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GEOLOGY

The Sosva–Lozva Graben: A Devonian–Carboniferous Extensional Structure at the Rear of an Active Continental Margin on the Eastern Slope of the Northern Urals

G. A. Petrov[a],* and Corresponding Member of the RAS A. V. Maslov[a]

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Abstract—Within the northern part of the Tagil paleo-island-arc structure in the Northern Urals, the Sosva–Lozva graben is identified. The graben is filled mainly with Devonian and Lower Carboniferous terrigenous and volcanic strata. The location of the graben to the west (in modern coordinates) of the supra-subduction igneous complexes and the composition of volcanic rocks, which combines the signs of igneous formations of convergent and divergent settings, suggest that this structure formed under extensional conditions at the rear of the active continental margin.

Keywords: Tagil paleo-island arc, graben, Northern Urals, stratigraphy, tectonics, magmatism

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The presence of Late Ordovician–Devonian island-arc structures on the eastern slope of the Urals is generally recognized ([7], etc.). However, the structural features and the directions of subsidence of the ancient subduction zones are interpreted differently by various authors. For example, based on studies of the petrology and geochemistry of volcanic rocks from the Late Ordovician–Early Devonian Tagil island-arc system in the area of the Ural superdeep borehole SG-4 in the Middle Urals, it was suggested that the subduction paleozone dipped eastward (in what follows, in modern coordinates) [4]. A similar conclusion was made in studying the zoning of the volcanism for the Devonian Magnitogorsk island arc [3]. There are also alternative views about the westward dipping subduction zone in the Devonian (e.g., [2], etc.). During the study of volcanic and sedimentary formations in the northern part of the Tagil megazone (Fig. 1), we discovered a Devonian–Early Carboniferous structure, which was called the Sosva–Lozva graben and was cut into the shelf carbonate platform lying on the complexes of the dead Late Ordovician–Early Devonian Island arc. Since the Devonian suprasubduction volcanic complexes are located eastward of the Sosva–Lozva graben, the latter can be interpreted as a result of extension at the rear of the active continental margin.

Three stages are usually distinguished in the Paleozoic history of the Tagil megazone: Late Ordovician–Lokhkovian, Pragian–Franskian, and Famennian–Tournaisian separated by the epochs of restructuring or a jump of the zone of subduction, and the zone of accretion ([7, 9], etc.). The first two stages are considered to correspond to the island-arc regime, and the latter is characterized by the setting of the active continental margin that appeared after the Eastern Ural blocks accreted to the "Ural" margin of Laurussia [7]. In this work, we study the compositional and structural features of the Devonian and Lower Carboniferous complexes on the eastern slope of Northern Urals.

Geological–structural zoning of the Devonian formations on the eastern slope of Northern Urals was undertaken for the first time by A.V. Peyve [5], who identified two structural zones, the western Petropavlovskaya zone and the eastern Tur'inskaya zone. Later, the complexes of the Petropavlovskaya zone were included in the West Tagil structural–formational zone (SFZ), and the complexes of the Tur'inskaya zone, in the East Tagil SFZ [1]. The Petropavlovskaya zone is characterized by terrigenous–carbonate sedimentary sequences, and the Tur'inskaya zone, by volcano-sedimentary sequences. Between the sedimentary (terrigenous–carbonate) and primarily volcanic facies settings, there is a transitional series of formations that reflects the conditions of the shelf of the nonvolcanic island arc, the inter-arc basin, and the active Devonian island arc [6]. The new data obtained has made it possible to specify these ideas significantly.

