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The Petrophysical Properties and Strength of Extrusive Rocks Discharged by Bezymianny Volcano, Kamchatka

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Abstract—This is the first petrophysical study of extrusive rocks (dacites to andesites) discharged by Bezymianny Volcano. We provide a comparative description of properties for extrusive rocks in accordance with identified age groups. We show the dynamics in the variation of extrusive rock properties in relation to their ages, with the result that the older a rock the higher are its density, strength, and elastic parameters. Rocks petrophysical features are compared between extrusive domes and lava flows. We argue for petrophysical properties to be applicable for deriving more accurate results for the genesis of rocks having similar petrophysical properties, in particular, rocks of extrusive and effusive origin.

Keywords: Bezymianny Volcano, extrusive dome, petrophysical properties

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INTRODUCTION

Petrophysical properties are to be understood as the whole set of physical and mechanical characteristics of rocks that can be determined by laboratory methods applied to rock specimens or can be calculated. Those characteristics include density, hydrophysical, acoustic, thermal, magnetic, and electrical ones, as well as strength and strain parameters. The latter are commonly referred to as physico-mechanical (in engineering geology) or geomechanical (in mining science) parameters, but essentially these too are physical characteristics describing the behavior of a rock in the physical field of mechanical stresses (*Gruntovedenie,* 2005). The main factors that control rock properties include the chemical and mineral compositions and structure (texture, structure, porosity, and cracking). The petrophysical parameters of volcanogenic rocks obviously depend on the thermodynamic conditions under which they were formed (the conditions of magma melting and magma crystallization, and magma composition) and subsequent secondary transformations affected by a variety of geological processes. It thus appears that, knowing how the properties depend on geological factors, we can also deal with inverse problems, namely, making use of petrophysical parameter values to reconstruct the geological conditions of rock generation. The petrophysical properties of rocks sampled on volcanoes in the Northern Volcanic Group in Kamchatka were studied by many researchers (e.g., Ladygin and Nikitin, 1980; Kozyrev, 1990; Girina, 1998; Ladygin and Okrugin, 1998; Ladygin et al., 2001, 2010, 2012, 2016, 2018, 2019; Ladygin and Frolova, 2002, 2006; Ladygin, 2014).

Bezymianny stands in the middle of the Klyuchevskoy Volcanic Group, Kamchatka (Fig. 1). It is currently one of the most active volcanoes worldwide. The volcano is studied by many researchers on account of its sudden resumption of activity in October 1955 after a repose period of one thousand years (Braitseva and Kiryanov, 1982), with its catastrophic eruption of March 30, 1956 discharging and removing over 3 km^3 of material (Gorshkov, 1957; Gorshkov and Bogoyavlenskaya, 1965; Bogoyavlenskaya and Kirsanov, 1981; Bogoyavlenskaya et al., 1991), and the ongoing growth of a lava dome in the explosive crater (e.g., Kirsanov et al., 1971; Kirsanov, 1979; Alidibirov et al., 1988; Girina, 2013; Girina et al., 2020a, 2020b, 2022; Ozerov et al., 2020).

The history of formation for Bezymianny Volcano has been long: 10 to 11 ka for Pre-Bezymianny and over 5.5 ka for Bezymianny proper (Braitseva and Kiryanov, 1982; Braitseva et al., 1990, 1995; Bogoyavlenskaya et al., 1991). It took this time for various facies of magmatic features to form, namely, extrusive domes, pyroclastic and lava flows. The composition of these features shows a sufficient diversity, ranging between dacites and basaltic andesites with various porphyritic phenocrysts (plagioclase, rhombic and monoclinic pyroxene, hornblende, titanomagnetite, and magnetite) and various groundmass textures

