of the rotational-indenter mechanism contributed to the compensatory coexistence of the regions of transpression and transtension, as well as the phenomena of lateral extrusion within the shear zone. The crustal destruction segment, evolved this way in the transtensional imbricate-fan zone, underwent long-term extension and subsidence which gave rise to the formation of the Onega trough. A relative decompression within an imbricate fan stimulated the development and localization of asthenospheric diapirs whose penetration into the crustal layers gave rise to a variety of compensation phenomena: deep-seated thrust faulting related to the mid-crustal mass flow from the Onega depression zone to its margins; gently-dipping dilatant normal-fault system formation compensating the mid-crustal thrust displacements and controlling the features of formation and migration of the OS basins, and magmatic and sillogenesis-related phenomena. A multilayer subhorizontal flow of rocks at the base of the OS occurred also in its sedimentary-volcanogenic section which, according to the mechanism of thin-skinned tectonics, gave rise to the development of crest-like and diapir-like folds.

The considered model is not a complete concept and can be viewed as a result of some generalization for the available (primarily geological-structural) materials, an incentive for discussions, and a reason for further study of the unique Onega structure.

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2. N.B. Kuznetsov, A.V. Poleshchuk, D.S. Dyakov, and E.A. Shalaeva – an equivalent contribution to a critical reconsideration of the intellectual content of an area of study, preparation of the text and graphics, and final approval of the version to be published.

12. DISCLOSURE

The authors declare that they have no conflicts of interest relevant to this manuscript.

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