[a] *Zavaritsky Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620016 Russia*
**e-mail: Georg_Petrov@mail.ru*

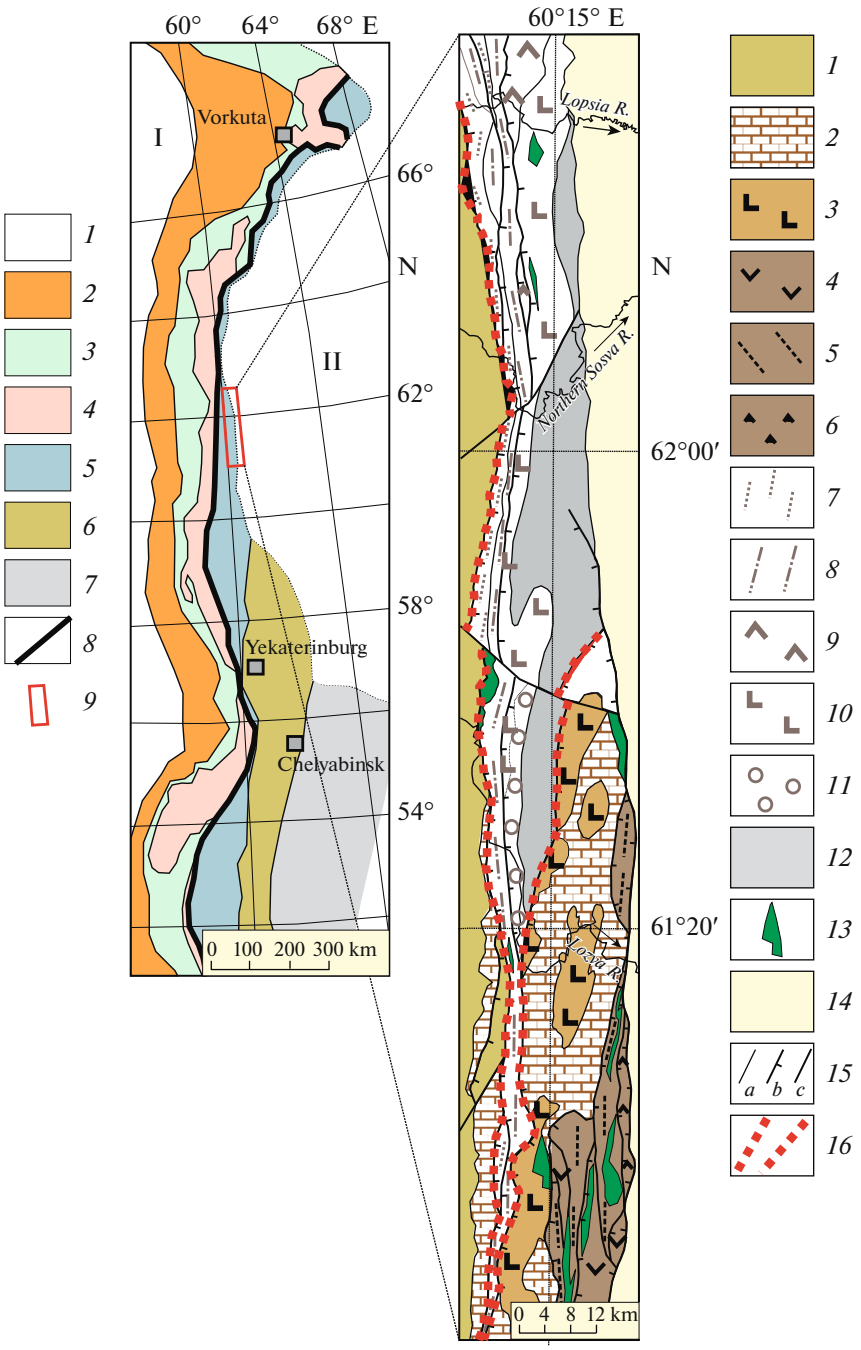

Fig. 1. (a) Location of the main Ural structures and (b) schematic geological map of the Sosva–Lozva graben. (a) (*1*) The sedimentary cover of the platforms: East European (I) and West Siberian (II); (*2–4*) the Paleocontinental Ural sector: (*2*) Cis-Uralian Foredeep, (*3*) West Uralian megazone (Paleozoic complexes of the passive continental margin and the continental slope), (*4*) Central Uralian Megazone (Precambrian formations); (*5–7*) Paleoocean sector of the Urals: (*5*) Magnitogorsk, Tagil, and Voykar–Shchuchya megazones (the island-arc formations are primarily Paleozoic), (*6, 7*) East Uralian and Trans-Uralian megazones (the collage of Paleozoic and Precambrian complexes); (*8*) Main Ural Fault; (*9*) the study area; (b) (*1–3*) West Tagil SFZ: (*1*) island-arc Silurian volcanic and sedimentary formations, (*2*) Devonian shelf terrigenous–carbonate sequences lying on the complexes of the dead Late Ordovician–Early Devonian island arc; (*3*) volcanic–sedimentary formations of the Perevozskaya Formation, D_1; (*4–6*) East Tagil SFZ, Krasnouralskaya subzone: (*4*) volcanic–sedimentary formations of the Krasnotur'insk (D_1) and Tal'tiiskya (D_{1-2}) formations, (*5*) carbonate–cherty–terrigenous rocks of the Langurskaya and Vysotinskaya formations, D_2, (*6*) volcanic–sedimentary rocks of the Limkinskaya Formation, D_{2-3}; (*7–12*) East Tagil SFZ, Nakhorskaya subzone (the Sosva–Lozva graben): (*7, 8*) volcanic–terrigenous rocks of the Lopsiiskaya (D_{1-2}) and Arbyn'inskaya (D_2) strata, (*9*) cherty–carbonate–terrigenous–volcanic Nakhorskaya stratum, D_3, (*10*) carbonate–terigenous–volcanic Ioutyn'inskaya stratum, D_3, (*11*) terrigenous Lozva Formation, D_3, (*12*) carbonate–volcanic–terrigenous formations, C_1; (*13*) gabbrodolerites