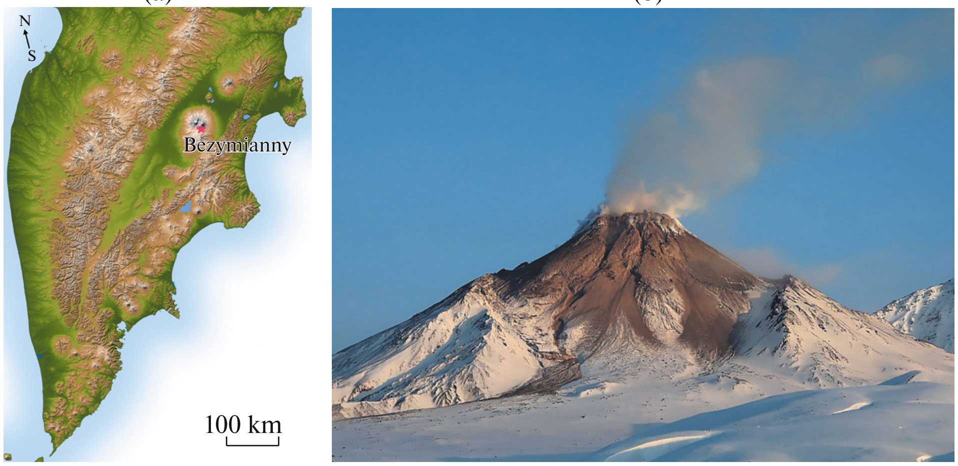

Fig. 1. Bezymianny Volcano: the location in the Kamchatka Peninsula (a) and a view from southeast, photographed by Yu.V. Demyanchuk on April 20, 2022 (b).

(hyalopilitic, intersertal, microlithic, etc.). Overall, all the three facies have been evolving synchronously, and are alternating within the volcanic edifice and adjacent areas. No substantial differences have been detected in comparisons of chemical and mineral composition between the lava flows rocks and the extrusive domes rocks ([Borisov and Borisova, 1974; Ladygin et al., 2019). This might be due to the fact that a single magma chamber was the source for them, but the different conditions for the discharge of lava onto the ground surface, the duration of its crystallization (i.e., different thermodynamic and fluidal conditions where the melt was cooling and crystallizing) led to differences in the structural and textural habit of the rocks, producing considerable differences in the petrophysical properties of the rocks that compose these facies.

The occurrence of the three facies is not uniform in the area of the volcano. The lava flows lie on all slopes of the volcanic edifice, as well as shielding the Novy Dome, which has grown in the 1956 explosive crater. The extrusions concentrate in the middle and south of the volcanic edifice, as well as occurring at its southern foot. The age of the extrusions varies within wide limits, between 11 000 to 40 years (Novy Dome). The pyroclastic flows, which have been forming since 1956 until the present, mostly concentrate in the Vostochnaya and Yuzhnaya valleys in the southeastern slope of the volcano, but also there are a few in all slopes and foots of the volcano, because pyroclastic material was showering on all slopes and foots of the volcano as explosive eruptions sent vertical eruption columns to heights above sea level that occasionally reached 15 km.

We gave a detailed description of the petrophysical properties of the Bezymianny lava flows in (Ladygin et al., 2012), while the present study focuses on a description of the extrusive features.

METHODS OF STUDY

We have surveyed and sampled 13 extrusive domes (Fig. 2). A total of 115 samples were available, which covered the entire range of rocks for each dome; these differed among themselves primarily in density, because this parameter largely controls most petrophysical properties, as well as strength and deformation characteristics.

Each sample was separated into for 2 to 5 specimens of regular geometric shape as rectangular prisms or cylinders ($h = d \sim 3$–4 cm) for study in the laboratory. We determined or calculated the following parameters of petrophysical properties and strength: bulk density (ρ, g/cm^3), grain density (mineral density) (ρ_s, g/cm^3), total porosity (n, %), water absorption (W, %), magnetic susceptibility ($\chi \times 10^{-3}$ SI units) (KT-6 kappameter), P-wave velocity in dry (V_p, km/s) and in water-saturation ($V_{p\,w}$, km/s) condition (ultrasound scan using IPA-59 and *Ultrazvuk* instruments), strength under uniaxial compression in dry (UCS (Uniaxial Compressive Strength) $_d$, MPa) and in water-saturated (UCS $_w$, MPa) condition and under tension (BTS (Brasilian Tensile Strength), MPa) (ZDM-10 and PSU-125 mechanical presses). All determinations were conducted following the standard procedures whose detailed descriptions can be found in (Frolova, 2015; *Laboratornye …,* 2017).

