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Volcanic Rocks of the Central Segment of the Vygorlat-Hutynskyi Range: Mineralogical and Petrological Characteristics

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Abstract

The article examines the mineralogical and petrological features of volcanic rocks in the central segment of the Vyhorlat-Hutynskyi Range, using quarries near the villages of Bilky and Ardanovo as representative study sites. The study aims to establish the mineral composition of the andesite-basalts, determine their structural, textural, and petrographic characteristics, and clarify the composition of the principal rock-forming minerals on the basis of microprobe analysis. Particular attention is given to plagioclases and pyroxenes, which are the main mineral components of the investigated volcanic rocks. The methodological basis of the study includes field geological observations, petrographic analysis of thin sections, microscopic investigations, and microprobe analysis of minerals. To determine the mineral composition, optical microscopy methods were applied, and triangular diagrams showing variations in the chemical composition of plagioclases and py-

roxenes were constructed using the Grapher computer program. Comparative and structural-mineralogical approaches were used to interpret the analytical results and establish the petrogenetic features of the volcanic rocks. It was established that the volcanic rocks exposed in the investigated quarries are represented by andesite-basalts with a porphyritic structure and an andesitic groundmass containing fragments of intersertal and pilotaxitic structures. The main rock-forming minerals were identified as plagioclases, represented by labradorite, bytownite, and anorthite, together with orthorhombic and monoclinic pyroxenes. Reaction rims, secondary mineral formations, and ore minerals, particularly magnetite and ilmenite, were also identified, indicating complex crystallization processes and subsequent secondary alteration of the volcanic rocks.

Keywords: andesite-basalts, volcanic rocks, plagioclase, pyroxene, microprobe analysis, petrographic studies

1. INTRODUCTION

Volcanic rocks of the Vyhorlat-Hutynskyi Range constitute an important component of the geological structure of the Transcarpathian internal depression and are of considerable interest for modern mineralogical and petrological research. Neogene volcanism in the Carpathian region played an important role in the formation of the present geological structure of Transcarpathia, and its products are represented by thick sequences of lava flows, tuffs, tuff breccias, and agglomerate breccias. Studying the mineral composition and petrographic features of these rocks makes it possible to establish regularities in the development of magmatic processes, determine the conditions of magma crystallization, and clarify the characteristics of volcanic structure formation within the central segment of the Vyhorlat-Hutynskyi Range.

This problem is particularly important because of the need to clarify the petrological characteristics of andesite-basalts of the Transcarpathian volcanic belt, which are valuable indicators of magmatic processes and the geodynamic evolution of the Carpathian region. Volcanic rocks of the central segment of the Vygorlat-Hutyn Range are characterized by complex structures, considerable mineralogical diversity, and manifestations of secondary alteration, all of which require comprehensive investigation using modern analytical methods. Petrographic and microprobe studies are especially important because they enable detailed examination of rock-forming minerals, determination of their chemical composition, and identification of the genetic features of the volcanic rocks.

Important study sites include quarries in the vicinity of the villages of Bilky and Ardanovo, where andesite-basalt lava flows with characteristic jointing and separation structures are well exposed together with associated tuffs and agglomerate breccias. Field geological observations indicate a complex history of lava-flow formation, expressed by the development of columnar, slab, and coarse-slab separation, as well as by the presence of brecciated marginal parts of the flows. These features make it possible to reconstruct the conditions of lava emplacement and cooling and to trace the subsequent processes of post-magmatic transformation.

Microscopic and microprobe analytical methods play a particularly important role in the study of volcanic rocks. Petrographic investigations make it possible to establish rock structures and textures, determine relationships among minerals, and identify secondary alteration of rock-forming components. Microprobe analysis, in turn, enables detailed determination of the chemical composition of plagioclases, pyroxenes, and ore minerals and supports their classification using compositional variation diagrams. Together, these approaches provide a basis for more accurate characterization of the mineralogical features of andesite-basalts and for interpretation of the conditions under which they formed.

Determination of the mineral composition of volcanic rocks is essential for understanding magmatic differentiation and the evolution of magma chambers within the Vygorlat-Hutyn volcanic chain. The presence of major plagioclase varieties represented by labradorite, bytownite, and anorthite, together with orthorhombic and monoclinic pyroxenes, indicates complex magma-crystallization conditions and changes in the physicochemical parameters of the magmatic environment. The identification of reaction rims, secondary mineral formations, and ore minerals also makes it possible to trace secondary alteration processes and the characteristics of mineral interactions during the cooling and subsequent evolution of lava flows.

Thus, the relevance of this study is determined by the need for a comprehensive investigation of the mineralogical and petrological features of volcanic rocks in the central segment of the Vyhorlat-Hutyn Range, clarification of their mineral composition, and establishment of the regularities governing the formation of andesite-basalt lava flows on the basis of combined petrographic and microprobe studies.

2. LITERATURE REVIEW

The mineralogical and petrological investigation of volcanic rocks of the Vyhorlat-Hutyn Range is an important direction of modern geological research in the Carpathian region. In the scientific literature, volcanic complexes of the Transcarpathian Inner Trough are considered components of Neogene volcanism in the Pannonian-Carpathian region, whose formation is associated with active geodynamic processes, magmatism, and the evolution of the Carpathian folded system [1–3]. Researchers emphasize that volcanic rocks of the Vyhorlat-Hutyn Range display a complex mineralogical structure and considerable diversity of magmatic series, reflecting the multistage formation of volcanic structures throughout the region.

A substantial body of research is devoted to the geological structure and petrology of the Transcarpathian volcanic belt. In the study by Vovkunovych et al. [4], the regional geological setting is considered in relation to the development of the Transcarpathian area. In broader petrological interpretations, andesite-basalt rocks of the Vygorlat-Hutyn Range are treated as products of magmatic differentiation associated with the evolution of calc-alkaline magmatic series. The mineral composition and textures of volcanic rocks can therefore provide evidence for reconstructing magma-chamber conditions, lava-flow cooling histories, and post-magmatic transformations.

A separate area of research concerns the petrographic analysis of andesite-basalts. Analysis of the works of Dias et al. [5], Askaripour et al. [6], and Ghorbani [7] demonstrates the importance of petrographic methods for characterizing

rock structure, texture, mineral composition, and related physical properties. In volcanic-rock studies, andesite-basalts commonly display porphyritic structures, andesitic or pilotaxitic groundmass textures, and phenocrysts of plagioclase and pyroxene. Relationships among the principal rock-forming minerals provide important information for identifying stages of magma crystallization and evaluating the physicochemical conditions under which volcanic rocks formed.

A significant body of research is also devoted to the mineralogical characteristics of plagioclases and pyroxenes in volcanic and related rocks. The studies of Fereidooni [8], Setiawati et al. [9], and Barthez et al. [10] illustrate the importance of mineralogical composition and plagioclase characteristics in interpreting rock properties and geological processes. The proportions of anorthite, albite, and orthoclase components in feldspars can provide information on compositional variation and magmatic evolution. Likewise, the occurrence of orthorhombic and monoclinic pyroxene varieties is important for interpreting crystallization sequences, cooling conditions, and subsequent mineral transformations in volcanic rocks.

