UAV Aeromagnetic Survey of the Valimyaki Complex (Northern Ladoga Area): First Estimates of the Buried Intrusion Structure

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Abstract: The Valimyaki intrusive complex is an early-orogenic gabbroid body of the Northern Ladoga region, composed predominantly of pyroxenites, gabbros, and diorites and historically known for titanium-magnetite mineralization concentrated in its near-surface marginal zones. At present, no reliable three-dimensional model of the Valimyaki massif exists, and its investigation is significantly constrained by difficult terrain accessibility. Multi-altitude UAV-based aeromagnetic surveying provides new opportunities for obtaining information on the deep structure of the intrusive complex. In 2023–2025, a series of surveys was carried out over the Valimyaki massif and Mäkisalo Island, the two main known surface expressions of the Valimyaki complex. As a result, maps of the anomalous magnetic field were obtained at several flight altitudes, enabling direct calculation of the vertical magnetic field gradient. The multi-level dataset considerably expanded the interpretational potential and the application of various field transformation and inversion techniques, including the equivalent-source method. Integrated analysis of the aeromagnetic data using spectral and mounting inversion methods yielded a consistent model of both deep-seated and near-surface magnetic sources, refining the internal structure and spatial extent of the Valimyaki massif.

Keywords: Valimyaki, Mäkisalo Island, Raakhe-Ladoga zone, UAV aeromagnetic surveying, multi-altitude aeromagnetic surveying.

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Research Article

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1. Introduction

The Valimyaki early-orogenic gabbroid complex in the Northern Ladoga region has been known since the second half of the 19th century, when titanium-magnetite ores were actively mined within its boundaries. Owing to the near-surface occurrence of the ore bodies concentrated mainly within pyroxenites and gabbro-pyroxenites, the mining technologies of that period allowed for open-pit exploitation. By the mid-20th century, after exhaustion of the shallow ore bodies, mining operations were terminated. Nevertheless, recent studies indicate potential mineralization prospects of the complex associated with deeper parts of the intrusion.

The intrusive complex consists mainly of the Valimyaki massif. The massif has an oval shape elongated in the northward direction and occupies an area of approximately 8–10 km^2 [*Proterozoic...*, 2020]. The second largest exposure of the complex is located in the southeastern part of Mäkisalo Island, about 2 km south of the Valimyaki massif (Figure 1A). In addition, several small isolated fragments of the intrusion are present in adjacent areas. At present, no complete and reliable three-dimensional geological model of the intrusion exists; however, the spatial distribution of known outcrops suggests a common deep-rooted source for both the continental and island occurrences. The massif represents a stratiform intrusion showing features of magmatic layering, with the primary rock composition varying from pyroxenite to diorite. The host rocks are quartz–biotite and staurolite schists of the Ladoga Series. The intrusion is cut by numerous cross-cutting dikes of dolerite, diorite porphyry, and plagioporphyry. At the Mäkisalo Island exposures, not only amphibolized gabbro but also norite has been reported. The entire intrusive body was substantially modified by superimposed processes, including folding deformations, regional metamorphism, and ultrametamorphism.

The Valimyaki mineralization is associated with lens-shaped titanium-magnetite ore bodies confined to amphibolized pyroxenites in the marginal parts of the massif. Several occurrences of noble-metal mineralization related to sulfides within titanium-magnetite ores have also been identified [*Proterozoic…*, 2020].

In such geological settings, high-resolution geophysical methods become essential for detailed structural investigations. Unmanned aerial vehicle (UAV) magnetic surveying has recently proven to be a highly efficient tool for mapping small-scale magnetic heterogeneities at low flight altitudes and with dense spatial sampling [*Jackisch et al.*, 2022]. Compared with conventional ground or crewed airborne surveys, UAV magnetometry provides enhanced spatial resolution and operational flexibility, while reducing terrain-related distortions and logistical constraints. These advantages are particularly significant for the study of compact intrusive bodies and contact zones, where rapid lateral variations in magnetic properties are expected.

Because of the lack of economic interest in further exploitation since the mid-20th century and due to difficult accessibility, detailed magnetic surveys of the massif were not previously conducted. The primary source of publicly available information to date remains the 1:500,000-scale airborne geophysical survey data used for the compilation of the state geological map [*Stepanov et al.*, 2013].

An experimental UAV-based aeromagnetic investigation of the Valimyaki complex conducted by researchers of the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, was initiated in 2023 and has been ongoing to the present day. The objectives include identification of magnetically contrasting lithological domains, 3D modeling of the intrusion body, and assessment of the spatial relationships between magnetic anomalies and known mineralization occurrences. An additional goal is to evaluate the methodological effectiveness of UAV-based magnetic multi-altitude surveying for high-detail geological mapping in the conditions of the Northern Ladoga region.