Simultaneously with the determinations of properties, we studied structural and mineralogical features of the rocks. Thin sections have been described for all lava samples using POLAM l-213M and Olympus BX-41 optical microscopes.

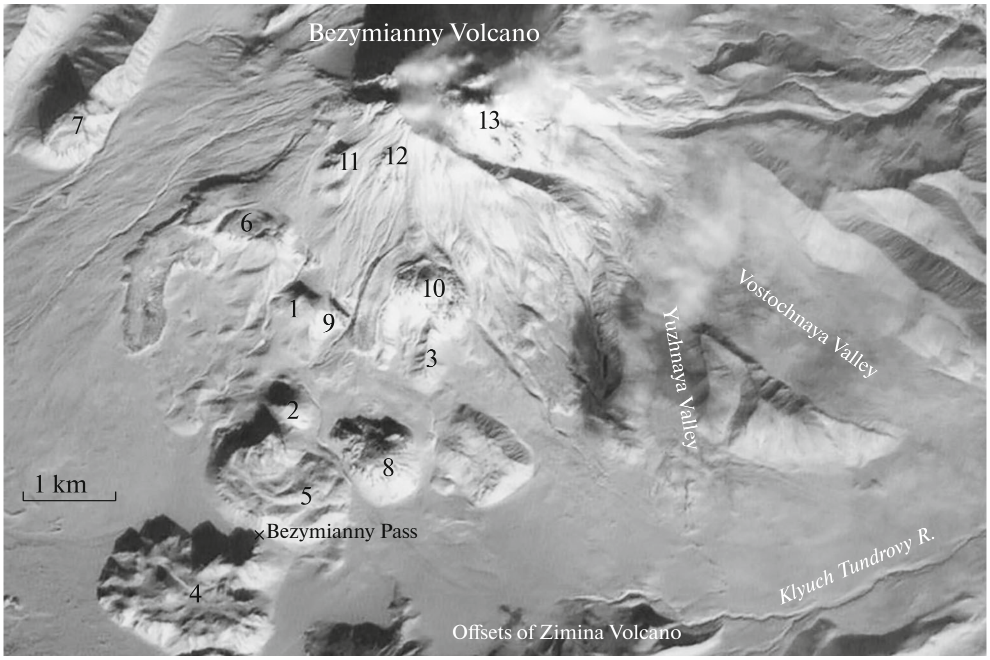

Fig. 2. Extrusive domes on Bezymianny Volcano as seen in an Aster image on February 24, 2005. (1) Gladky, (2) Pravilny, (3) Pestrye Khrebtiki, (4) Plotina, (5) Stupenchaty, (6) Dvuglavy, (7) Kulich, (8) Ekspeditsiya, (9) Pobochny, (10) Lokhmaty, (11) Pogrebenny, (12) Vysoky, (13) Novy.

THE BEZYMIANNY EXTRUSIVE FEATURES

Different authors have reported the presence of up to 17 extrusive domes in the southern part of Bezymianny Volcano (Bogoyavlenskaya, 1957, 1960; Gorshkov and Bogoyavlenskaya, 1965; Ermakov, 1977; Braitseva et al., 1990; Almeev et al., 2013). The best pronounced feature is a chain of four coalesced extrusive domes which blocks the intersecting valleys of the Klyuch Tundrovy and Studenaya rivers; the chain has been called *Plotina* by S.A. Konradi in 1909 (Konradi, 1911). Subsequently, the name became attached to the three extrusions south of the Bezymianny Pass. The extrusion north of Plotina was named Sedlo, but later on part of it was called Stupenchaty Dome, while the rest received the name of Pravilny Dome (Gorshkov and Bogoyavlenskaya, 1965). Researchers had varying opinion on the ages of the extrusions and on whether they belonged to Bezymianny Volcano, but were unanimous in asserting that the Plotina extrusions were among the oldest in the area (Zavaritsky, 1955; Piip, 1956; Bogoyavlenskaya, 1957, 1960; Ermakov, 1977). The extrusion was either considered to be an independent feature that was squeezed upwards between Bezymianny and Zimina volcanoes (Konradi, 1911; Timerbaeva, 1967; Ermakov, 1977) or a lateral feature that was part of Bezymianny (Piip, 1956; Gorshkov and Bogoyavlenskaya, 1965).

