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Research article

Some features of geological structure of the Shikotan Island (Lesser Kuril Arc)—A view from "Space"

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Abstract: In this paper, for the first time, we used Google Earth, an easily accessible method for obtaining geological information to study Shikotan Island (Lesser Kuril Arc). Google Earth flight mode made it possible to examine coastal cliffs on the island, which are inaccessible for hiking or walking, whereas 3-D visualization mode helped us study topographic features, tectonic dislocations, and sediment layering hidden by vegetation and soil, thereby significantly expanding understanding of the geologic structure of the island. Researchers conducting studies in the northwestern part of the island (Tat'yana Cape) discovered a previously unknown structure—a dike field. In the southern part, two thrust faults were identified: An unnamed peak and Tomari Mountain, previously considered a volcano. In the southwestern part of Shikotan Island, there are four unknown volcanic peaks. Together with the Notoro Volcano, they mark the rim of an interpreted caldera of a paleovolcano, which could have been the main unknown source of tuffaceous material for the Mesozoic-Cenozoic deposits of the Matakotanskaya, Malokuril'skaya, and Zelenovskaya Suites. It has been shown that the gabbroid massif of Tsunami Bay (northeastern part of the island) is an autochthonous (local) formation, and not allochthonous, that is, brought from the Pacific Ocean, as evidenced by an intrusive contact with the rocks of the Malokuril'skaya Suite. Despite these positive results, analysis of satellite images of Shikotan Island unexpectedly has not confirmed the existence of the Central Shikotan thrust fault, the largest previously mapped tectonic structure on the island. This work confirms that Google Earth is a very useful tool for geological research in remote areas.

Keywords: Lesser Kuril Arc; Shikotan Island; Malokuril'skaya; Matakotanskaya and Zelenovskaya

Suites; thrusts; dikes; volcanoes; gabbroid intrusive massifs

1. Introduction

The object of research interest in this work is Shikotan Island. Although larger islands exist in the Kuril Arc, Shikotan is the largest (10 × 20 km) island in the more seaward outer island chain known as the “Lesser Kuril Arc”, or the Albian-Paleocene Malokuril’skaya paleo-island arc system [1,2]. The island is composed (Figure 1A) of rocks of the Krabozavodskaya (basalt pillow lava with pillows suspended in a hyaloclastite matrix; the formation thickness is more than 150 m), Matakotanskaya (basalts, andesite-basalts, lava breccias, agglomerate tuffs, tuffaceous sandstones; thickness—500–600 m), Malokuril’skaya (tuffaceous sandstones, siltstones, tuffs; thickness—300 m), and Zelenovskaya (basalts, andesite-basalts, lava breccias, agglomerate tuffs, volcanogenic-sedimentary rocks; thickness—500–600 m) Suites. Pillow lavas of the Krabozavodskaya Suite were formed in underwater conditions. The bulk of the volcanic material of other formations is the product of effusive and explosive volcanism of terrestrial volcanoes.

A significant part of the island is represented by intrusive massifs composed of gabbroid composition. On the northeastern coast of Shikotan Island, gabbroid intrusive massifs make up the basement of the ridge represented by Shikotan and Krainiya mountains (Figure 1B). Field data [3] indicate an intrusive contact between the gabbroid massif of Shikotan Mountain and the overlying Malokuril’skaya Suite, which provides evidence for autochthonous formation. However, according to other concepts [4], these massifs are allochthonous, derived from the mafic layer of the Earth’s oceanic crust and thrust onto Shikotan Island.

Researchers [5,6] found the presence of two volcanoes on the island: Tomari and Notoro (Figure 1B). The base of the Notoro Volcano is about 3 km in diameter, the height above sea level is 330 m, and the average height above the surrounding relief is 150–200 m, as measured by the authors.

