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GEOLOGY

Sill Genesis in the Paleoproterozoic Tectonic Evolution of the Onega Trough, Baltic Shield

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Abstract—This study considers the role of sill genesis in the tectonic evolution of the Onega Trough during the Middle to Late Paleoproterozoic (Jatulian–Vepsian). The evolution of the Onega Trough is divided into three stages: pre-sill, or preparatory, subsynchronous, and post-sill. Sill magmatism manifested itself most completely at the subsynchronous stage of the evolution of the Onega Trough within the initial, principal, and final phases of sill genesis. Sill formation followed the stage of regional downwarping of the area reaching its maximum during the Early Ludicovian. Paragenesis of sills and high carbon shungite rocks was accompanied by the formation of peperites, while sills influenced the structure of the host rocks. A model reflecting the regular patterns of manifestations of sill genesis identified in the Onega Trough has been proposed.

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The Onega Trough is located in the vicinity of the Baltic Shield, southeast of it, and has an isometric shape and a long history of geological evolution. The trough formed on the Karelian Massif of Archean consolidation and developed during the Middle to Late Paleoproterozoic, with a considerable proportion of the volcanogenic–sedimentary rock sequence being rich in intrusive sheets. The formation of such sheets is traditionally associated with the melt filling in subhorizontal decompactification and fracturing zones that could have arisen due to (1) monoclinal fold of the Earth's crust [1], (2) subsidence of basement blocks [2], (3) rearrangement of stress fields from the archlike uplift regime to the depression downwarping regime following the activity peak of the volcanic zones [3], i.e., in the course of the evolution of the area according to the (conventionally) brittle scenario at the stage that preceded sill genesis.

The factual material collected in recent years, in particular, the peperite rocks encountered by the author with his colleagues, which are new for the Paleoproterozoic in Karelia (an overview is presented in [4]) and are indicators of plastic relationships between the sills and the host rocks and allows identifying an additional subsynchronous stage in the evolution of the structure and proposing a model reflecting the regular patterns of manifestations of sill genesis in the Onega Trough at the preceding, accompanying, and subsequent stages of its formation.

There are two paleobasin structures in the Onega Trough that formed successively: North Onega (100 × 120 km) filled in with Jatulian–Kalevian rocks and West Onega (60 × 100 km) formed by Vepsian sediments. Sill genesis in the North Onega structure manifested itself during the initial, principal, and final phases with a total duration of ~40 Ma during the Late Jatulian–Ludicovian [5, 6]. Sill genesis in the West Onega structure manifested itself only once during the Vepsian, ~1770 Ma [7].

Relative to the sill genesis period, the area of the North Onega Paleobasin underwent three stages of evolution: *pre-sill, subsynchronous,* and *post-sill.* At the *pre-sill* stage, Jatulian terrigenous–carbonate volcanogenic–sedimentary units formed up to 400 m thick on the periphery and 300–700 m thick in the center of the structure. During the Late Jatulian, the downwarping area spread to the entire structure. It was limited by the coastline whose position is interpreted on the periphery of the paleobasin [8]. During the *initial phase of sill genesis,* bodies of differentiated metagabbrodolerites up to 200 m thick intruded into Upper Jatulian units on the periphery of the downwarping area. Sills are contorted to form folds concordant to the host rocks. At the contacts, there are xenoliths of host rocks, near-contact breccias, diatremes, and fluidisates [9] indicating that magma intruded into water bearing sediments in the context of small depths [10]. The primary mineral linearity reflects the current direction of the melt [1] in the feeding channels of the