The paper presents the materials of the magnetic survey conducted in Northern Ladoga area using an unmanned aerial vehicle. The first results of the quantitative interpretation of the measured magnetic field data in terms of the features of the Valimyaki intrusive complex underground distribution and magnetic properties are discussed and the directions of further studies are outlined.

2. Multi-Altitude Aeromagnetic UAV Survey

The preliminary stage of the study, conducted in 2023, included aerial photogrammetric surveying on a Geoscan-101 UAV and the generation of digital terrain and elevation models. These models were subsequently used for planning terrain-following flight missions and for the further interpretation of the UAV aeromagnetic survey data.

Aeromagnetic surveying over the Valimyaki massif was carried out in 2024 [*Taran et al.*, 2025] using a GeoShark quantum aeromagnetometer mounted on a Geoscan-401 UAV. The survey was conducted along eight flight lines spaced at 500 m at three altitude levels following the local topography. The flight missions were designed to maintain a constant clearance of the sensor above the ground surface. The vertical spacing between adjacent survey levels was 30 m, with the lowest flight altitude of 340 m above ground level (AGL). The structural features of the massif are clearly expressed in the relief, with total elevation differences exceeding 100 m.

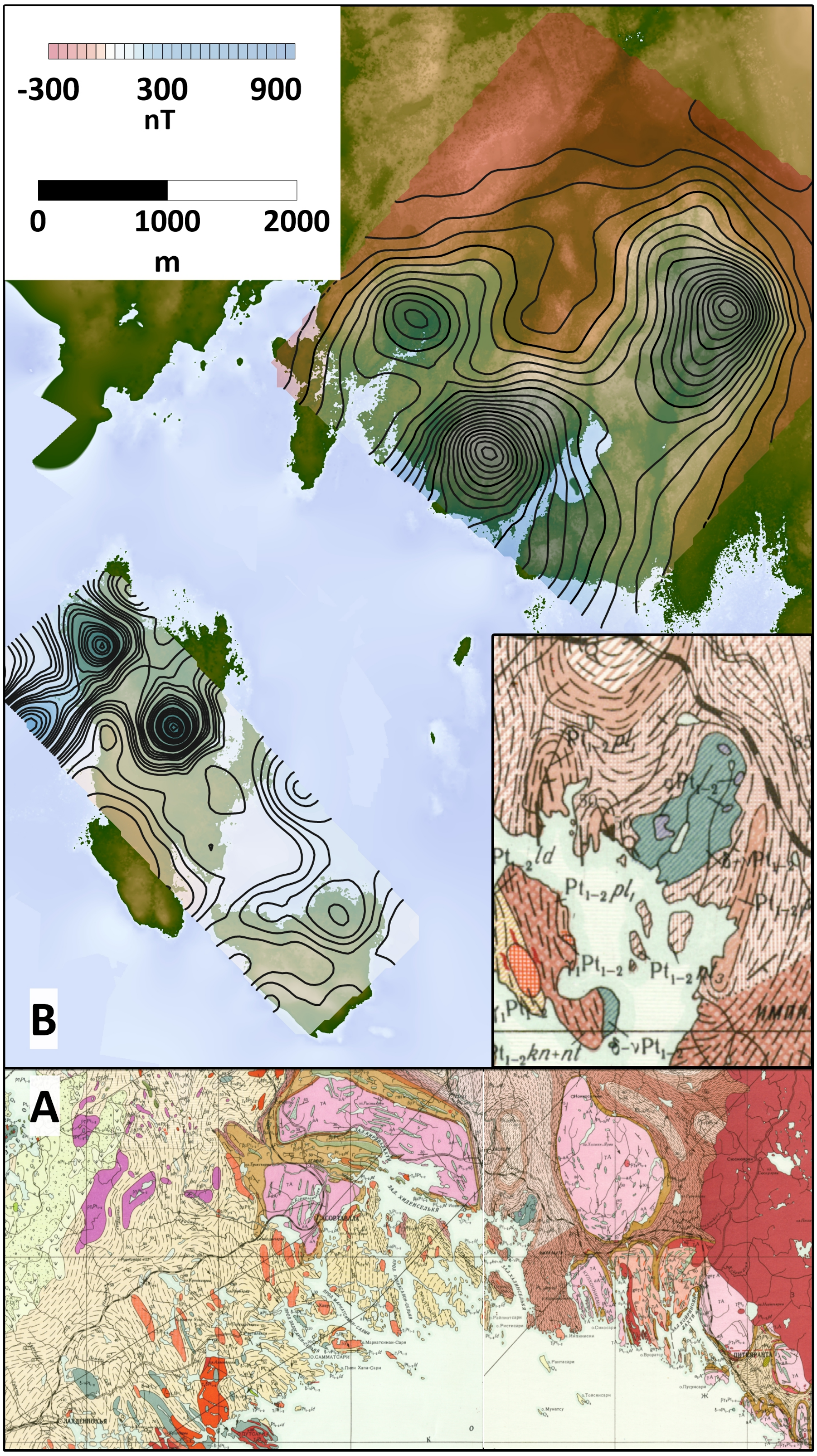

Figure 1. The Valimyaki intrusive complex. (A) Location of the complex shown in gray on the 1:200,000 geological map (sheet P-36-XIV) in large- and small-scale view; (B) Digital terrain model of the Valimyaki massif area with overlaid anomalous magnetic field isolines of the UAV aeromagnetic survey acquired at a flight altitude of 340 m above the Valimyaki massif and 200 m above Mäkisalo Island.

Since, in addition to mapping the anomalous magnetic field, the experiment was aimed to estimate the vertical magnetic gradient from multi-altitude data, strict repetition of flight trajectories in both altitude and plan view was required. To achieve this, the flight mission planning ensured duplication of not only the terrain-following surface shapes but also control altitude reference points for each survey level.