According to tephrochronological evidence (Braitseva et al., 1990), the oldest features (the second half of the Upper Pleistocene) are the Gladky, Pravilny, and Pestrye Khrebtiki (Raschlenenny) extrusive domes composed of dacites. Somewhat later, during phase II of the glaciation, tuya-type domes were formed as a result of subglacial effusions, namely, Plotina, Stupenchaty, Dvuglavy, and Kulich, whose composition is consistent with hornblende andesite and pyroxene andesite. All of these had formed before Pre-Bezymianny Volcano (before 11 000 B.P.). The Ekspeditsiya and Pobochny extrusive domes were growing at the same time as the Bezymianny stratovolcano, during the time span 3300–5500 B.P. The Lokhmaty Dome was formed during 1000–1350 B.P. Apart from those mentioned above, there are also undated domes, viz., Vysoky and Pogrebenny in the upper part of the present-day Bezymianny stratovolcano edifice. Novy Dome is the youngest, having been growing since April 1956 until now (Gorshkov and Bogoyavlenskaya, 1965; Braitseva et al., 1990; Girina, 2013; Girina et al., 2022). V.A. Ermakov (1977) believes that the southern Plotina dome (which he has given the name of Kulisa) to be the oldest among the extrusions. He has identified one-phase domes (Kulisa and Kulich) and two-phase domes (Stupenchaty and Dvuglavy). The original tabular surface of the latter type is usually deformed by more viscous and more acid obelisks emplaced later on. A typical obelisk of this kind is the Pravilny Dome in his opinion; the name of an obelisk must also be given to the Pobochny fissure dome that is structurally connected to the Dvuglavy Dome. He also thinks that lateral extrusions is the correct name to term the youngest domes that were formed concurrently with Bezymianny, viz., Ekspeditsiya, Lokhmaty, Pogrebenny, and Vysoky.

Different researchers relied on different principles when subdividing the extrusions into sets. G.E. Bogoyavlenskaya (1957) identified three sets of domes based on differences in the constituent rocks, as, e.g., Gladky and Pravilny are composed of dacites; Lokhmaty, Ekspeditsiya, and Pobochny consist of hornblende andesites with numerous homogeneous inclusions that show a great diversity of size; Dvuglavy and Stupenchaty are composed of pyroxene andesites. A.Yu. Ozerov et al. (1997) have divided the extrusions into two sets based on their ages: those before the origination of Bezymianny Volcano (15–20 ka B.P.) and those which were formed simultaneously with it (5–5.5 ka B.P.). The first set includes Gladky, Pravilny, Pestrye Khrebtiki, Plotina, Stupenchaty, Dvuglavy, Razlaty, and Kulich, while the other is made up of Lokhmaty, Ekspeditsiya, Treugolny Zub, and Ekstruzivny Greben (Pogrebenny).

This study treats the rocks of the extrusive domes by subdividing them into four sets. The first three sets include the domes based on their ages, according to (Braitseva et al., 1990). Our fourth set includes those domes which stand on the Bezymianny stratovolcano edifice (Lokhmaty, Vysoky, Pogrebenny) and inside it (Novy Dome). Our brief description of dome morphology is based on (Bogoyavlenskaya, 1957, 1960; Gorshkov and Bogoyavlenskaya, 1965; Ermakov, 1977; Kirsanov, 1979). The petrographic description is ours.

The first set includes the oldest domes (Gladky, Pravilny, and Pestrye Khrebtiki), which had formed before Pre-Bezymianny originated (before 11 ka B.P.) (Braitseva et al., 1990).