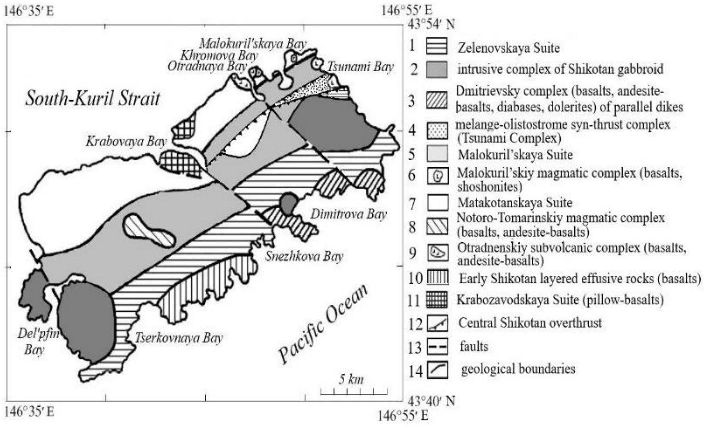
According to some researchers [4,7], the largest tectonic structure of the island is the main structural suture—the Central Shikotan thrust fault. This structure is a thrust of dislocated rocks (tuffaceous sandstones, basalts, and their tuffs immersed in the terrigenous matrix) of the southern part of the island onto a monoclinal, undisturbed sedimentary stratum of its northern part. This structure is represented in the Tsunami Bay area (Figure 1A), where sedimentary formations of the Malokuril’skaya Suite are tectonically overlapped by rocks of the olistostrome complex. The structural suture extends from northeast to southwest along the northern length of the island [4].

A feature of the geological structure of the island is the widespread development of parallel dikes (basalts, andesites) in the eastern part of Shikotan Island (Figure 1A), which indicates a geodynamic regime of extension [2]. The dike complex on Shikotan Island is an intra-arc spreading structure, with a total dike thickness on the Dimitrov Peninsula of about 3 km [2]. Dike complexes are also found in the southwestern part of Shikotan Island (small gabbroid bodies, basalt dikes and sills, thin basalt and andesite-basalt dikes) in Zvezdnaya Bay and at Uglovoy Cape (Figure 1).

Despite the intensive geological study of the island [1–3,8–12], there are questions that need to be addressed: (1) The presence or absence of the inferred main structural suture—the Central

Shikotan thrust fault; (2) relationship of the Lesser Kuril Arc with the main Kuril volcanic island arc; (3) whether the gabbroid massifs are local or alien, that is, thrust onto the Kuril Island Arc system from the Pacific Ocean basin; and (4) identification of sources of pyroclastic material for tuffs and volcanic-sedimentary rocks of the island.

The research aims to obtain additional information about the geologic development history of Shikotan Island using satellite images obtained with the Google Earth program. The authors set the following tasks to achieve this goal: (1) To investigate the features of the relief of the island from various angles; (2) to highlight geological structures and determine their sizes; (3) to describe and graphically represent the structures highlighted; and (4) to show the advantages of the above-mentioned program in the study of the results of geological processes on the surface of the Earth.



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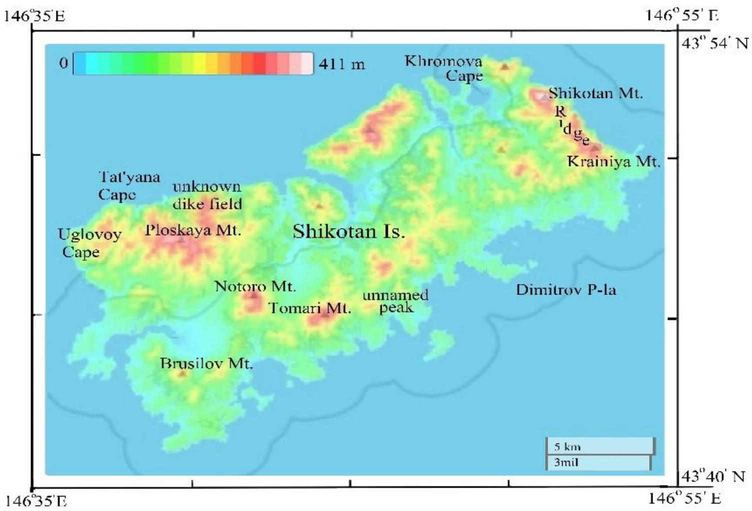

B

Figure 1. Geological scheme of Shikotan Island. Source: [1,2].