During post-processing, the sensor position was refined using differential GNSS positioning. Ground-based GNSS observations were carried out with a reference station consisting of an OS-113 receiver (Orient Systems) paired with a choke-ring antenna (CHCNAV).

Aeromagnetic surveying over Mäkisalo Island was performed in 2025 following the same methodology along four flight lines with a spacing of 400 m. For flight safety reasons, the surveys were conducted at lower altitudes than over the massif, at 200 and 240 m above ground level.

Based on the survey results, maps of the anomalous magnetic field (Figure 1B) and its vertical gradient (Figure 2), derived from multi-altitude aeromagnetic data [*Taran et al.*, 2025], were produced. Comparison with the structural scheme of the Valimyaki massif [*Proterozoic…*, 2020] indicates that the known ore-bearing pyroxenite outcrops identified during past mining operations generally flank the maxima of the anomalous field but do not coincide exactly with its extrema. The maxima of the vertical gradient further suggest that the magnetically anomalous bodies are predominantly shallow.

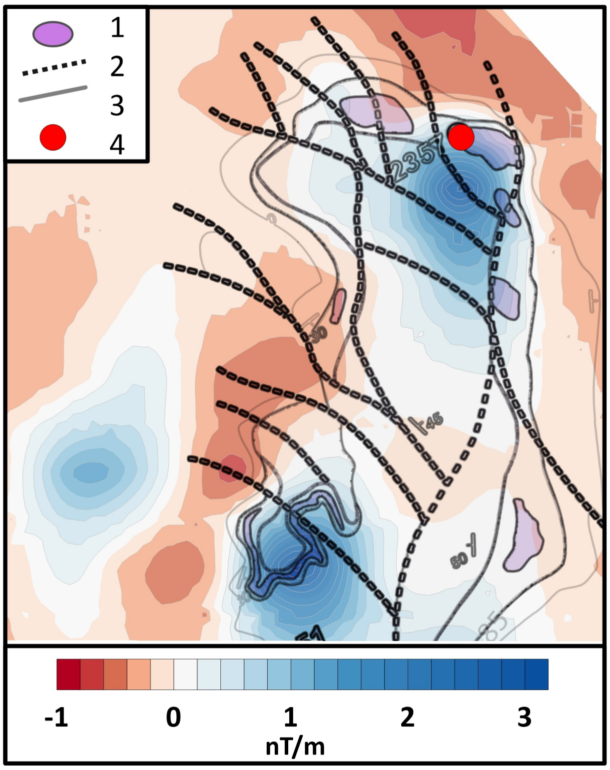

Figure 2. Map of the vertical gradient of the anomalous magnetic field over the Valimyaki massif with the structural scheme of the massif after [*Taran et al.*, 2025] overlaid. 1 – known shallow ore-bearing pyroxenite outcrops; 2 – faults; 3 – boundaries of zonal structural units; 4 – sampling point 2357.

Over Mäkisalo Island (Figure 3), the anomalous magnetic field exhibits much lower amplitudes—ranging from −40 to 280 nT – even though the survey was conducted at lower altitudes. In comparison, maxima over the continental massif reach 950 nT, while at the mapped outcrops of the Valimyaki complex the amplitude reaches only 50 nT. An elongated anomalous zone in the northeastern part of the island aligns with the strike of the anomaly detected beyond the massif boundaries. It also exhibits a similar amplitude of the vertical gradient of the anomalous magnetic field, which may indicate comparable depths of the causative bodies.