Modern researchers devote considerable attention to microanalytical methods in the study of volcanic rocks. Salimian et al. [11] and Iltireh and Kadioğlu [12] demonstrate the analytical value of electron-microprobe techniques for determining mineral chemistry, while Leichter et al. [13] illustrates the growing use of advanced analytical and computational approaches in petrographic studies. Electron microprobe analysis provides high-precision compositional data and can be used to investigate crystal zoning, reaction boundaries, and secondary mineral alteration. In combination with compositional diagrams, these data are useful for classifying plagioclases and pyroxenes and for interpreting genetic features of volcanic rocks.

Another important area of research concerns ore and accessory minerals associated with volcanic and hydrothermally altered rocks. The works of Miladinović et al. [14] and Baba-zadeh et al. [15] provide mineralogical and geochemical information relevant to volcanic complexes and ore-forming environments. Minerals such as magnetite, ilmenite, and other oxide phases can serve as useful indicators of redox conditions and may provide additional constraints on the physicochemical evolution of magmatic and post-magmatic systems.

Considerable attention in modern literature is also given to the structural characteristics and emplacement behavior of lava flows. Hartmann et al. [16], Dietterich et al. [17], and Harris et al. [18] analyze different aspects of lava-flow structure, emplacement, cooling, and post-emplacement modification. The morphology and internal organization of lava bodies are closely related to cooling rate, flow dynamics, rheological conditions, and interactions with the surrounding environment. Brecciation and associated volcanoclastic material in marginal zones may therefore provide important evidence for reconstructing the evolution of individual lava flows.

Thus, analysis of the scientific literature shows that, despite the substantial amount of research devoted to volcanic rocks of the Transcarpathian region, the mineralogical and petrological characteristics of andesite-basalts in the central segment of the Vyhorlat-Hutynskyi Range remain insufficiently characterized in an integrated manner. Particular attention should therefore be given to the combined use of petrographic and microprobe investigations to clarify mineral composition, crystallization features, and the formation conditions of volcanic rocks exposed in quarries near the villages of Bilky and Ardanovo.

3. MATERIALS AND METHODS

The research is based on a comprehensive investigation of volcanic rocks from the central segment of the Vyhorlat-Hutyn Range using field-geological observations, petrographic methods, and electron microprobe analysis. The information base of the study includes results of field investigations conducted in quarries near the villages of Bilky and Ardanovo, microscopic examination of petrographic sections, electron-microprobe data for rock-forming minerals, and scientific publications addressing mineralogical, petrological, and volcanological problems of the Carpathian region.

The methodological basis of the study is an integrated mineralogical-petrological approach that combines field observations, petrographic analysis, and investigation of mineral chemical composition in order to establish the formation characteristics of andesite-basalt rocks. Application of this approach made it possible to trace relationships among structural and textural features, mineral composition, and crystallization conditions and to interpret these characteristics within a coherent petrological framework.

During the field stage, geological methods for describing volcanic outcrops were applied to establish the morphological characteristics of lava flows, the nature of their separation or jointing, and the spatial distribution of volcanic formations. Field observations included descriptions of andesite-basalt flows, tuffs, tuff breccias, and agglomerate breccias; identification of columnar, slab, and coarse-slab separation; and documentation of features characteristic of the marginal parts of lava flows. Representative samples of volcanic rocks were then selected for subsequent laboratory investigation.

Petrographic analysis of thin sections was used to determine the mineral composition and structural and textural characteristics of the rocks. Microscopic investigations were carried out in transmitted light using a polarizing microscope. This approach made it possible to identify the principal rock-forming minerals, determine their spatial relationships, characterize the structures and textures of the andesite-basalts, and document manifestations of secondary alteration. Particular attention was paid to phenocrysts of plagioclase, orthorhombic and monoclinic pyroxenes, olivine, and ore

minerals.

Electron microprobe analysis was used to clarify the chemical composition of the principal rock-forming minerals. For this purpose, polished sections were prepared from the selected rock material, and their surfaces were carefully polished to ensure measurement accuracy. Microprobe investigations made it possible to determine the contents of major oxides in plagioclases and pyroxenes, including Na_2O , MgO , Al_2O_3 , SiO_2 , K_2O , CaO , TiO_2 , MnO , and FeO . The resulting analytical data provided the basis for mineral classification and for interpretation of their compositional and genetic characteristics.

To interpret the microprobe results, triangular diagrams showing variations in mineral chemical composition were constructed using the Grapher computer program. These diagrams made it possible to identify compositional groups of plagioclases and pyroxenes, determine relationships among their principal components, and classify the minerals according to established mineralogical schemes. The approach allowed pyroxenes to be separated into orthorhombic and monoclinic varieties and showed that the analyzed plagioclases are represented mainly by labradorite, bytownite, and anorthite.

A comparative method was used to evaluate the results of field, petrographic, and microprobe investigations of volcanic rocks from the quarries near Bilky and Ardanovo. This comparison made it possible to identify common and distinctive features of mineral composition, structural characteristics, and secondary alteration processes in the andesite-basalts of the central segment of the Vygorlat-Hutynskyi Range and to assess similarities between the two investigated localities.

Methods of analysis, synthesis, and systematic generalization were used to integrate the obtained results. These methods made it possible to establish regularities in the formation of the investigated volcanic rocks, characterize features of magma crystallization, and trace manifestations of post-magmatic transformation. Particular attention was given to relationships among mineral composition, structural characteristics, and the inferred formation conditions of the lava flows.

Microscopic and microprobe investigations were carried out in the Laboratory of Physics and Technology of Nanostructures, Department of Solid State Physics, Faculty of Physics, Ivan Franko National University of Lviv. The resulting data provide a comprehensive basis for mineralogical and petrological characterization of andesite-basalts from the central segment of the Vygorlat-Hutyn Range and support further investigation of volcanic rocks throughout the Transcarpathian region.

4. RESULTS

The investigated quarry is located near the village of Bilky on the right bank of the Perekop River and represents one of the characteristic outcrops of volcanic rocks in the central segment of the Vygorlat-Hutynskyi Range. In the upper part of the section, corresponding to the roof of the lava flow, tuffs and tuff breccias composed of clastic volcanogenic material of variable grain size were identified (Figure 1a). The presence of these tuff breccias indicates that explosive volcanic processes accompanied the formation and emplacement of the volcanic complex.



a)



b)

Figure 1. Tuff breccia fragments that make up the roof of the lava flow (a) and andesite-basalt outcrops of the Bilky quarry (b)

Source: authors' own development

The central part of the Bilky quarry is composed of massive dark-gray volcanic rocks affected by intense fracturing (Figure 1b). Macroscopically, the rocks are characterized by a dense structure and by a well-developed fracture system, which most likely reflects both cooling-related contraction of the lava flow and subsequent tectonic influences on the exposed volcanic body.