Note: A: (1–4) Late Shikotan geological and petrographic complex (GPC) (Maastrichtian-Eocene), (5–6) Malokuril'skiy GPC (Maastrichtian-Danish), (7–9) Matakotanskiy GPK (Campanian-Maastrichtian), (10–11) Early Shikotan GPC (Albian-Campanian), and (12–14) geological boundaries. B: topographic map.

2 Materials and methods

Based on 3D visualization and interpretation of data in the flight mode, the authors could (1) examine the coastal cliffs of the island that were inaccessible “on foot”, (2) obtain a visual representation of overthrusts and faults, (3) detect dike fields, (4) identify layering of sedimentary rocks crumpled into folds, and (5) measure the dimensions of sedimentary strata.

3 Results and discussion

Earlier, the authors obtained additional data on the structure of the bottom of the Sea of Okhotsk with the help of the Google Earth program [13]. On Shikotan Island, they also clarified the stratigraphy [14–16]. However, the work to obtain new geological data on the development history of the island with the above-mentioned program is presented here for the first time.

According to BG Goliokko [7], the Central Shikotan thrust fault is in the Tsunami Bay area (Figure 1A). There is no evidence of it in the literature. On the satellite image of the coastal cliff of Tsunami Bay from the northeast (Figure 2A), the Tsunami rock complex comprises the lower part of the section, and the rocks of the Malokuril’skaya Suite compose the upper part. We can see no signs of thrust rocks from the lower part of the cliff onto the rocks of its upper part. They are absent. The only tectonic structure on the cliff is the fault at the base of Shikotan Mountain (Figure 2B). We infer that this fault was probably formed as a result of the intrusion of the gabbroid massif into the rocks of the Malokuril’skaya Suite from below.

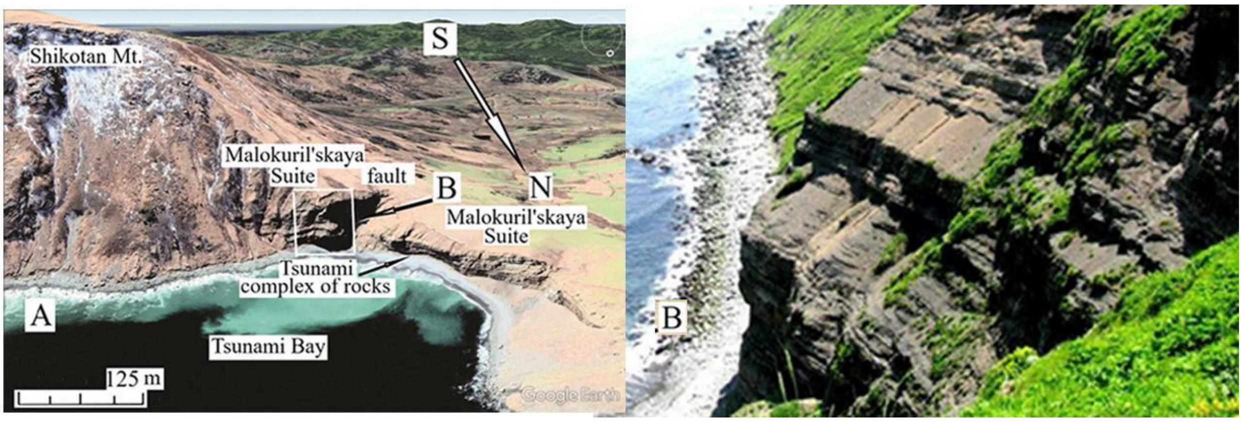

Figure 2. Tsunami Bay. *Source*: Compiled by the authors.