Petrophysical measurements of massive gabbro samples with Ti-mt ore inclusions, collected by Yu. A. Morozov and M. A. Matveev [*Taran et al.*, 2025] (IPE RAS) near the closed mines (sampling point 2357), reveal extreme magnetic susceptibility values of 15,000–40,000 × 10^{-5} SI units. In contrast, rocks sampled from the marginal parts of the massif and from the surrounding host formations exhibit much lower susceptibility, ranging from 0 to 50 × 10^{-5} SI units. The laboratory measurements revealed low magnetic properties of gabbro samples from the moderate magnetic anomaly areas of the massif.

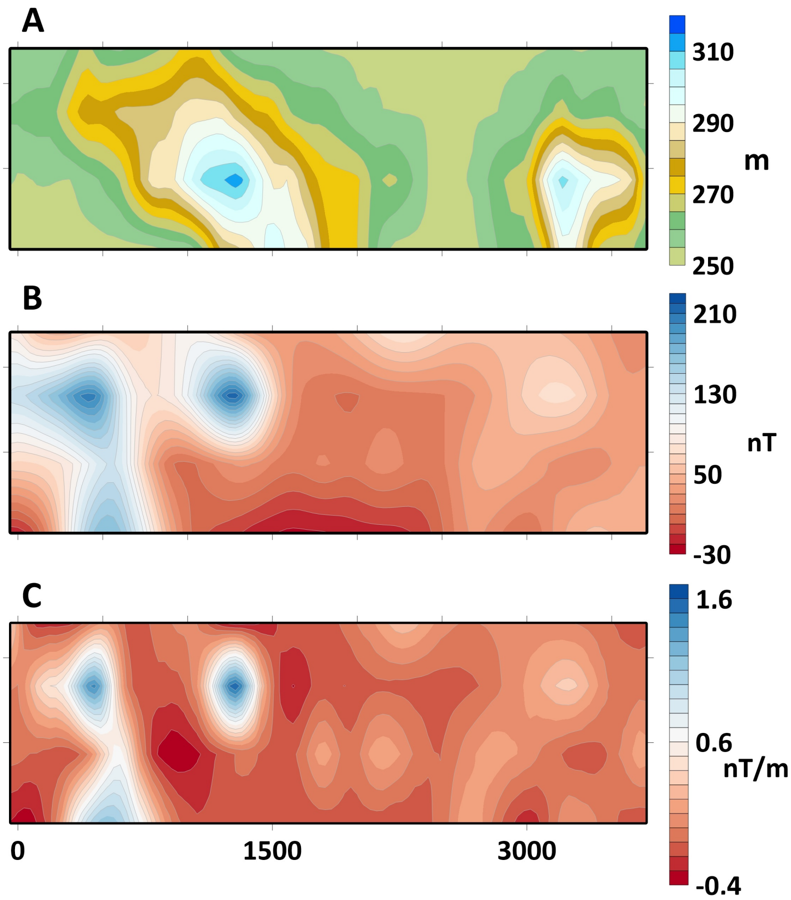

Figure 3. Aeromagnetic surveying over Mäkisalo Island. (A) Altitude level 240 m AGL (GPS height); (B) Anomalous magnetic field; (C) Vertical gradient of the anomalous magnetic field.

3. Inversion

The first inversion experiments of the anomalous magnetic field data acquired at the 340 m altitude level were performed to obtain an initial idea of the volume distribution of magnetic sources. For this purpose, three-dimensional spectral inversion technique [*Mitsyn*, 2018] realized in the GIS Integro software package [*Kobrunov and Varfolomeev*, 1981] according to the approaches of [*Cheremisina et al.*, 2021; *Priezzhev*, 1989] (commonly named as "Priezzhev's method") was applied.

After pre-processing to remove high-frequency noise, the magnetic field was extrapolated, according to the requirements of the inverse problem statement. The inversion was performed in a three-dimensional grid parametrization with cell parameters of 50 m × 50 m × 25 m (X, Y, Z) and model space dimensions of 5300 m × 5600 m × 2500 m (X, Y, Z). The modeling field was calculated at 440 m above sea level (accounting for the average elevation of the massif ∼100 m). The extrapolation of the anomalous field around the modeling area was based on the periodic continuation approach.

Taking into account the strong non-uniqueness of the solution of the potential fields' inverse problem (existence of a wide range of petrophysical parameter underground distributions, equivalent in terms of satisfaction to the observed fields) the application of inversion techniques should be carried out under objective external constraints. In the Priezzhev's spectral method these constraints can be applied by selecting the inversion procedure parameters responsible for the character of spatial-depth dependence of the magnetic susceptibility/magnetization (or density). The iterative selection of the specific function parameters describing this dependence would be perform on the basis of independent reference data (geophysical or geological) or – relying upon the preliminary regional experience.