Petrographic examination of the sections made it possible to establish the mineral composition and structural and textural characteristics of the volcanic rock. The phenocryst assemblage is dominated by relatively large plagioclase crystals (Figure 2) accompanied by smaller grains of orthorhombic and monoclinic pyroxene. The abundance of monoclinic

pyroxene is approximately comparable to, or slightly greater than, that of orthorhombic pyroxene in the studied material.

A characteristic feature of the orthorhombic pyroxene is the development of reaction rims composed of monoclinic pyroxene, indicating changes in the physicochemical conditions during magma crystallization. Isolated olivine grains were also identified in the sections; they are characterized by an approximately isometric form, imperfect cleavage, and straight extinction. The groundmass consists predominantly of plagioclase microlites, volcanic glass, and monoclinic pyroxene. Opacitic rims are developed around some pyroxene grains, indicating secondary mineral alteration during cooling or later post-magmatic transformation. Iron hydroxides are also present, whereas ore minerals are only rarely observed in the conventional petrographic sections.

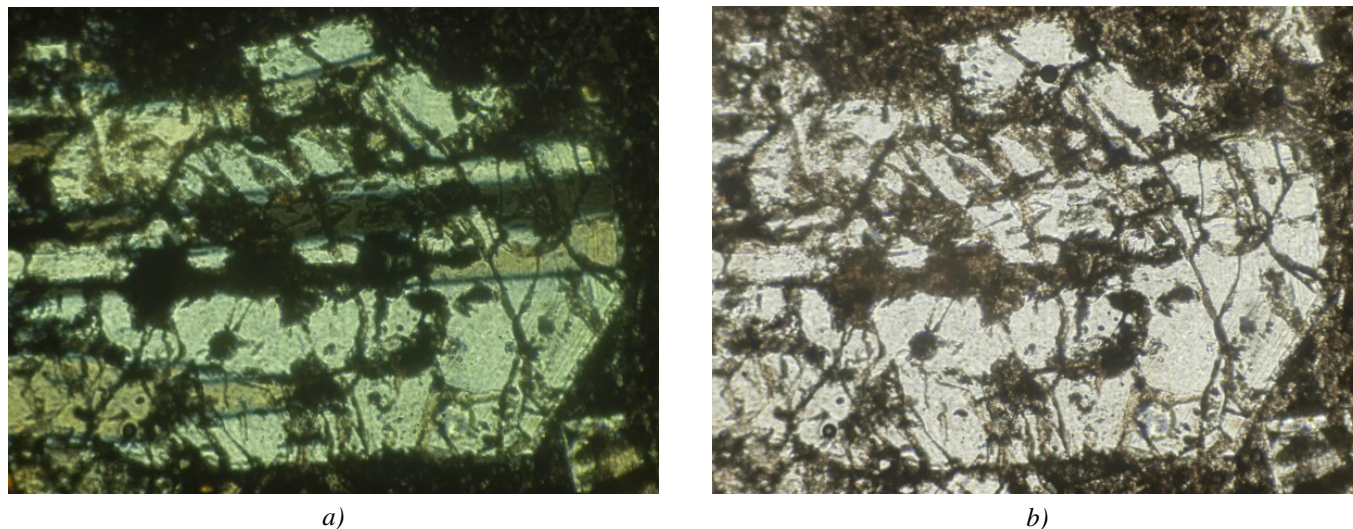


Figure 2. *Plagioclase phenocryst in volcanic rock from the quarry in the village of Bilky*

Source: authors' own development

The rock is characterized by a porphyritic structure, whereas the groundmass is andesitic and locally contains fragments of an intersertal structure. The combined mineralogical, structural, and textural characteristics therefore allow the investigated volcanic rock to be classified as andesite-basalt.

For electron microprobe investigation, polished sections were prepared from the selected rock material (Figure 3). Careful polishing of the analytical surfaces provided suitable conditions for high-precision determination of the chemical composition of individual rock-forming mineral phases and for reliable comparison of the obtained microanalytical results.



Figure 3. *Selected rock material and polished section prepared for microprobe analysis (Bilky village)*

Source: authors' own development

Microprobe investigations made it possible to characterize the chemical composition of both rock-forming and ore minerals in the andesite-basalts. Intergrowths of ilmenite and magnetite were recorded in the analyzed samples (Figure 4), indicating complex crystallization conditions in the magmatic melt and variations in the redox regime during the evolution of the magmatic system.

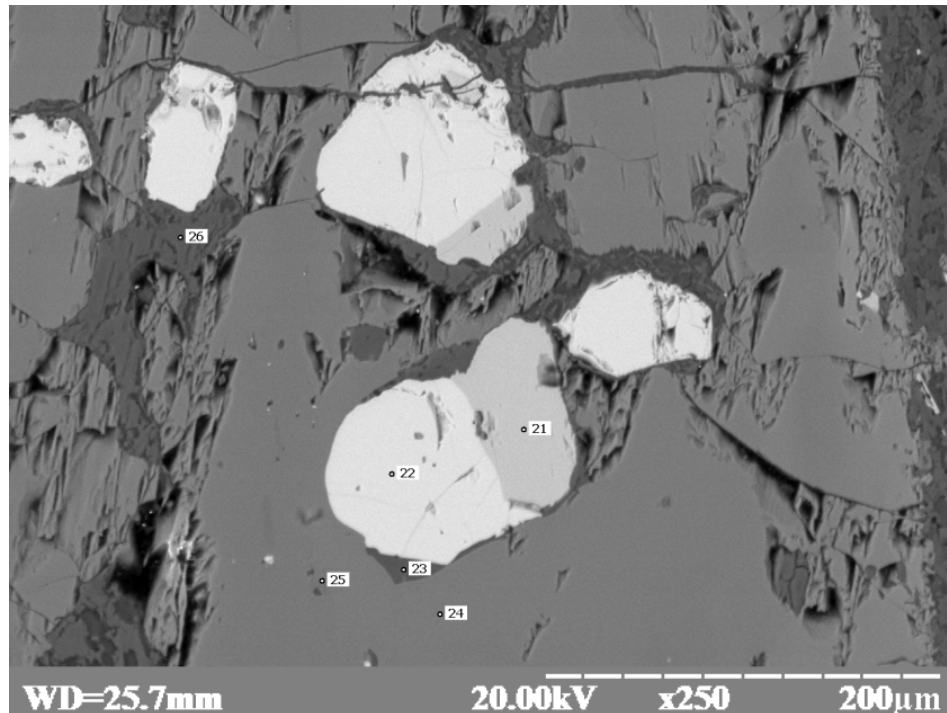


Figure 4. Intergrowth of the ore minerals ilmenite and magnetite in andesite-basalt from the Bilky village quarry

Source: authors' own development

Examination of the polished sections enabled detailed analysis of the microstructural relationships among individual mineral phases. In particular, phenocrysts of plagioclase and pyroxene are clearly distinguishable in the rock structure and occur in close association with finely dispersed inclusions of the magnetite ore phase (Figure 5). These relationships provide additional evidence for interpreting the crystallization sequence and subsequent mineral-scale transformations.