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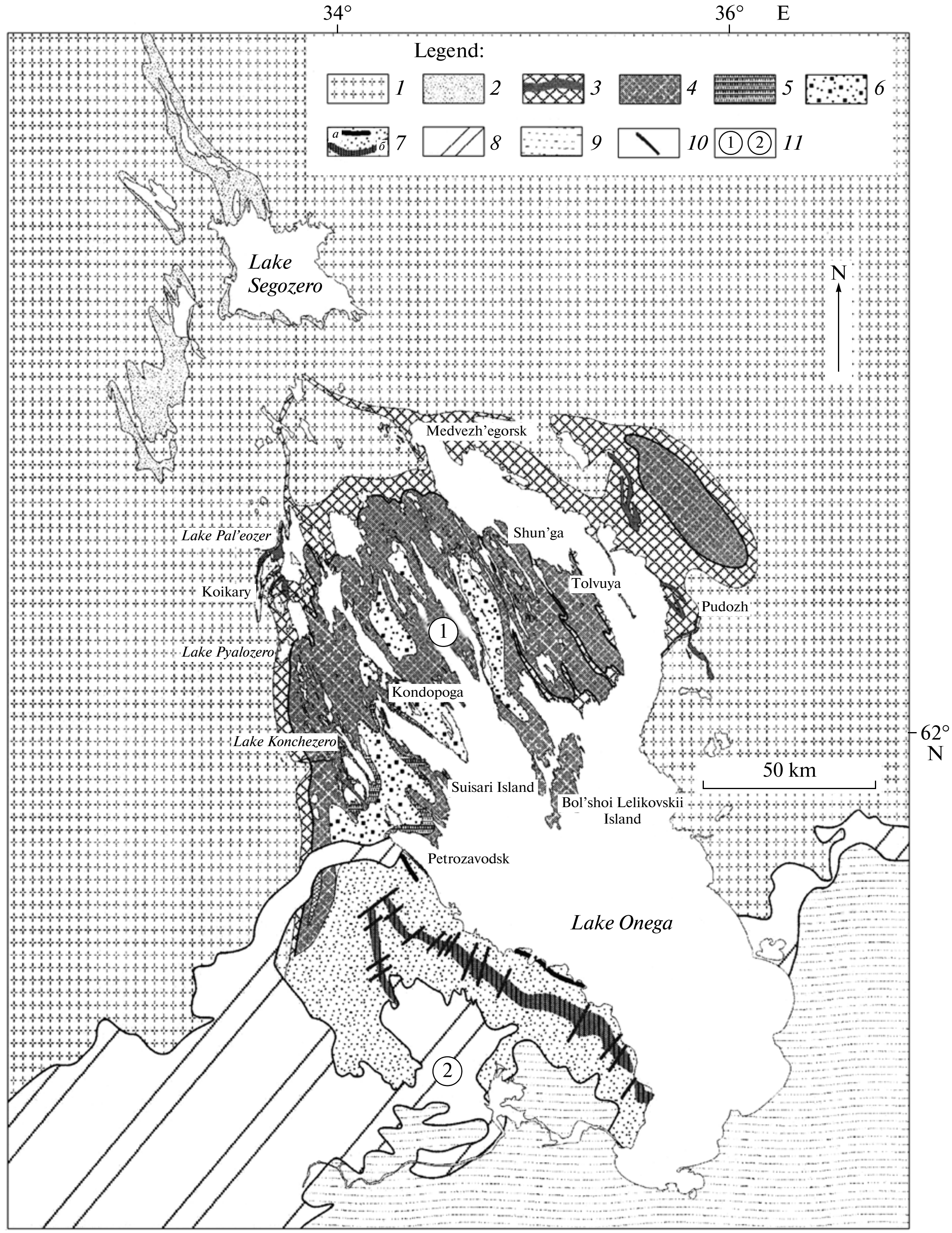

Fig. 1. A simplified map showing the geological settings of the Paleoproterozoic Onega Trough (compiled using calculations [14], geological data [1, 2, 4, 5, 7–13], and the author's own observations). (*1*) Granite–gneisses of the basement, Sumian and Sariolian superhorizons, (*2*, *3*) jatulian: (*2*) segozero horizon, (*3*) segozero and onega horizons with metagabbrodolerite sills, (*4*, *5*) ludicovian: (*4*) zaonega suite with metagabbrodolerite sills, (5) suisar' suite with peridotite sills, (*6*) kalevian, (*7*) vepsian: (*a*) mafic lavas, (*b*) a metagabbrodolerite sill, (*8*) riphean and vendian, (*9*) platform cover, (*10*) faults of the West Onega structure, (*11*) Names of the structures (numbers in the circles): (1) North Onega, (2) West Onega.