of the Ivdelskii complex, D_3; (*14*) Meso-Cenozoic cover of the West Siberian Platform; (*15*) (*a*) intrusive and stratigraphic boundaries, (*b*) upthrows and overthrusts, (*c*) faults with complicated and unidentified kinematics; (*16*) the Sosva–Lozva graben contours.

The geological surveys on the eastern slope of Northern Urals and the creation of the Ural Series Legend [1] revealed quite significant changes in the composition of the Devonian formations of the same age along the strike (in the meridional direction), which were manifested in the identification of the Nakhorskaya and Krasnouralskaya subzones as part of the East Tagil SFZ (Fig. 2). It was assumed that the stratons of the Nakhorskaya subzone are located northward of the rocks of the Krasnouralskaya subzone, replacing the latter by facies; however, the character and the causes of this variability were unknown. We showed that the geological formations of the Nakhorskaya subzone constitute a large graben expanding in the northerly direction (Fig. 1), having its boundaries transformed by later overthrusts and overlain by Mesozoic–Cenozoic deposits to a considerable degree.

Three groups of substantial Devonian structural complexes corresponding to different paleo-settings have been identified in the geological structure of the study area: (1) the flat shelf of nonvolcanic islands (the dead Late Ordovician–Early Devonian island arc), the West Tagil SFZ; (2) the inter-arc trough and the active island arc, the Krasnouralskaya subzone of the East Tagil SFZ; and (3) the graben cut into the shallow-water shelf, the Nakhorskaya subzone of the same SFZ. Since the Przhidolian–Lokhovian Turinskaya (Petropavlovskaya) formation completes the Late Ordovician–Early Devonian formational series of the island-arc system [6], we briefly characterize the Devonian strata and formations, starting from the Praghian Stage.