In our case there was no retrospective geophysical information on morphology and depth of localization of the Valimyaki intrusion therefore the spectral inversion parameters were chosen in accordance with the general geological concept available and the experience from similar (in some aspects of the characteristics of the studied intrusive objects) investigations [*Kulyandina et al.*, 2025].

The results of spectral inversion (Figure 4) indicate extremely high values of excessive (effective or contrasting) magnetic susceptibility inside a large buried anomalous body in the form of a thick sheet, with its center of mass being located at a depth of approximately 1 km. The dimensions of this body exceed the boundaries of the known surface exposures of the massif and extend further south toward Mäkisalo Island, beyond the modeling space domain, suggesting the possible existence of common deep roots for the continental and island occurrences of the complex.

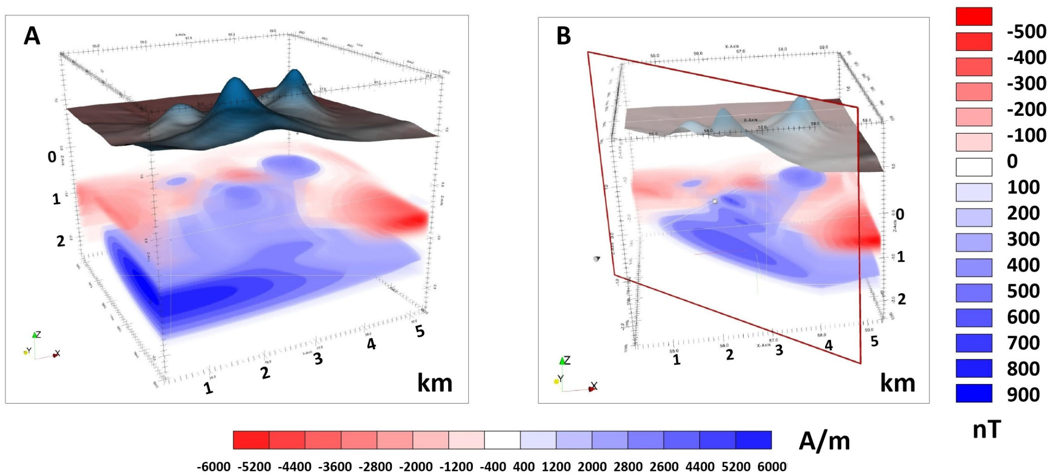

Figure 4. Three-dimensional model of the volumetric distribution of excess (effective) magnetization of the Valimyaki massif obtained from 3D spectral inversion using the Priezzhev method implemented in the GIS Integro software package [*Kobrunov and Varfolomeev*, 1981]. (A) The model in comparison with the overlying relief map of the anomalous magnetic field (survey altitude of 340 m above ground level); (B) dissected by an arbitrary subvertical section plane.

Zones of intense local extrema of the observed magnetic field are projected onto "mushroom-shaped" intrusions representing sub-vertical apophyses rising from the stratiform body and reaching the ground surface in areas where Ti-mt ore bearing pyroxenites are exposed.

At the second stage of the quantitative interpretation of the new magnetic field data on the Valimyaki complex, the so-called "mounting method" of potential field inversion was applied [*Dolgal et al.*, 2012; *Strakhov and Lapina*, 1976] to improve the reliability of the reconstruction of the underground morphology of the magnetic intrusion. This method is based on an iterative change in the geometry of objects responsible for the observed potential field anomalies – adding or removing individual cells comprising an object in order to minimize the misfit between the calculated and observed anomalous fields.

The mounting (also called "assembling") method was used in the variant implemented in the GIS Integro software package [*Mitsyn and Bolshakov*, 2021]. The non-uniqueness problem is still inherent in this approach but it can be rather effectively regularized by introducing a reasonable initial model as well as a hypothesis about the physical properties of the object under study.

The starting inversion model of the magnetic intrusive body was formed based on the results of the spectral inversion. It was defined as an ensemble of three shallow objects corresponding to the maxima of the anomalous magnetic field and its vertical gradient, as well as to the known surface outcrops of pyroxenites within the massif. The deeper part of the model was represented by a massive lens-shaped body with a center of mass at a depth of approximately 1.5 km (Figure 5a). The corresponding model magnetic response is shown in Figure 5c (the misfit with observed field – 103.47 nT).