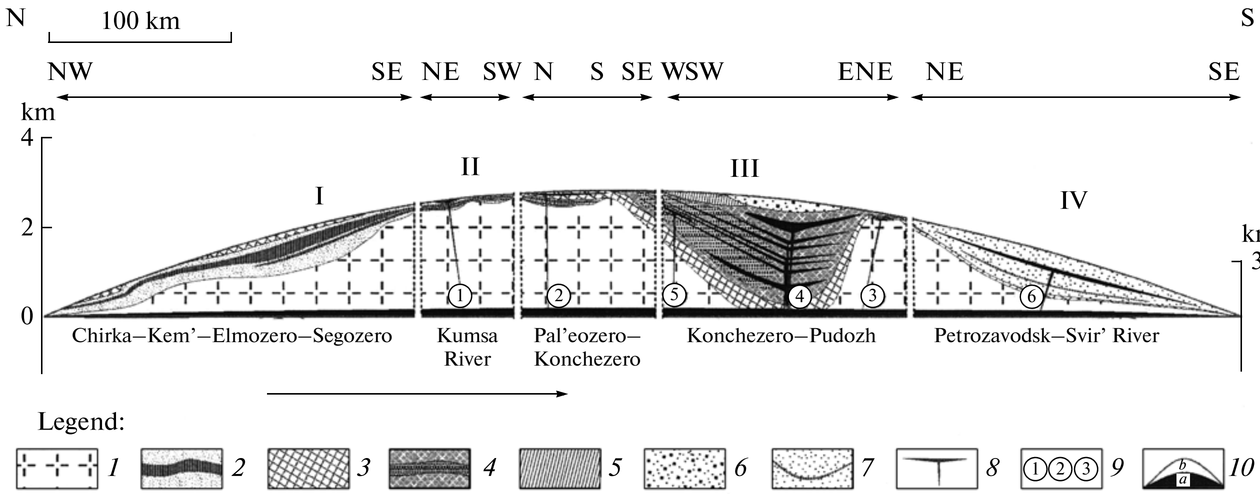

Fig. 2. A model reflecting the regular patterns of sill genesis processes in the tectonic evolution of the Paleoproterozoic Onega Trough at the Jatulian–Vepsian stages of the structural evolution (compiled using calculations [14], geological data [1, 2, 4, 5, 7–13], and the author's own observations). (*1*) Granite–gneisses of the basement, Sumian and Sariolian superhorizons, (*2*, *3*) Jatulian: (*2*) Segozero horizon, (*3*) Onega horizon, (*4*, *5*) Ludicovian: (*4*) Zaonega Suite, (*5*) Suisar' Suite, (*6*) Kalevian, (*7*) Vepsian, (*8*) Sills, (*9*) Sill numbers: (1) Mednogorsk, (2) Koikar–Svyatnavolok, (3) Gabnev and the feeding Pudozhgorsk intrusion, (4) Zaonega sills, (5) Konchezero, (6) Ropruchei, (*10*) Earth surface curvature: (*a*) real scale (the scale is shown on the right side of the figure), (*b*) with an increasing vertical scale (the scale is shown on the left side of the figure). The Roman numerals denote: (I) Segozero Trough, (II) Units dome, Kumsa structure, (III) North Onega Trough, (IV) West Onega structure. The arrow shows the direction of the migration of downwarping regions and magmatism areas.

sills from the center of the structure to the periphery, to the flexure bend area confining the downwarping area.

At the *subsynchronous* stage of the evolution of the North Onega Paleobasin, high carbon sedimentary and volcanogenic units formed whose total thicknesses in the center of the structure are 1500–1700 m, and on the periphery, up to 600–700 m [11]. In the central portion, the bedding is complicated by the phenomena of plastic redistribution of matter (injection folds and boudinage) [4, 12] and peperites [4], the latter being a result of sill intrusion into plastic unlithified high carbon rocks.

Undifferentiated sheets of metagabbrodolerites of the *principal phase of sill genesis* formed in the entire structure and have a total thickness (without considering the sediments that delaminate the sills) of up to 900 m in the center and up to 500 m on the periphery [11]. The sills and host rocks are contorted to form folds. The feeding channels of this phase are interpreted to be both on the western extension and in the central, most submerged part of the structure.

At the end of the subsynchronous stage of the evolution of the paleobasin, ~400 m thick Suisarian chemogenic, pyroclastic, and laval masses formed on the western extension to the structure. Differentiated ultramafic sills of the *final phase of sill genesis* were encountered only within the area where Suisar' rocks are widespread. The sills having a thickness of up to 150 m each intruded high carbon shungite units whose thickness is on the order of 600 m on the western extension to the structure [5]. These units are overlain in the rock sequence by the effusives of the Suisar' Suite that are comagmatic to the sills, with a thickness of ~400 m. The sills are contorted to form folds concordant to the host rocks. In the near-contact zones, there are the xenoliths and the phenomena of bedding cutoffs and assimilation of the host rocks reflecting the active nature of the intrusion of the melt into brittle lithified masses. Interpretations of the flow of the melt confirm the presence of feeding channels of the sills in the most downwarped areas [5].