The Praghian *Perevozskaya Formation* (D_1pr) represented by various carbonate rocks lies nonconformably in the West Tagil SFZ on volcanic and sedimentary rocks of the Turinskaya formation, and in some sections, it occurs without visible nonconformity. Volcano-sedimentary sequences composing the anticline cores in the eastern part of the study territory also fit into it with a degree of conditionality [6] (Fig. 1). The latter display interlayering of tuff gravelstones, tuff sandstones, tuff siltstones, and tuff conglomerates, containing the bodies of dacites, daciandesites, basalts, andesibasalts and their tuffs, and interlayers of limestones and cherty siltstones. The volume of volcanic rocks increases upward through the section. Earlier an assumption was made about the deposition of the described formations in the interarc trough located between the carbonate shelf of the dead Silurian island arc and the Devonian volcanic island arc, but taking into account almost the complete identity of the composition and age of volcanic rocks from the Perevozskaya Formation and from the Krasnotur'insk Formation located to the east [6], the allochtonous occurrence of volcano-sedimentary rock plates on the carbonate autochthon is not inconceivable. In accordance with the modern stratigraphy scheme for the Urals [1], the *Vagranskaya* (D_1vg) and *Tal'tiiskaya* ($D_{1\text{-}2}tl$) *formations* dominated by bank limestones interlayered with terrigenous rocks and bauxites are reported to lie nonconformably on the Perevozskaya Formation. The Eifel *Langurskaya Formation* (D_2ln), conformably overlying the Tal'tiiskaya Formation, has restricted distribution. Its composition is dominated by bank limestones. The Eifel–Zhivetian *Vysotinskaya Formation* (D_2vs) is characterized by the primary distribution of limestones interlayered with terrigenous rocks and bauxites. The Zhivetian–Frasnian *Shegul'tanskaya Formation* ($D_{2\text{-}3}šg$) nonconformably overlies the deposits of the Vysotinskaya Formation; it is also composed of bank limestones. The *Kedrovskaya Formation* (D_3kd) is spread fragmentarily and is represented by clay shales and cherts interlayered with limestones [1].

The stratified formations of the Krasnoural'skaya subzone of the East Tagil SFZ in the study area are represented by a pack of tectonic plates thrusted over the complexes of the West Tagil SFZ. Therefore, the contacts of stratons are most often tectonically sheared and it is not always possible to interpret their sequence. The Praghian–Emsian *Krasnotur'inskaya Formation* (D_1kt) consists of lava and tuffs of basalts, trachibasalts, trachiandesibasalts, andesibasalts, andesites, trachyandesites, daciandesites, and dacites; there are also tuffites, tuff sandstones, tuff siltstones, tuff gravelstones, tuff conglomerates, carbonaceous–siliceous and calcareous–clay shales, cherty siltstones, and limestones. The geochemical features of volcanic rocks indicate that they are attributed to the igneous formations of the island arcs and are comparable with those that are typical of volcanic rocks from the Perevozskaya Formation [6]. The *Tal'tiiskaya Formation* ($D_{1\text{-}2}tl$) is identified in small blocks and has a similar composition. The *Langurskaya* Formation (D_2ln) is also spread insignificantly; it is recorded to have tuff siltstones, tuff sandstones, calcareous and cherty siltstones, sandstones, argillites, and clay shales. The *Vysotinskaya Formation* (D_2vs) is present in narrow tectonic blocks; it hosts limestones, tuff sandstones, tuff siltstones, tuff gravelstones, crystal tuffs, carbonaceous–carbonate and clay–carbonate shales, sandstones, siltstones, and interlayers of silicites. The Zhivetian–Frasnian *Limkinskaya Formation* ($D_{2\text{-}3}lm$) consists of andesibasalts, andesites, daciandesites, dacites, rhyolites, trachyandesibasalts, trachyandesites, trachydacites, their tuffs, clastolava, and limestones; tuffites, tuff sandstones, tuff siltstones, tuff gravelstones, and cherty siltstones are encountered in lesser amounts. The geochemical parameters of volcanic rocks from the Limkinskaya Formation indicate that they were deposited in the suprasubduction setting [6].