The application of the mounting method also permits a specification of petrophysical parameters of the causative bodies. Two susceptibility classes were assigned during modeling: 15,000 and 40,000 × 10^{-5} SI units, which were based on measured values obtained from the rock samples collected at sampling point 2357. The magnetic susceptibility of the host environment (non-magnetic schists of the Ladoga Series and gabbro rocks of the Valimyaki complex) was set to zero.

The convergence curve of the inversion procedure exhibited a rapid decrease for the first tens of iterations and distinct inflection at the 60th iteration and then it gradually reduced to stably negligible values of misfit. The model obtained at the 60th iteration was chosen as a final one (Figure 5b), with observed and modeling data RMS misfit amounting to approximately 16.22 nT (the final model response is presented in Figure 5d).

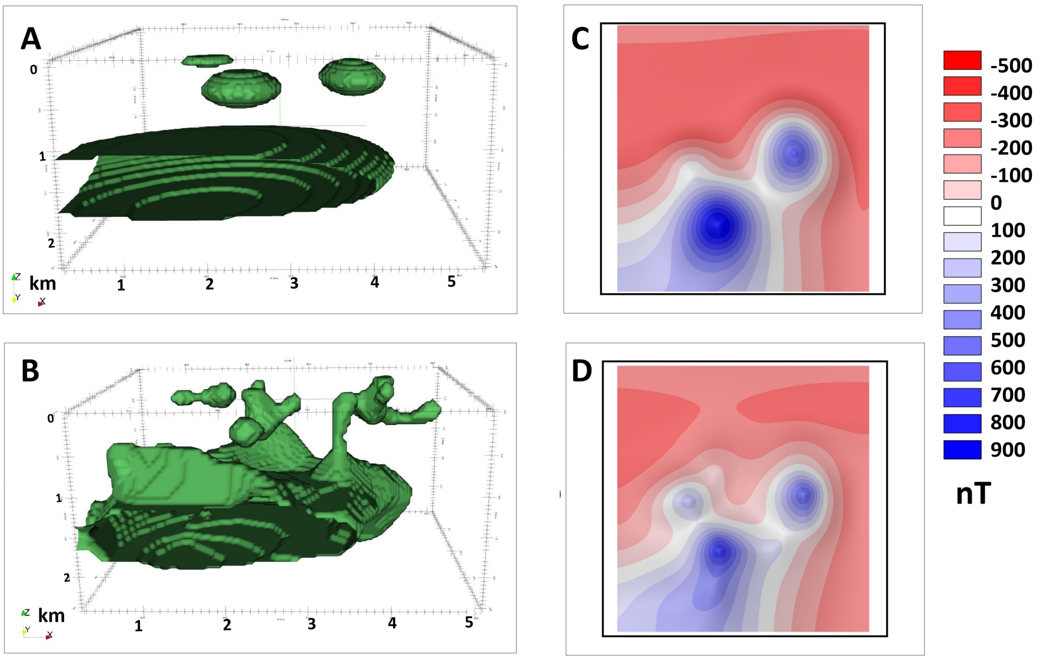

Figure 5. Stages of the anomalous magnetic field inversion performed with a help of the mounting method [*Mitsyn and Bolshakov*, 2021] for the Valimyaki massif area: the starting and the final models (A, B) and their magnetic responses (C, D, correspondingly). The green color shows the consolidated surface of magnetic intrusive formations.

4. Discussion of the Results

In the results of UAV aeromagnetic survey conducted over the Valimyaki intrusive complex the maps of the anomalous magnetic field and its vertical gradient (Figure 1-3) were obtained, which clearly reveal pronounced magnetic heterogeneity associated with both near-surface ore-bearing pyroxenite bodies and deeper-seated magnetized sources.

Comparison with existing geological data indicates that surface pyroxenite occurrences generally border magnetic maxima but do not fully coincide with anomaly extrema, emphasizing the three-dimensional character of mineralized bodies.

The morphology of the highly magnetic species of the Valimyaki intrusive complex has been recovered at the underground levels in the course of the inversions of the UAV magnetometry data. The consistent volumetric model of the magnetic susceptibility underground distribution was constructed on the basis of the results of the most objective, unprejudiced spectral 3D inversion, which helped reveal domains of the brightly contrasting magnetization. Further, more detailed model elaboration (in absolute magnetic susceptibility units) was performed by the mounting method of magnetic inversion that reduced solution non-uniqueness.

The final inversion results indicate the presence of a large, sheet-like buried body of extremely high magnetization with a center of mass located at a depth of approximately 1.5 km. The lateral extent of this body exceeds the known surface boundaries of the Valimyaki massif and continues southward toward Mäkisalo Island, suggesting a common deep root system linking the continental and island exposures of the complex. Local magnetic extrema are associated with subvertical apophyses rising from the main stratiform body and locally reaching the surface in areas of pyroxenite outcrops, known from the geological map and may be unknown yet (Figure 6).