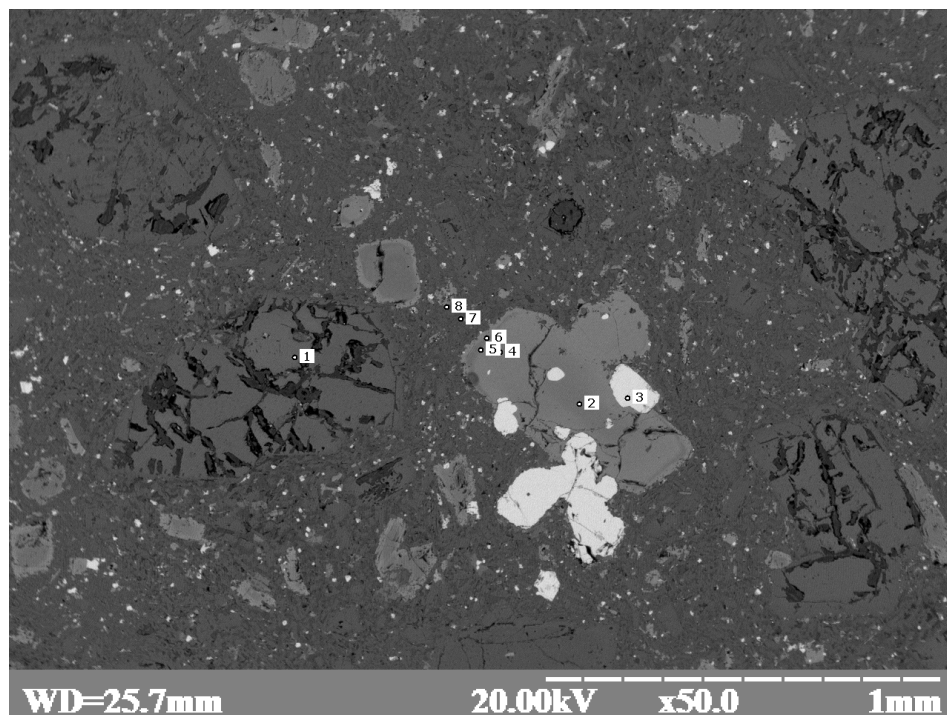


Figure 5. Plagioclase and pyroxene phenocrysts with inclusions of the ore mineral magnetite in andesite-basalt from the Bilky village quarry

Source: authors' own development

The results of the microprobe analyses of plagioclases and pyroxenes are presented in Tables 1 and 2. The analytical data characterize the contents of the principal oxides in the investigated minerals, including Na₂O, MgO, Al₂O₃, SiO₂, K₂O, CaO, TiO₂, MnO, and FeO. Analysis of plagioclase composition revealed substantial variation in the proportions of calcium- and sodium-bearing components, indicating the presence of compositionally different plagioclase varieties within the andesite-basalts. The relatively high CaO and Al₂O₃ contents in most analyses are consistent with the predominance of calcium-rich plagioclase members.

Table 1. Chemical composition of plagioclases (wt. %) from Bilky village

Sample No.	Analysis No.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	MnO	FeO	Σ
Bilk-12	1	0.92	0.83	34.46	45.11	0.00	18.49	0.01	0.33	100.14
Bilk-12	7	4.08	0.72	28.90	56.06	0.41	11.59	0.00	0.74	102.51
Bilk-12	9	3.97	0.89	29.06	55.15	0.25	11.90	0.06	0.79	102.07
Bilk-12	14	1.33	0.76	32.96	48.15	0.28	16.97	0.00	0.07	100.53
Bilk-12	26	2.94	0.60	29.94	52.77	0.30	12.86	0.00	1.15	100.55
Bilk-12	44	4.50	0.58	27.31	52.67	0.31	10.12	0.00	0.76	96.26
Bilk-12	36	4.49	0.69	29.13	55.83	0.44	11.24	0.00	0.49	102.30
Bilk-12	31	3.39	0.81	28.57	53.16	0.31	12.26	0.00	0.39	98.89

Source: authors' own development

Table 2. Chemical composition of pyroxenes (wt. %) from Bilky village

Sample No.	Analysis No.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	FeO	Σ
Bilk-12	4	0.00	16.57	0.82	50.42	0.08	1.33	0.08	0.70	24.86	94.86
Bilk-12	5	0.00	20.61	1.75	51.06	0.05	1.63	0.33	0.40	19.34	95.16
Bilk-12	6	0.00	13.36	0.59	47.85	0.00	4.01	0.38	1.23	25.25	92.67
Bilk-12	8	0.00	13.08	0.51	49.52	0.11	4.89	0.19	0.70	25.41	94.40
Bilk-12	16	0.00	19.03	0.78	34.06	0.00	0.37	0.92	0.37	32.29	87.82
Bilk-12	17	0.21	22.61	2.43	53.23	0.06	1.59	0.29	0.44	19.42	100.28
Bilk-12	18	0.00	16.68	0.43	52.16	0.13	1.59	0.00	1.06	26.41	98.45
Bilk-12	19	0.00	19.52	0.74	33.08	0.00	0.42	0.43	0.59	33.21	87.99
Bilk-12	20	0.00	28.08	0.02	37.12	0.15	0.13	0.36	0.34	30.75	96.97
Bilk-12	24	0.00	19.25	1.50	51.81	0.00	1.20	0.03	0.53	21.80	96.37
Bilk-12	2	0.00	20.19	0.61	51.85	0.15	1.20	0.00	0.54	19.89	94.43

Source: authors' own development

The pyroxene analyses show substantial variation in the relative contents of MgO, FeO, and CaO, allowing the presence of both orthorhombic and monoclinic pyroxene varieties to be traced. Higher FeO contents in some analyses indicate more iron-rich pyroxene compositions, whereas elevated MgO contents characterize more magnesian phases that likely formed during earlier stages of crystallization of the magmatic melt. The generally low contents of TiO₂ and MnO reflect minor isomorphous substitutions within the mineral structures and provide additional information on the physicochemical conditions of crystallization.

The obtained microprobe data were subsequently used to construct triangular diagrams showing variations in mineral chemical composition with the Grapher software package (Figure 6). These diagrams provide a convenient graphical basis for comparing the compositional relationships among the analyzed plagioclase and pyroxene grains.

The triangular diagrams were used to classify plagioclases according to the proportions of albite, anorthite, and orthoclase components and to classify pyroxenes according to the En–Fs–Wo system. Plotting the analytical points on these diagrams made it possible to identify compositional groupings of the mineral phases, evaluate patterns in their distribution, and clarify their genetic relationships with the processes of magmatic differentiation and crystallization.