Note: A: View from the northeast to the coastal cliff, where Shikotan Mountain is on the left, and the relationship between the rocks of the Tsunami complex and the rocks of the Malokuril’skaya Suite is in the center. B: northern dip of sedimentary rocks of the Malokuril’skaya Suite (ground photographs, view from the northwest).

Analyzing satellite images of the southern part of Shikotan Island (Figure 1B), the authors identified two thrust faults intersect at the base of an unnamed peak and Tomari Mountain (previously considered a volcano) (Figure 3). These structures with a length of one to two kilometers (unnamed peak and Tomari Mountain, respectively) are clearly expressed in topographic relief.

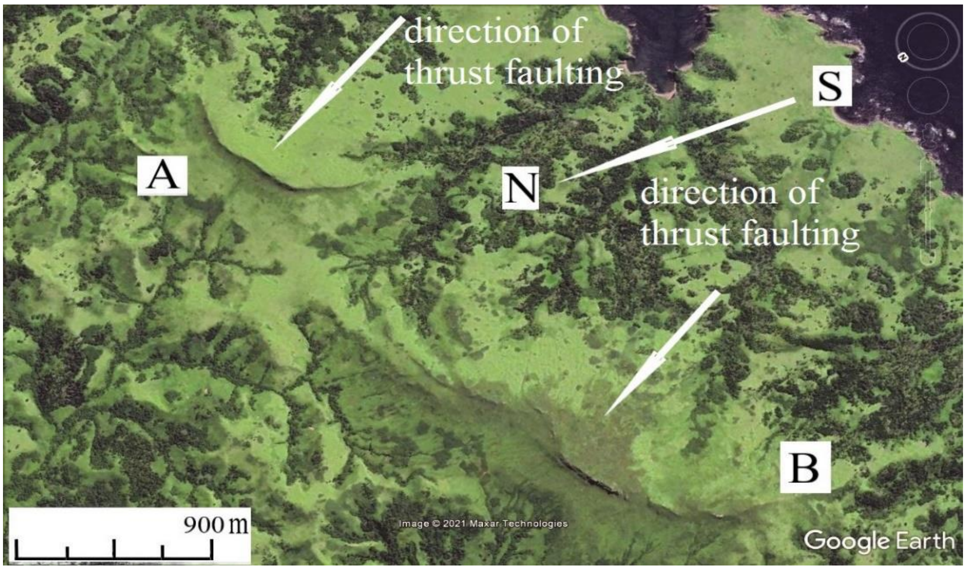

Figure 3. System of two thrust faults (length of about 3.5 km) and direction of their movement (southwestern part of Shikotan Island).

Note: A: First thrust fault (unnamed peak) and B: Second thrust fault (Tomari Mountain, before considered a volcano); view from the northwest.

In this area, there is a boundary between two geological complexes (Figure 1A): Late Shikotan GPC and Early Shikotan GPC presented by predominantly sedimentary and volcanic rocks, respectively. The sedimentary rocks of Zelenovskaya Suite (Maastrichtian-Eocene) are intensively folded while the layered basalt lavas (the tops of unnamed peak and Tomari Mountain, Albian-Campanian) are bedded horizontally [2]. The images (Figure 3) provide a visual representation of southwest-directed thrust faulting (small features 1000–2000 m), which can be seen from above. According to studies [3,7], the length of the Central Shikotan thrust fault is from 10 km to 20 km. This should have been clearly viewed in the relief, but there is no evidence of the existence of such structural sutures. The absence of this large compression structure on the maps of the geological structure of the island is also noted by some authors [9,17]. Volcanic island arcs are often formed under conditions of prevailing crustal compression while the dike belts are structures of stretching. The presence of four fields of dike swarms—one is about 3 km in diameter in the southeast part of the island (Dimitrov Peninsula (Figure 1) with an average width of the island of about 10 km and three centers in the west—indicate the existence of crustal extension, which is not typical for island arcs.