The Lower Middle Devonian (Praghian–Eifel) formations of the Nakhorskaya subzone are hosted by the *Lopsiiskaya stratum* ($D_{1\text{-}2}$lp), which includes polymictic conglomerates, tuffogenic–siliceous shales,

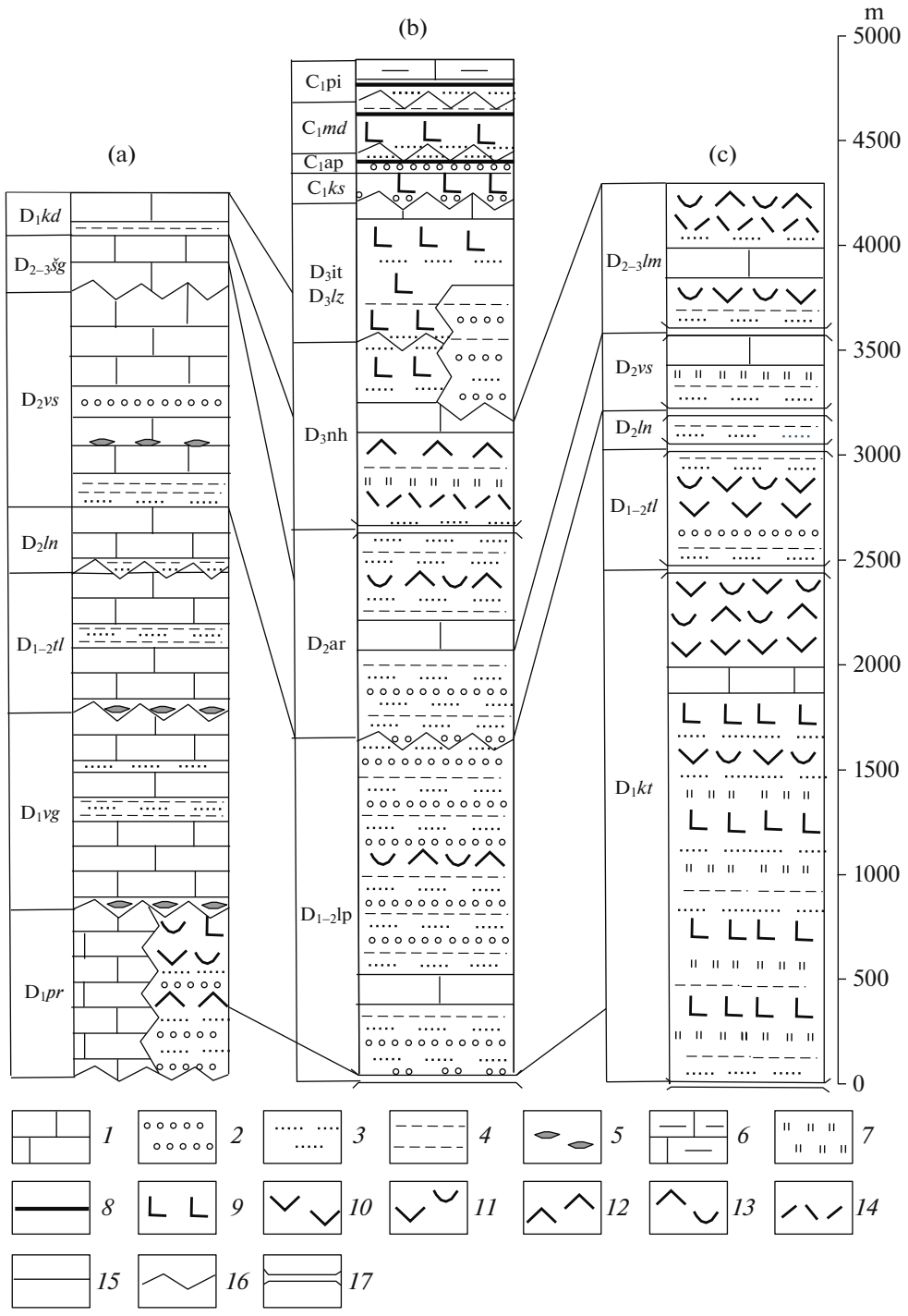

Fig. 2. Schematic lithological columns of (a) the Devonian and Carboniferous sequences of the West Tagil SFZ (shelf formations on the complexes of the dead Late Ordovician–Early Devonian island arc), (b) the Nakhorskaya subzone (the Sosva–Lozva graben), and (c) the Krasnouralskaya subzone of the East Tagil SFZ (the Devonian island-arc system). Explanation of the indices for the formations is given in the text. (*1*) Limestones, (*2*) tuff gravelstones and tuff conglomerates, (*3*) tuff sandstones, (*4*) tuff siltstones and argillites, (*5*) bauxites, (*6*) clay limestones and marls, (*7*) cherts, (*8*) coals, (*9*) basalts, (*10*) andesites and andesibasalts, (*11*) tuffs of andesite composition, (*12*) dacites, (*13*) tuffs of dacite composition, (*14*) rhyolites, (*15*) conformable stratigraphic boundaries, (*16*) stratigraphic unconformities, and (*17*) tectonic boundaries.

tuffites, tuff conglomerates, tuff sandstones, tuff siltstones, sandstones, vitric tuffs of primarily acid composition, and limestones. The fragments contain various volcanic rocks, cherts, siltstones, and limestones, and calcareous olistostrome horizons are recorded. The Zhivetian *Arbyn'inskaya stratum* (D_2ar), having a composition similar to that of the Lopsian stratum, lies nonconformably upward through the section. The Frasnian *Nakhorskaya* stratum (D_3nh) consists of basalts, andesibasalts, andesites, daciandesites, dacites, rhyodacites, rhyolites, trachybasalts, trachyandesites, and their tuffs, as well as tuff sandstones, tuffites, gravelstones, sandstones, clay shales, cherts, silicites, and limestones. Basalts and andesibasalts of the Nakhorskaya stratum are normal- and moderately-alkaline, highly titanous (TiO_2 is 1.12–2.05, 1.58 wt %, on average), moderately aluminiferous (Al_2O_3 is 15.90–18.60, 16.87 wt % on average) rocks with a moderate content of MgO (5.41–6.20, 5.70 wt % on average) and a