According to the constructed diagrams (Figure 6), the plagioclases in the investigated andesite-basalts are represented mainly by calcium-rich varieties, particularly labradorite, bytownite, and anorthite. Their compositions are consistent with crystallization from a relatively high-temperature, comparatively basic magmatic melt. The pyroxenes form two principal groups, orthorhombic and monoclinic. Orthorhombic pyroxene is represented mainly by hypersthene, whereas pigeonite predominates among the monoclinic varieties. This mineral assemblage is characteristic of andesite-basalt rocks and records the complex physicochemical evolution of the magmatic environment.

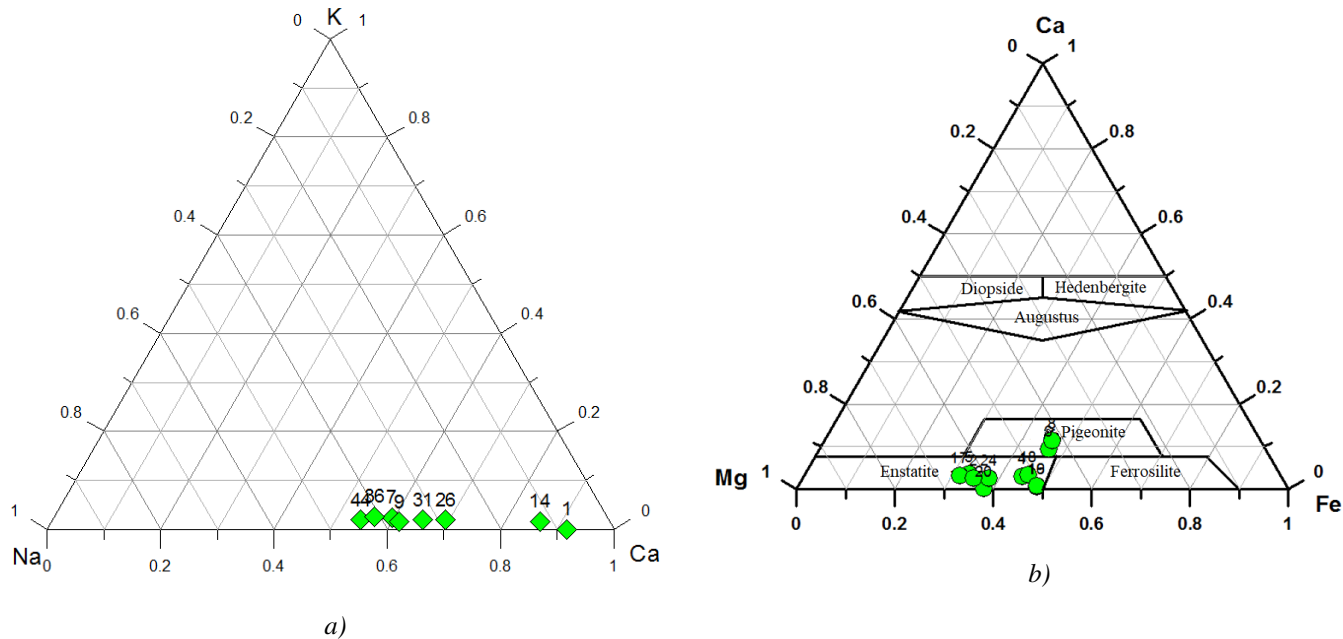


Figure 6. Variations in the chemical composition of plagioclases (a) and pyroxenes (b), constructed from microprobe data for volcanic rocks from the Bilky quarry

Source: authors' own development

The quarry located northwest of the village of Ardanovo, on the right bank of the Sobatyn River, a tributary of the Irshava River, is an important geological site for studying volcanogenic formations of the Transcarpathian region. In geostructural terms, the area lies within the zone of Neogene volcanic development, which determines the specific lithological composition and the structural and textural characteristics of the exposed rocks. The outcrop is approximately 250 m long and reaches a height of about 50 m, providing excellent exposure for detailed geological and field-based analysis (Figure 7).



Figure 7. General view of the quarry in the northern outskirts of the village of Ardanovo

Source: authors' own development

The lithological structure of the section shows clear vertical differentiation. In the lower part of the outcrop, volcanic rocks display columnar separation, with individual columns reaching approximately 6 m in diameter. This morphology is typical of relatively slow cooling in massive parts of lava flows and reflects thermal contraction during solidification. In the upper part of the section, the rocks pass into plate-like separation, indicating a change in cooling conditions

and, in particular, a higher rate of heat transfer. Another important feature is the occurrence of crescent-shaped lava tongues oriented from west to east, which helps reconstruct both the direction of lava movement and the dynamics of flow emplacement.

Within the lava-flow wedging zone, which is clearly exposed in the quarry wall, rocks displaying coarse-plate separation are observed (Figure 8a). This structural feature marks an important transition within the internal architecture of the lava flow.



Figure 8. Coarse-plate separation in andesite-basalt (a) and the marginal part of the lava flow (b)

Source: authors' own development

At a distance of approximately 100 m from this section, the character of the separation changes to a more tabular form, reflecting a gradual transition from the central toward the peripheral parts of the lava flow. Along the outcrop, a systematic change in separation morphology can be traced from subhorizontal plate-like bodies to more cylindrical forms, which are characteristic of the marginal portions of the flow (Figure 8b).

These structural features indicate a complex combination of lava crystallization, thermal contraction, and deformation processes operating while the lava body cooled and interacted with its surrounding geological environment.

Additional evidence supporting interpretation of the marginal part of the lava flow is provided by the presence of tuffs and agglomerate breccias, whose fragments reach sizes of up to approximately 50 cm (Figure 9). Such volcanoclastic formations may result from fragmentation of lava and interaction with a gas-rich environment, indicating explosive or mixed volcanic conditions during emplacement. Taken together, the field observations make it possible to reconstruct the formation conditions and internal structural organization of the investigated lava flow in greater detail.



Figure 9. Fragments of agglomerate breccia and tuff from the Ardanovo village area

Source: authors' own development

Petrographic investigations performed by optical microscopy made it possible to establish the mineral composition and structural and textural characteristics of the rocks. Plagioclase forms the dominant phenocryst phase and commonly shows secondary alteration accompanied by the development of carbonate material, indicating post-magmatic hydrothermal processes. Orthorhombic and monoclinic pyroxenes occur in subordinate amounts. Some monoclinic pyroxenes are surrounded by reaction rims composed of secondary actinolite, suggesting metasomatic transformation under conditions of enhanced fluid activity. Olivine is also present locally and is partly altered, in some cases being preserved only as pseudomorphic forms.

The rock is characterized by a porphyritic structure produced by relatively large phenocrysts enclosed within a fine-grained groundmass. The groundmass has an andesitic structure with local pilotaxitic fragments, reflecting the oriented arrangement of plagioclase microlites within a glassy or cryptocrystalline matrix (Figure 10). These textural relationships are consistent with rapid cooling of the residual melt after earlier phenocryst crystallization.