The *dike fields* of the Dimitrov Peninsula are visible in the relief of its northeastern and southwestern coasts. Dikes and dike complexes near the coast in satellite imagery are “teeth” with straight, parallel edges (depending on the rock weathering rate). They have a southwest-northeast strike. On the coast of Zvezdnaya Bay, the dikes are invisible from height, and at Uglovoy Cape, they are poorly identified. Their strike is north-south. To the east (about 1 km), near Tat’yana Cape

(Figure 1B), a previously unknown field of dikes (1.5 × 0.5 km) was established by authors through satellite images (Figure 4).

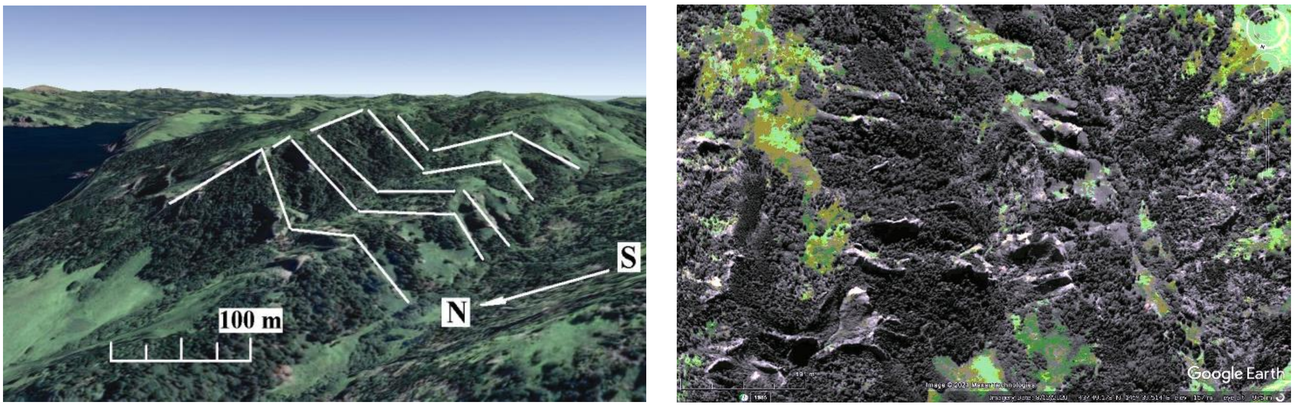

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Figure 4. A: A previously unknown dike field (northwestern coast of Shikotan Island, 1.4 km east of Tat'yana Cape); view from the west. The lines show the strike from southwest to northeast. B: A closer view showing "teeth" with straight, parallel edges.

The average size of the dikes (measured by the authors on images) is from 100 m long and 20 m wide. The strike is southwest-northeast, similar to the dikes of the Dimitrov Peninsula.

Gabbroid massifs. The Google Earth program allows consideration of the coastal cliffs of Krainiya and Shikotan mountains (Figure 1B) inaccessible for hiking, the base of which is composed of gabbroid [2,4]. The cliffs are also part of them, but the authors could not identify them using Google Earth imaging (Figure 5).

The main volume of rocks that compose the cliffs of Krainiya and Shikotan mountains are represented by the dislocated rocks of the Malokuril'skaya Suite, for which bedding is a characteristic structural feature. Layered, folded sedimentary rocks [2,4] are well exposed on satellite images. In the stratotype section of the Malokuril'skaya Suite (on the Khromov Peninsula between Malokuril'skaya and Khromova bays (Figure 1B), the sedimentary rocks are bedding, which is visible (despite vegetation and layer of soil) on the satellite images (height view) (Figure 6).