varying content of K_2O (0.44–2.13, 1.34 wt % on average). The content of rare-earth elements (REEs) in the rocks is rather high (63.97–126.49, 102.51 μg/g on average). The average value of the light-to-heavy lanthanoid ratio (LREE/HREE) is 4.32 (minimum 4.08, maximum 4.7). The Ni/Co ratio = 1.96. The average content of Zr is 172.87 μg/g (93.6–239.00 μg/g), and that of Nb is 4.52 μg/g (2.30–6.76 μg/g). In the Th/Yb–Ta/Yb plot [13], the points of compositions of the Nakhorskaya volcanic rocks fall into the field of island arc formations (Fig. 3). Thus, volcanic rocks of the Nakhorskaya stratum have some kind of duality: the Ti content is too high in them for the island-arc formations, but, as for the other parameters, they correspond to suprasubduction igneous rocks. Such features can be explained by the mixing of magmas molten from the depleted mantle of the suprasubduction wedge and from the "enriched" deep mantle source.

The overlying Famennian *Ioutyn'inskaya stratum* (D_3it) is formed by basalts, dolerites, andesibasalts, their tuffs, tuff sandstones, conglomerates, sandstones, siltstones, and limestones. The basalts of this stratum are rocks of normal alkalinity, with a moderate content of TiO_2 (0.93–1.55, 1.30 wt % on average), moderately aluminiferous (Al_2O_3 is 16.20–17.90, 16.70 wt % on average) rocks with a high content of MgO (4.10–10.10, 7.09 wt % on average) and a nonuniform distribution of K_2O (0.14–1.94, 0.76 wt % on average). The content of REEs in them is lower than in volcanic rocks of the Nakhorskaya stratum (45.34–87.32, 64.27 μg/g on average), $LREE/HREE_{avg} = 3.87$ (minimum 2.80, maximum 5.29). The Ni/Co_{avg} ratio is 3.43, and the average Zr content is 122.52 μg/g (minimum 83.40, maximum 180.00 μg/g). Nb_{avg} = 2.85 μg/g (1.63...4.44 μg/g). In general, the geochemical parameters of volcanic rocks correspond to the island arc formations. In the southern part of the graben, volcanic formations of the Nakhorskaya and Ioutyn'inskaya strata are replaced by facies from the Frasnian–Fammenian *Lozva Formation* (D_3lz), composed of interlayered conglomerates, greywacke sandstones, gravelstones, and siltstones [1].