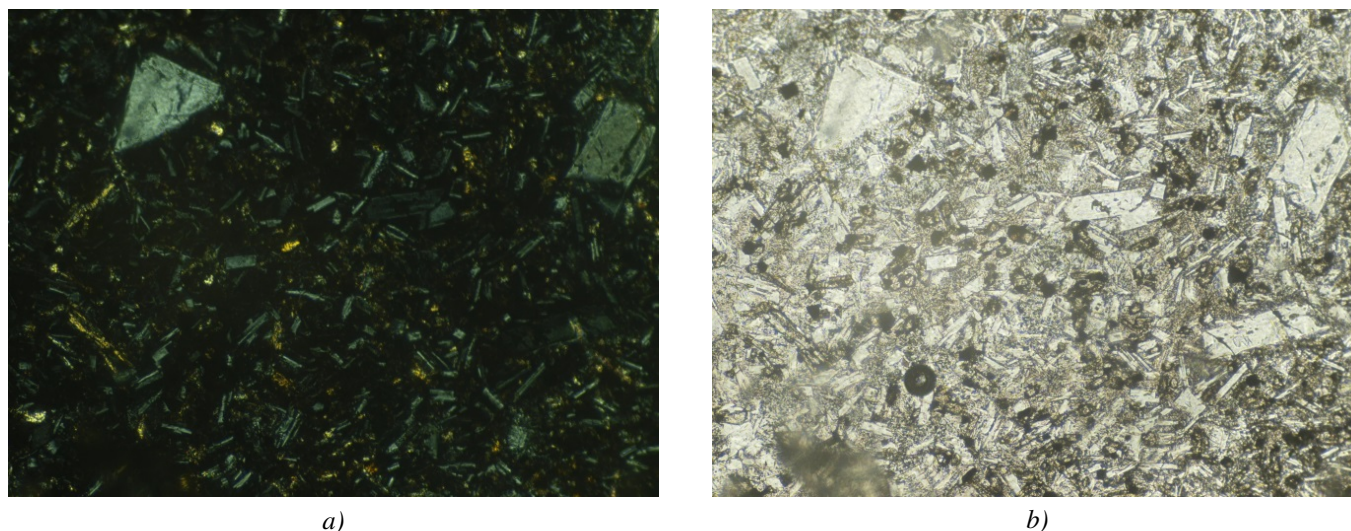


Figure 10. Andesitic structure of the andesite-basalt groundmass from the Ardanovo village area

Source: authors' own development

The combination of these mineralogical, structural, and textural features makes it possible to classify the investigated rock as andesite-basalt and is consistent with the observed composition of its phenocryst assemblage and fine-grained groundmass.



Figure 11. Selected rock material and polished section prepared for microprobe analysis (Ardanovo village)

Source: authors' own development

To improve the accuracy of mineral-composition determination, polished cross sections were prepared from the selected rock material (Figure 11) and subsequently examined by electron microprobe analysis (Figure 12). This analytical approach makes it possible to obtain quantitative chemical data for individual mineral phases at high spatial resolution and to evaluate compositional differences among adjacent grains and inclusions.

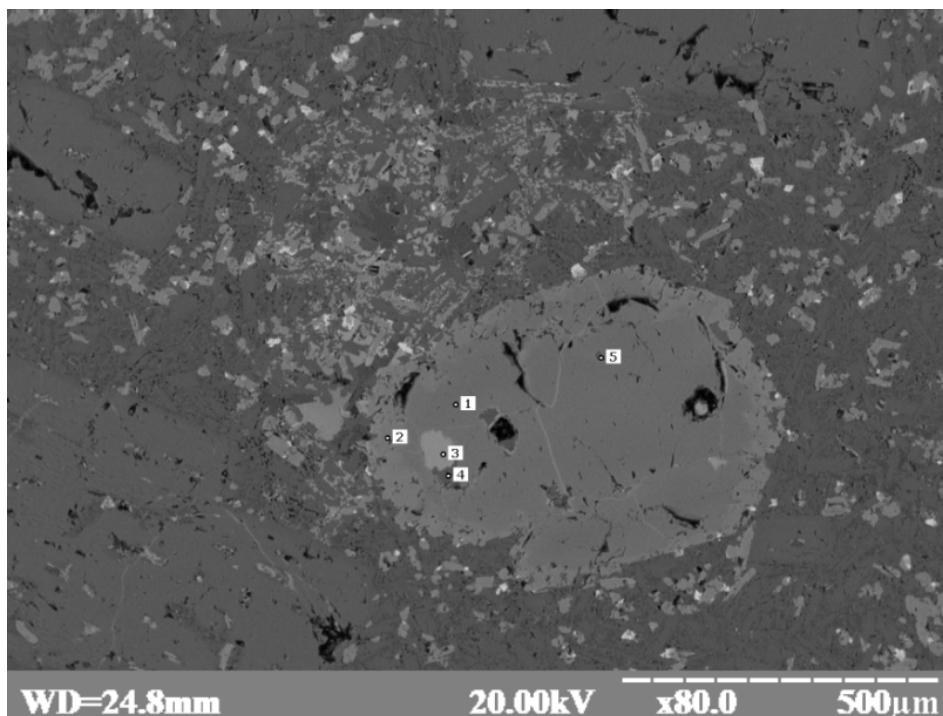


Figure 12. Pyroxene phenocryst with inclusions of plagioclase and the ore mineral magnetite in andesite-basalt from the Ardanovo village area

Source: authors' own development

The microprobe results presented in Tables 3 and 4 demonstrate compositional variations in plagioclases and pyroxenes from the Ardanovo material and provide the analytical basis for subsequent mineral classification and graphical interpretation.

Table 3. Chemical composition of plagioclases (wt. %) from the village of Ardanovo

Sample No.	Analysis No.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	FeO	Σ
AR15-1	4	4.14	0.85	25.25	52.03	0.73	9.94	0.03	0.05	1.15	94.16
AR15-1	9	3.95	0.82	26.53	52.90	0.71	10.41	0.12	0.00	1.23	96.67
AR15-1	25	2.19	1.01	31.10	48.46	0.25	14.64	0.00	0.00	0.73	98.38
AR15-1	30	4.63	0.75	25.07	51.95	0.48	10.04	0.00	0.04	0.94	93.90
AR15-1	28	2.66	0.93	31.08	47.97	0.16	14.20	0.00	0.00	0.55	97.54

Source: authors' own development

Table 4. Chemical composition of pyroxenes (wt. %) from the village of Ardanovo

Sample No.	Analysis No.	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	FeO	Σ
AR15-1	1	0.00	22.84	1.82	50.98	0.11	1.37	0.34	0.62	15.94	94.02
AR15-1	2	0.12	17.73	0.61	51.14	0.14	3.84	0.30	0.49	21.80	96.16
AR15-1	7	0.00	14.99	0.55	49.07	0.00	3.84	0.41	0.86	22.72	92.46
AR15-1	10	0.21	8.37	0.32	45.21	0.03	3.63	0.18	1.19	31.72	90.87
AR15-1	14	0.00	20.42	1.82	50.14	0.01	1.54	0.23	0.26	20.23	94.65

Source: authors' own development

In particular, the analyzed plagioclases show a broad range of calcium- and sodium-bearing components, allowing them to be assigned to relatively calcium-rich members of the plagioclase series. The pyroxenes display pronounced variation in magnesium, iron, and calcium contents, reflecting compositional diversity associated with different stages and physicochemical conditions of crystallization.