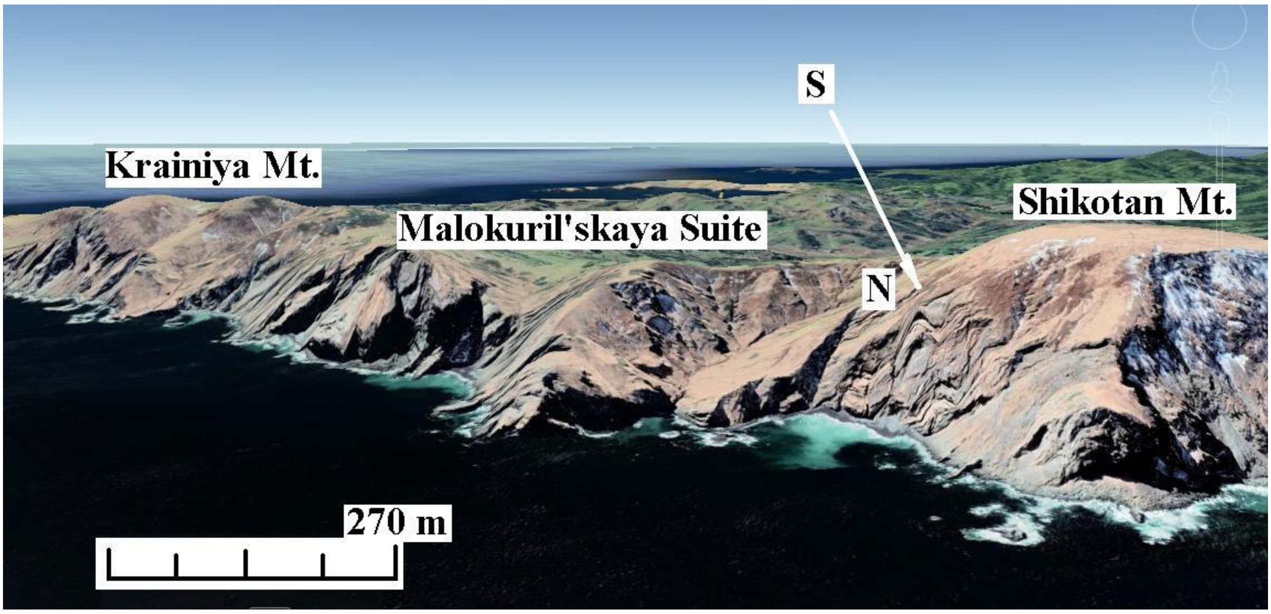

Figure 5. Coastal cliffs between Krainiya and Shikotan Mountains composed of sedimentary rocks of the Malokuril'skaya Suite with well visible folds; view from the north.