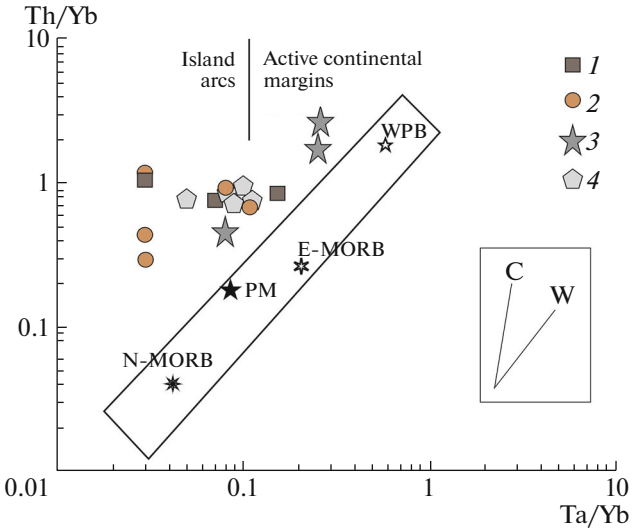

Fig. 3. The Th/Yb–Ta/Yb plot for basalts and andesibasalts of the Sosva–Lozva graben. Volcanic rocks: (*1*) Nakhorskaya stratum, D_3, (*2*) Ioutyn'inskaya stratum, D_3, (*3*) Kos'inskaya Formation, C_1, (*4*) Mednogorskaya Formation, C_1. Intermediate compositions of the rocks in the reference settings: N-MORB and E-MORB after [14], PM (the primitive mantle) after [15], and WPB (within-plate basalts) after [10]. The trends of the igneous series determined by crustal contamination (C) and differentiation of mantle magmas (W) after [8].

The Carboniferous section starts from the Early Tournaisian *Kos'inskaya* Formation (C_1ks), including greywacke sandstones, tuff sandstones, tuff siltstones, argillites, cherts, cherty shales, basalts, tuffs, limestones, and conglomerates. The basalts of the Kos'inskaya Formation have normal alkalinity. They are characterized by varying contents of TiO_2 (1.17–2.59, 1.66 wt % on average), as well as Al_2O_3 (14.3–17.70, 16.40 wt % on average), MgO (5.13–7.19, 5.83 wt % on average), and K_2O (0.42–1.15, 0.71 wt % on average). The content and degree of differentiation of REEs is higher than in volcanic rocks of the Ioutyn'inskaya stratum (ΣREE = 61.30–102.19, 84.29 μg/g on average, LREE/HREE = 3.24–6.97, 4.86 on average). The Ni/Co_{avg} ratio is equal to 3.11, and the average Zr content is 238 μg/g (166–331 μg/g). Nb_{avg} = 5.03 μg/g (4.02–5.98 μg/g). On the Th/Yb–Ta/Yb plot, the representative points of volcanic rocks are located in the fields of island arcs and active continental margins (Fig. 3). The geochemical features of volcanic rocks can be interpreted as those that reflect the process of mixing of the substance of the depleted upper mantle processed by subduction fluids and the substance of the "enriched" deep mantle source, which does not contradict the ideas about its forma-

tion in the setting of extension at the rear of the active continental margin.