The *post-sill stage* of the evolution of the paleobasin is characterized by accumulation of Kalevian amagmatic shallow water terrigenous masses [13] that are up to 500 m thick in the center of the structure and situated on the underlying units of the subsynchronous stage of the evolution of the paleobasin with erosion and angular unconformity.

In the West Onega Paleobasin, masses of quartzite–sandstones with a total thickness of over 1500 m and interbeds of mafic lavas formed at the *pre-sill stage* during the Vepsian [13]. Sill genesis in this area manifested itself in the formation of a body of differentiated metagabbrodolerites up to 180 m thick [1, 14]. The thickness of the masses under the sill is over 1000 m, while the units above it are ~450 m thick [14]. The sill generally lies conformably on the host rocks; however, it does not have a distinct position in the rock sequence [14]. The sill intruded into brittle lithified masses [14], and the interpretations of the current direction of the melt indicate that the feeding channel was located in the most submerged part of the structure [1].

The identified patterns of manifestations of sill genesis in the tectonics of the Onega Trough are explained as follows. When a sedimentary basin forms, newly formed beds undergo compression [15]. The beds undergo maximum compression at the level of the chord of the Earth's surface, and the distance to it depends on the size of the downwarping area. The same compressing stresses prevent magma from moving from the depths to the surface, which governs a favorable position for sill formation, namely near the chord of the Earth's surface.

In the light of this interpretation, we can explain the fact that the sills of the *early phase of sill genesis* (Figs. 1, 2) formed on the periphery of the paleobasin, rather than in its central portion. If the width of the downwarping area is 100–200 km, the distance to the level of the chord of the Earth's surface would be 200–800 m [15]. Therefore, the depth of downwarping of the paleobasin calculated based on the thickness of the accumulated masses (500–700 m) was insufficient for sill intrusion in the most submerged part. The sills of the early phase formed within the flexure bends separating the downwarping and uplift areas [1].

The magnitude of downwarping at the subsynchronous stage (over 1700 m) considerably exceeded the calculated depth to the chord level (200–800 m) [15]. The masses reached the sill intrusion area in a plastic state. After that, *sill genesis of the principal phase* manifested itself in the entire North Onega Paleobasin. Paragenesis of sills and high carbon masses was accompanied by the formation of peperites [4] indicating that the melt ascending to the surface reached water-saturated horizons as impermeable beds under which the sills of this phase formed. The thermal effect of the sills on plastic sediments caused deformations and movements of masses, with boudins and injection folds being formed [4].

At the end of the subsynchronous stage of downwarping, differentiated Suisar' sills of the *final phase* formed at a depth of ~300 m, near the chord level. The insignificant width of the downwarping area and, therefore, the small potential room for intrusions affected the sizes of the sheets.

Subsequent downwarping that had been caused partly by a reduction in the thickness of the sills (due to cooling down of the sills) and the host rocks (due to secondary compaction of the sediments) was accompanied by accumulation of amagmatic units of the post-sill stage of the evolution of the North Onega Paleobasin during the Kalevian.

In the West Onega Paleobasin, sill genesis manifested itself only once, following accumulation of over 1500 m of sediments. The magnitude of downwarping exceeded the calculated depth to the chord level (200–800 m) [15]. The sill was formed, since the ascending melt reached an impermeable bed, a barrier represented by compact quartzite–sandstones.

Thus, sill genesis of the Onega structure is closely associated with the kinematics of the downwarping area and the position of the chord of the Earth's surface at the key stages of its evolution. The intrusion of the sills followed downwarping that took place in the entire North Onega Paleobasin. The room for the sills of the early phase appeared as a result of the formation of a flexure bend confining the sedimentation area. The peak of sill formation coincided with the period of the maximum downwarping of the paleobasin and was accompanied by paragenesis of sills and high carbon rocks. Deformations that occurred following the sill formation period and accumulation of the masses at the post-sill stage of the evolution of the North Onega Paleobasin are likely a consequence of the reaction of the host rocks to the processes associated with cooling down and the reducing volume of the intrusive sheets. After the sill genesis period, cold intrusions made the structure harder, which promoted conservation of the isometric shape of the Onega Trough during the period of folded deformations during the Svecofennian.

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