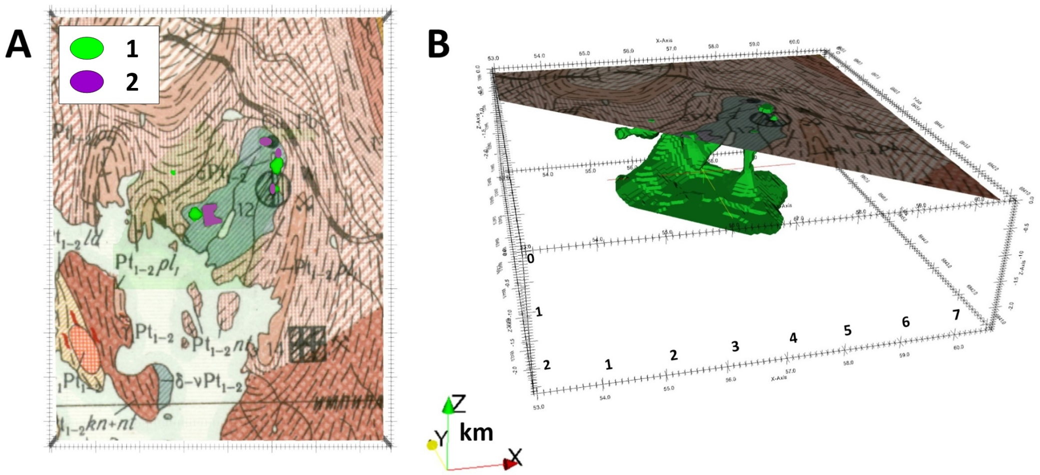

Figure 6. Assembling of the fragment of the geological map with the Valimyaki complex outcrop and its magnetic intrusive bodies recovered by the mounting method inversion of the UAV magnetometry data (A)in the top view (B) in the cross section. 1 – inversion result, 2 – known shallow ore-bearing pyroxenite outcrops.

Considering the reliability of the magnetic model constructed one should take into account the following issues: 1) limitation of the used inversion techniques, which operate with the modeling fields calculated on the horizontal plane (440 m above sea level in our case), while the survey was performed at the constant level above geographic relief; 2) absence of the solid local (regional) constraints on the parameters of the spectral inversion procedure; 3) limitation of the assumption of the existence of two (only!) classes of anomalous objects, which are characterized by uniform magnetization; 4) necessity of complete coverage of the area of the Valimyaki complex distribution by magnetic field survey.

The 4th point requires continuation of the magnetic surveying above lake waters in the strait between the land and Mäkisalo Island, as well the 3rd one will not obtain any resolution before more precise sampling (or drilling) and laboratory measurements of the physical properties of the rocks will be carried out.

In order to obtain more constraints for the inversion procedure regularization additional, independent geophysical investigation are ultimately needed: electrical, electromagnetic, seismic soundings, detailed gravity survey or at least any of them.

While the first problem can be solved already in near time with a help of anomalous magnetic field transformation by the equivalent source method [*Gordin et al.*, 2006], widely used in geophysical interpretation of potential fields. The method enables gridding of irregularly distributed observations, continuation of fields upward or downward, and computation of directional derivatives. This approach is commonly limited by the availability of data from a single realization of measurements, which are typically acquired at variable altitudes and on irregular observation grids. In the case of the Valimyaki massif studies multi-altitude aeromagnetic surveying was already performed. The availability of an ensemble of anomalous field realizations obtained from independent measurement levels provides improved constraints for estimating the parameters of equivalent sources. Using data acquired at three altitude levels above the Valimyaki massif, the magnetic field can be continued to a unified elevation above the geoid applying the algorithm reconstruction of the harmonic component of the magnetic field modulus developed in [*Gordin et al.*, 2006]. Moreover, resulting maps of the anomalous magnetic field will be largely free of interpolation artifacts intrinsic to UAV magnetic surveys, primarily high-frequency profile noise and irregular sampling effects, as the spacing along profiles and between profiles differ by up to two orders of magnitude.

The problems of the current stage of the magnetic field inversion for studying the internal structure of the Valimyaki intrusion form the plans for the future geophysical investigations of this area.

5. Conclusion

High-resolution multi-altitude UAV-based aeromagnetic surveying conducted over the Valimyaki intrusive complex has provided new insights on its internal structure and spatial extent. The inversions of the survey data result reveal the presence of a large, sheet-like buried intrusive body of high magnetization with a center of magnetic mass at a depth of approximately 1.5 km. The lateral extent of this body exceeds the geological boundaries of the Valimyaki massif and continues southward toward Mäkisalo Island, suggesting a common deep root system linking the continental and island exposures of the complex. Local magnetic extrema are associated with subvertical apophyses rising from the main stratiform body and locally reaching the surface in areas of pyroxenite outcrops.