On the basis of the data presented in Table 3 and Table 4, triangular diagrams of chemical-composition variation were constructed using Grapher software (Figure 13). The distribution of analytical points on these diagrams makes it possible to distinguish orthorhombic and monoclinic pyroxenes and to determine the positions of plagioclases within the relevant compositional series. In particular, the plagioclases are represented mainly by labradorite and bytownite, both belonging to the more calcium-rich part of the plagioclase series.

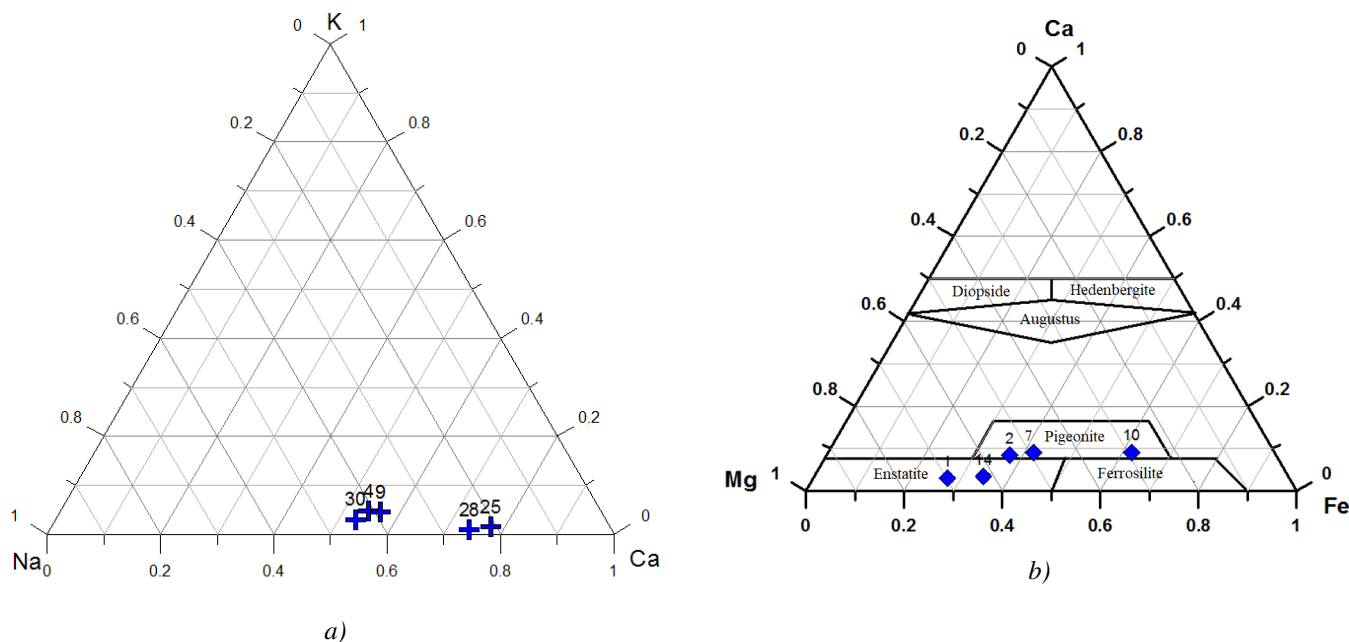


Figure 13. Variations in the chemical composition of plagioclases (a) and pyroxenes (b), constructed from microprobe data for volcanic rocks from the Ardanovo quarry

Source: authors' own development

The orthorhombic pyroxenes are represented by bronzite and hypersthene, whereas the monoclinic pyroxenes are represented predominantly by pigeonite. This mineral assemblage is characteristic of the investigated andesite-basalt rocks and reflects the conditions of mineral crystallization both within the magma reservoir and during subsequent emplacement and cooling of the lava flow.

Thus, the integrated combination of field observations, petrographic investigations, microprobe analyses, and graphical interpretation provides a comprehensive characterization of the geological and mineralogical features of the quarry near the village of Ardanovo. The obtained results are important for reconstructing the formation conditions of volcanic rocks in the region and provide a useful analytical basis for subsequent geodynamic, mineralogical, and petrogenetic investigations.

Microscopic and microprobe investigations were performed in the Laboratory of Physics and Technology of Nanostructures, Department of Solid State Physics, Faculty of Physics, Ivan Franko National University of Lviv. The use of these laboratory facilities supported a high level of analytical precision and strengthened the reliability and reproducibility of the mineral-composition data obtained during the study.

5. DISCUSSION

The results obtained from petrographic and microprobe investigations of volcanic rocks from quarries near the villages of Bilky and Ardanovo substantially clarify the conditions under which andesite-basalts of the central segment of the Vyhorlat-Hutynskyi Range formed. The combined data also make it possible to compare the investigated rocks with broader petrological interpretations of Neogene volcanism in the Carpathian region and to identify both local characteristics and features of wider regional significance.

First, the mineral composition established from petrographic observations and microprobe data (Figures 2, 10; Tables 1–4) is consistent with the interpretation of the studied rocks as andesite-basalts belonging to a calc-alkaline volcanic association. Petrographic characterization provides the principal basis for identifying mineral relationships and textural features in such rocks, as illustrated by analytical approaches discussed by Dias et al. [5]. The dominance of calcium-rich plagioclases, including labradorite, bytownite, and anorthite, together with both orthorhombic and monoclinic pyroxenes (Figures 6, 13), indicates high-temperature crystallization followed by a more complex evolutionary history of the magmatic system.

Variations in the chemical composition of plagioclases indicate compositional heterogeneity and multistage crystallization. In particular, the elevated contents of CaO and Al₂O₃ in many analyses (Tables 1, 3) are consistent with early crystallization of calcium-rich plagioclase from a comparatively basic melt. More sodium-rich compositions may reflect later magmatic differentiation, changing crystallization conditions, or possible interaction between melts of different compositions. The broader importance of mineralogical and textural characteristics for interpreting rock properties and evolutionary processes is emphasized by Fereidooni [8] and Ghorbani [7], although the specific compositional interpretation

presented here is based directly on the microprobe data obtained in this study.