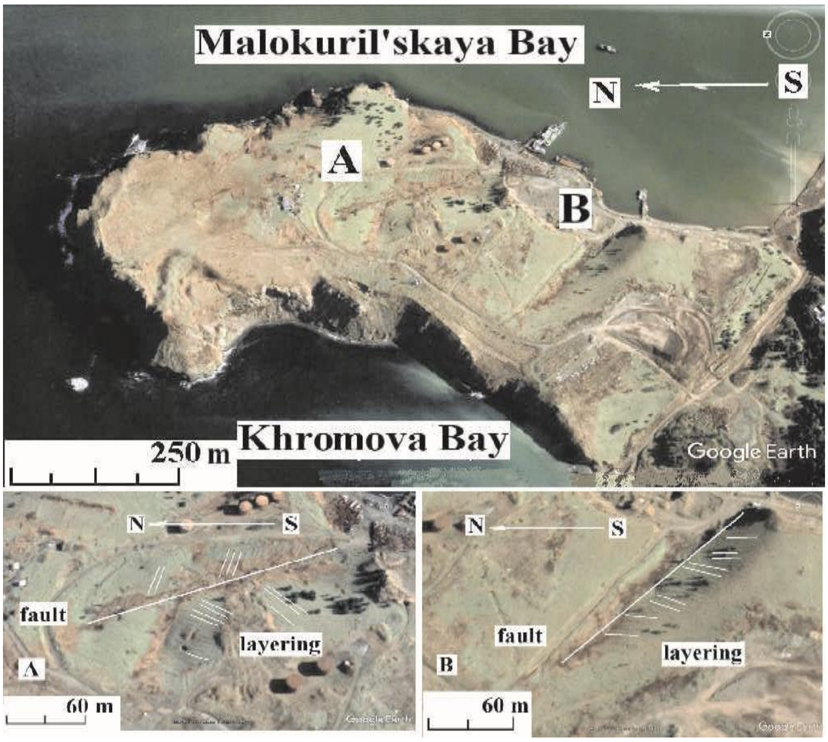

Figure 6. Satellite image of the outcrops of rocks of the stratotype section of the Malokuril'skaya Suite (on the Khromov Peninsula between Malokuril'skaya and Khromova Bays), where layering is well visible in some areas (underlined with white lines).

The satellite image allows measuring of the bedding of the sedimentary strata—five layers in the plan are about 20 m in total thickness. Similar bedding outcrops are also visible on the surface of a significant part of the slopes of Shikotan Island and the upper part of the slopes between Krainiya and Shikotan mountains (Figure 5). In the southern part of Krainiya and Shikotan mountains, they have a southern dip. In the northern part of the ridge (on the northern slope of Shikotan Mountain (Figures 1B and 2A,B)) they have a northern dip. This may indicate the uplift of rocks of the Malokuril'skaya Suite during the formation of intrusive bodies.

Thus, the gabbroid massif of Tsunami Bay (northeastern part of the island) is an autochthonous (local) formation, and not allochthonous, that is, brought from the Pacific Ocean as evidenced by an intrusive contact with the rocks of the Malokuril'skaya Suite.

Source of explosive material. The analysis of satellite images of Shikotan Island indicates the existence of five volcanic constructs in the southwestern part of the island (Figures 1B and 7): Notoro Volcano, with a crater diameter (c.d.) of about 700 m; unnamed volcanoes 1, 2, and 4, c.d. −50, 130, and 450 m, respectively; and Brusilov Mountain, c.d. −420 m.