Multi-altitude surveying gives new opportunities for geophysical interpretation of the anomalous magnetic field. It enables direct estimation of the vertical magnetic field gradient, which is insensitive to regional field components and free from the constraints inherent to spectral-domain computation methods. In addition, multi-altitude data facilitate cross-verification within inversion procedures and allows to construct more stable and reliable equivalent-source models. The activity on the application of the equivalent source method of anomalous magnetic field transformation has already started with a goal to increase the resolution and reliability of the magnetic inversions.

Future integrated geophysical investigations in the Valimyaki intrusive complex area will provide not only solid grounds to improve the resolution of the magnetic features of the intrusion but also give an opportunity to carry out a modeling of consistent spatial distribution of other physical properties in the interiors to put constraints on the mineral systems associated with this unique magmatic object.

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References

Cheremisina E. N., Finkel'shtein M. Ya., Deev K. V., et al. GIS INTEGRO. Status and prospects for development in the context of import substitution // Geologiya nefti i gaza. — 2021. — No. 3. — P. 31–40. — https://doi.org/10.31087/0016-7894-2021-3-31-40. — (In Russian).

Dolgal A. S., Balk P. I., Demenev A. G., et al. The finite-element method application for interpretation of gravity and magnetic data // Bulletin of Kamchatka Regional Association "Educational-Scientific Center". Earth sciences. — 2012. — 19(1). — P. 108–127. — (In Russian).

Gordin V. M., Tikhotskii S. A. and Shur D. Yu. Reconstruction of the harmonic component of the magnetic field modulus anomalies // Izvestiya, Physics of the Solid Earth. — 2006. — Vol. 42, no. 4. — P. 334–343. — https://doi.org/10.1134/s1069351306040082.

Jackisch R., Heincke B. H., Zimmermann R., et al. Drone-based magnetic and multispectral surveys to develop a 3D model for mineral exploration at Qullissat, Disko Island, Greenland // Solid Earth. — 2022. — Vol. 13, no. 4. — P. 793–825. — https://doi.org/10.5194/se-13-793-2022.

Kobrunov A. I. and Varfolomeev V. A. One approach of density equivalent representation and using it for gravity field interpretation // Izvestiya AN SSSR. Fizika Zemli. — 1981. — No. 10. — P. 25–44. — (In Russian).

Kulyandina A. S., Filippova A. I. and Sokolova E. Yu. Geophysical Imaging of the Crust for the Source Area of the Khastakh Earthquake (NE Margin of the Siberian Platform, Yakutia) // Russian Journal of Earth Sciences. — 2025. — Vol. 25. — ES4008. — https://doi.org/10.2205/2025es001004.

Mitsyn S. V. On numeric implementation of spectral method of gravimetry inverse problem // Geoinformatika. — 2018. — No. 3. — P. 89–97. — (In Russian).

Mitsyn S. V. and Bolshakov E. M. Assembly method in GIS INTEGRO and its usage for solving of gravitational inverse problem // Geoinformatika. — 2021. — No. 3. — P. 36–47. — https://doi.org/10.47148/1609-364x-2021-3-36-47. — (In Russian).

Priezzhev I. I. Spectral and statistical analysis of airborne geophysical data in the ASOM-AGS/EC system. Dissertation of a candidate of technical sciences. — MGRI, 1989. — (In Russian).

Proterozoic Ladoga structure (Geology, deep structure and mineral genesis) / ed. by N. V. Sharov. — Petrozavodsk (Russia) : KarSC RAS, 2020. — 434 p. — (In Russian).

Stepanov K. I., Sanin D. M. and Sanina G. N. State geological map of the Russian Federation scale 1:200,000, second edition, Karelian series, sheets P-35-XXIV, P-36-XIX. Explanatory note. — Moscow (Russia) : VSEGEI, 2013. — 230 p. — (In Russian).

Strakhov V. N. and Lapina M. I. Mounting method for solving the inverse problem of gravimetry // Doklady AN SSSR. — 1976. — Vol. 227, no. 2. — P. 344–347. — (In Russian).

Taran Y. V., Aleshin I. M., Matveev M. A., et al. Preliminary Results of Field Geological and Geophysical Studies of the Vyalimyaki Massif (Northern Ladoga Region) // Izvestiya, Atmospheric and Oceanic Physics. — 2025. — Vol. 61, no. 7. — P. 824–833. — https://doi.org/10.1134/S0001433825701117.