The identification of two principal pyroxene groups is also important and is expressed both in petrographic observations (Figure 2) and in the microprobe results (Tables 2, 4; Figures 6, 13). Orthorhombic pyroxenes, including hypersthene and bronzite, are interpreted as relatively early crystallization phases, whereas monoclinic pigeonite represents a compositionally distinct pyroxene group associated with subsequent stages of melt evolution. Reaction rims around some crystals indicate changes in thermodynamic and chemical conditions, including temperature, melt composition, and fluid activity, during the later evolution of the magmatic system.

Particular attention should be given to the ore minerals represented by magnetite and ilmenite. Their occurrence and intergrowth relationships indicate variations in the redox conditions of the magmatic environment and provide additional evidence for changes during crystallization and post-magmatic evolution. The regional geological framework of the Transcarpathian Basin and associated magmatic systems is discussed by Kitchka et al. [3]; within this broader context, the magnetite-ilmenite assemblage observed in the present samples supports interpretation of the studied andesite-basalts as products of a chemically evolving magmatic system. More detailed oxybarometric calculations would be required to quantify oxygen-fugacity conditions reliably.

The structural and textural characteristics of the rocks also have important petrogenetic significance. The porphyritic structure, together with an andesitic groundmass containing local intersertal and pilotaxitic elements, indicates a two-stage crystallization history: relatively slow formation of phenocrysts in a subsurface magma reservoir followed by more rapid cooling and crystallization of the residual melt during lava emplacement. This interpretation is consistent with the general development of porphyritic andesite-basalt lava flows and with the contrasting grain sizes observed between phenocrysts and groundmass.

Interpretation of the field data provides additional information on the internal structure and cooling history of the lava flows. Columnar, plate-like, and coarse-plate separation reflect different thermal and mechanical regimes during solidification. Columnar separation is generally associated with contraction during relatively uniform cooling of massive parts of a flow, whereas plate-like and coarse-plate forms are more characteristic of zones affected by stronger thermal gradients or marginal deformation. The occurrence of breccia formations and tuffs (Figure 9) further indicates interaction between lava, fragmented volcanic material, gases, and the surrounding environment and may record locally complex eruptive or emplacement processes.

Comparative analysis of the Bilky and Ardanovo quarries indicates a close mineralogical and petrological relationship between the two investigated volcanic occurrences. Despite several differences in structural and textural characteristics, the principal mineral assemblages and chemical features of the rocks are broadly similar (Tables 1–4). These similarities suggest formation within a common regional magmatic system or within genetically related magmatic centers that developed under comparable physicochemical conditions.

At the same time, secondary alteration features, including carbonatization of plagioclase, development of actinolite reaction rims, and opacitic alteration of pyroxenes, demonstrate a significant influence of post-magmatic processes, particularly hydrothermal activity. These modifications complicate reconstruction of the completely primary mineral assemblage, but they also provide valuable information on the evolution of the geological environment after the main stage of magma crystallization and lava emplacement had ended.

Thus, the results indicate that the andesite-basalts of the central segment of the Vyhorlat-Hutyn Range formed through a complex, multistage magmatic evolution involving crystallization in a magma reservoir, emplacement as lava flows, comparatively rapid cooling of the groundmass, and subsequent post-magmatic alteration. The integrated use of petrographic observations and microprobe data not only clarifies the mineralogical and petrological characteristics of the investigated rocks but also contributes to a more detailed understanding of the processes responsible for the development of volcanic structures within the Vyhorlat-Hutyn Range as a whole.

6. CONCLUSIONS

The study established that the investigated volcanic rocks are represented by andesite-basalts characterized by a porphyritic structure and an andesitic groundmass containing local intersertal and pilotaxitic elements. These structural and textural relationships indicate a two-stage crystallization history in which phenocrysts formed before the finer-grained groundmass and record contrasting cooling conditions during the evolution and emplacement of the magmatic melt.

The principal rock-forming minerals were determined to be plagioclases and pyroxenes. The plagioclase assemblage is represented mainly by calcium-rich varieties, particularly labradorite, bytownite, and anorthite, as confirmed by the microprobe results and compositional diagrams. These mineral compositions are consistent with crystallization from a relatively high-temperature magmatic melt of comparatively basic composition and with subsequent compositional evolution during cooling.

Two principal types of pyroxene were identified: orthorhombic pyroxenes represented by hypersthene and bronzite, and monoclinic pyroxene represented mainly by pigeonite. Their coexistence reflects the multistage character of magma

crystallization and changes in the physicochemical conditions of the melt during the progressive evolution of the volcanic system.

Ore minerals represented predominantly by magnetite and ilmenite were identified, including characteristic intergrowths between these phases. Their presence provides evidence for variable redox conditions during mineral formation and records additional aspects of the physicochemical evolution of the magmatic and post-magmatic environment.

Field investigations revealed several characteristic structural features of the lava flows, including columnar, slab-like, and coarse-slab separation, together with tuffs and agglomerate breccias in marginal parts of the volcanic bodies. These observations indicate complex emplacement and cooling conditions involving variations in heat transfer, mechanical contraction, fragmentation, and interaction between lava and the surrounding environment.

Variations in the chemical composition of plagioclases and pyroxenes reflect the processes of magmatic differentiation and changing crystallization conditions and may also be compatible with interaction or mixing between compositionally distinct melts. These features confirm the complex and multistage nature of the evolution of the investigated magmatic system.

Secondary mineral alterations were also documented, including carbonatization of plagioclases, formation of actinolite-bearing reaction rims around pyroxenes, and opacitic alteration. These features indicate the influence of post-magmatic hydrothermal and fluid-related processes that affected the rocks after their primary crystallization and emplacement.

Comparative analysis of the results obtained for the Bilky and Ardanovo quarries demonstrates substantial mineralogical and petrological similarity between the two localities. This similarity supports interpretation of the investigated rocks as products of a single regional magmatic system or of genetically related magmatic centers within the central segment of the Vygorlat-Hutynskyi Range.

The obtained results expand current understanding of the conditions under which andesite-basalts of the Transcarpathian volcanic belt formed and provide a basis for further investigation of the petrogenesis, geodynamic evolution, mineralogical specialization, and post-magmatic alteration of volcanic rocks in this region.

Overall, the conducted study confirms the complex and multistage nature of volcanic-rock formation in the central segment of the Vygorlat-Hutyn Range and demonstrates the value of combining field observations, petrographic analysis, and electron microprobe methods for a comprehensive reconstruction of mineral composition, crystallization history, and lava-flow evolution.

AUTHORSHIP AND CONTRIBUTIONS

Dmytrii Biruk: Conceptualization, Methodology, Writing – original draft. Iryna Poberezhska: Software, Funding acquisition, Writing – review & editing. Nataliia Bilyk: Resources, Formal analysis, Validation. Leonid Skakun: Visualization, Project administration, Supervision. Oleksandr Kostiuk: Investigation, Data curation, Writing – review & editing.

All authors contributed substantially to the conception, methodological development, and preparation of the study, critically reviewed the manuscript for important intellectual and scientific content, approved the final version, and agreed to remain accountable for all aspects of the work.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

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