Above lies the *Apsinskaya stratum* (C_1ap), containing variegated conglomerates, polymictic sandstones, siltstones, argillites, coal seams, tuffs, and tuff conglomerates of basic composition, basalts, clay-siliceous shales, and limestones. The rocks of the Kos'inskaya stratum and the Apsinskaya Formation are unconformably overlain by basalts, andesibasalts, andesites, tuffs interlayered with siltstones, sandstones, limestones, and clay shales of the Late Tournaisian *Mednogorskaya Formation* (C_1*md*). The Mednogorskaya volcanic rocks are characterized by a nonuniform distribution of TiO_2 (1.22–2.17, 1.69 wt % on average), a moderate aluminum content (Al_2O_3 is 16.50–17.40, 16.86 wt % on average) and magnesium content (MgO is 3.65–6.55, 5.16 wt % on average), and a quite high content of K_2O (0.62–2.12, 1.08 wt % on average). The REE content in them is higher than in volcanic rocks of the Kos'inskaya Formation (77.02–121.62, 103.06 μg/g on average). The $LREE/HREE_{avg}$ parameter equals 4.17 (3.76–5.36). The Ni/Co_{avg} ratio is 3.26. The average Zr content is 212.6 μg/g (132–331 μg/g), while the average Nb content is 4.48 μg/g (2.81–5.98 μg/g). The compositional features of basalts and andesites do not contradict the model of their forming within the rift structures at the rear of the active continental margin.

The Paleozoic section of the Nakhorskaya subzone is completed by the Late Tournaisian–Early Visean *Sand-limestone stratum* (C_1pi), represented by interlayered polymictic sandstones, argillites, marls, limestones, calcareous-clayey shales, and clayey limestones; thin coal layers are recorded.

The above description shows that the typical features of sedimentation within the Nakhorskaya subzone are the dominant terrigenous facies and the almost total amagmaticity (except for the rare interlayers of vitric and crystal tuffs) in the Early and Middle Devonian. The presence of calcareous olistostrome horizons in the Devonian strata point to the occurrence of carbonate rocks in the source areas; the fragments of Devonian conglomerates include limestones, polymictic sandstones, siltstones, gravelstones, siliceous-clayey shales, dolerites, and effusive rocks of basic-intermediate composition; the sandstones consist of fragments of clay shales, siltstones, limestones, and cherts and crystals of plagioclase and chlorite, less frequently quartz. We suggest that in the studied (not overlain) part of the Sosva–Lozva graben, the source area was located westward of this structure (in modern coordinates). The tuffs in the Lower and Middle Devonian stratons consist of crystalloclasts of plagioclase, less frequently quartz, fragments of dacites, rhyolites, and sometimes andesites. It is evident that volcanic material was released from the east, since westward of the Sosva–Lozva structure, no Devonian volcanic structures are known.

Igneous activity started in the Late Devonian. It has an antidromic character; volcanic rocks demonstrate "mixed" geochemical parameters that are typical of igneous rocks of convergent and divergent settings. Sedimentary and igneous–sedimentary sequences of the Nakhorskaya subzone are confined by east-dipping overthrusts (Fig. 1); here, the general structure is a monocline complicated by folded deformations. In the southern part of the study area, thin-layered carbonate–siliceous–terrigenous formations along the fault system are cut into the carbonate platform, which makes it possible to interpret this structure as a deformed graben [6]. In the regional plan, the graben extends in the northerly direction and intersects the structures of its margin at an acute angle. The normal faults of the west wing were likely transformed into overthrusts at the stage of collision, while discontinuous faults of the east boundary were overlain by allochthonous plates. Since the region of active island-arc volcanism was located east of the Sosva–Lozva graben in the Devonian, we assume that the formation of the graben was associated with the extension processes at the rear of the active continental margin with a subduction zone dipping westwardly. The geochemical parameters of the volcanic rocks distributed here do not contradict this interpretation. Another variant is that until the Late Devonian the subduction zone dipped to the east, which is consistent with the data on the more southern Ural areas ([3, 4], etc.), which was followed by a jump and a change in the direction of the dip to the west. In this case, at the first stage the Sosva–Lozva graben was developed as a structure of the fore-arc (inter-arc) basin, and afterwards, its evolution continued as an extension structure at the rear of the active continental margin. It is likely that in the different parts of the Ural paleoocean there were subduction zones of different directions, as is also observed currently in the area of the Sunda archipelago ([11, 12], etc.).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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