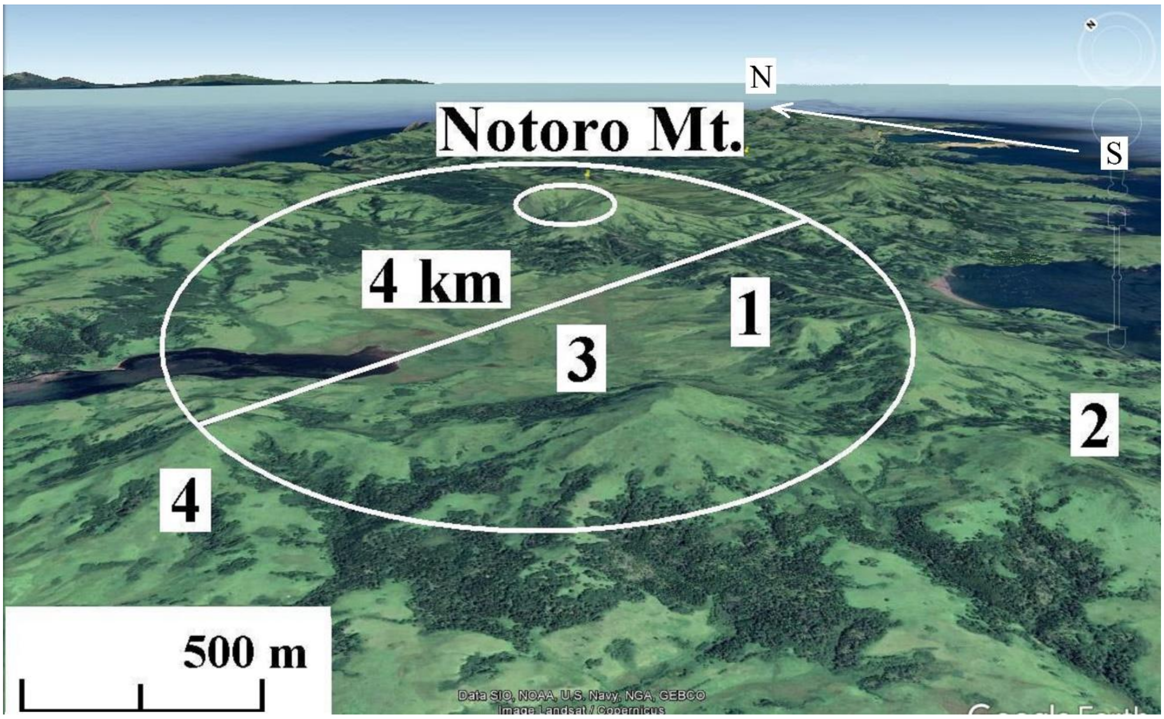

Figure 7. Volcanic constructs of Shikotan Island. Volcanic highs here are interpreted as forming a caldera of a stratovolcano. Defined on the maps: Notoro Mountain and 3—Brusilov Mountain. Determined in the satellite images: 1, 2, 4—unnamed volcanoes.

These volcanoes, united by a single ridge, probably represent the edge of a large caldera (about 4 km in diameter) of an ancient stratovolcano. The closest analog of a caldera of this size is the Golovnin Volcano caldera on Kunashir Island. The relatively small size of Notoro Mountain (the base of about 3 km in diameter, the height above sea level of 330 m, and the average height above the surrounding relief of 150–200 m, as measured by the authors) suggests that it is not the main source of volcanic material for the mentioned above sedimentary formations. Lavas of basalts, andesites, and lava-breccia could have formed during the eruption of stratovolcanoes and fissure eruptions. A large volume of pyroclastic material, typical of the sedimentary formations, likely formed during the eruption of a larger volcanic edifice or structure such as a buried caldera.

4 Conclusions

The presence of satellite images offered by the Google Earth program enables one to view, in detail, Shikotan Island from different angles. Although the Central Shikotan thrust fault appears in previous maps [2,4,7], its existence is not confirmed by image analysis. Previously unknown compression (thrust) structures are established: An unnamed peak and Tomari Mountain. These structures indicate the movement of blocks of the Earth's crust from the Pacific Ocean basin, which supports what is understood about the geological structure of Shikotan Island.

The view from "space" confirms the existence of a dike belt on the Dimitrov Peninsula and establishes the presence of a fourth, previously unknown, dike field east of Tat'yana Cape (Figure 1B). The presence of four centers of extension on Shikotan Island, which is part of a volcanic island arc, determines its unique geologic structure.

The analysis of the images of the northeastern part of the island unambiguously indicates the autochthonous (local) genesis of the gabbroid massif of Krainiya and Shikotan Mountains. Gabbroid makes up the base of the ridge, and sedimentary rocks of the Malokuril'skaya Suite are developed in its upper part and the coastal cliff of the northeastern part of this ridge (Figure 1B). They were uplifted and dislocated with the development of numerous folds during the formation of the gabbroid massif.

In the southwestern part of the island, four previously unknown volcanic peaks have been identified; together with Notoro Volcano, they probably mark the caldera (with a diameter of about 4 km) edge of a largely collapsed stratovolcano. With the destruction of its upper, now absent part during explosive eruptions, the volcanogenic material that formed the peak of the volcano could participate in the formation of the Matakotanskaya, Malokuril'skaya, and Zelenovskaya Suites, which suggests solving the problem of the source of pyroclastic material for the deposits of these formations.

The material obtained with the Google Earth program expands the understanding of the geological structure of Shikotan Island, enables problems to be solved in the history of its formation, and suggests that the existing retrospective models of the formation of the island are far from complete.

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Author contributions

Conceptualization: E.P.T. and A.V.M.; Data curation: E.P.T. and A.V.M; Investigation: E.P.T. and A.V.M.; Methodology: E.P.T. and A.V.M.; Validation: E.P.T. and A.V.M.; Visualization: E.P.T. and A.V.M.; Writing—original draft: E.P.T. and A.V.M.; Review & editing: A.V.M.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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