The Gladky and Pravilny domes are cone-shaped hills composed of viscous lava; they have been heavily smoothed by erosion. They stand at an altitude of 1650 m. Their summits are composed of a drift of blocks with a characteristic thin tabular jointing ranging in thickness between a few millimeters and a few centimeters. The lavas are of light grey and light rose color; they are dense, and are hornblende dacites in composition. The average concentration of SiO_2 is 64.63% for Gladky (3 samples) and 65.46% for Pravilny (5 samples) (Braitseva et al., 1990; Almeev et al., 2013). The lavas have a porous structure and a porphyritic texture with an intersertal groundmass texture. As well, Pravilny very rarely was found to contain lavas with hyalopilitic intersertal and hyalopilitic groundmass texture. The Pravilny rocks contain 40–60% of porphyritic phenocrysts, with the respective value for Gladky being 20–35%. The phenocrysts consist of plagioclase and hornblende, with few cases of plagioclase only being in the Pravilny lavas. The groundmass consists of volcanic glass and the minerals plagioclase, hornblende, and titanomagnetite; no hornblende is observed in some samples. Of the ore minerals, titanomagnetite is characteristic for Gladky (up to 10%), while ilmenite and magnetite occur in Pravilny, apart from titanomagnetite (up to 10%).

The Pestrye Khrebtiki Dome (Raschlenenny) stands near the southern foot of the Bezymianny edifice; it is partially overlain by Lokhmaty rocks. The Pestrye Khrebtiki lavas are dacites. The mean concentration of SiO_2 is 67.28% (9 samples) (Braitseva et al., 1990; Almeev et al., 2013). The rock structure is porous, the texture is porphyritic, the groundmass texture is intersertal. The amount of phenocrysts in the lava is 10% on average. The phenocryst composition mostly includes hornblende and plagioclase with very rare cases of plagioclase alone. One occasionally notes the replacement of hornblende with magnetite. The groundmass consists of glass, plagioclase, and ore minerals; hornblende is also encountered. The ore minerals are titanomagnetite (~3–5%) and magnetite, with the concentration of ore minerals increasing to reach 10% in the presence of magnetite.

The second set includes domes that are younger than the oldest set (tuya type): Plotina, Stupenchaty, Dvuglavy and Kulich (Braitseva et al., 1990).

The Plotina Dome consists of three coalesced, large, extrusive domes extending east–west. The lower parts of the dome slopes are covered with drift in about two thirds of the area, while further upwards one can see monolithic extrusive lava with vertical columnar jointing that occasionally becomes large-block jointing. The western slope is bounded by nearly vertical dikes whose rocks show columnar jointing. The lava is dark grey hornblende and pyroxene andesite. The mean concentration of SiO_2 is 56.84% (15 samples) (Ermakov, 1977; Almeev et al., 2013).

The structure of the Plotina rocks is porous, the lava texture is porphyritic, the groundmass texture is intersertal hyalopilitic, occasionally intersertal doleritic, intersertal, or hyalopilitic. The amount of phenocrysts varies between 1 and 70% (30–40% on average). The phenocryst composition in different lava samples is hornblende and plagioclase; pyroxene and plagioclase; occasionally hornblende, pyroxene, and plagioclase; occasionally it is plagioclase alone or else just pyroxene. The groundmass association (glass, plagioclase, hornblende, and titanomagnetite) occasionally also shows pyroxene, or else this may be present instead of hornblende. The concentration of titanomagnetite varies between 1 and 10% (6% on average), with magnetite being rare.

The Stupenchaty Dome sits on the southern slope of the volcano at altitudes of 1450–1500 m. The relative height of the dome is 250 m. Stupenchaty has a scarp-like tall wall of the northern slope crowned with a monolith. Lava tongues go down in layers from the monolith around the summit, but no original banding or structures of lava flow can be detected. The dome is composed of dark grey two-pyroxene andesite. The mean concentration of SiO_2 is 57.47% (6 samples) (Braitseva et al., 1990; Almeev et al., 2013). The rocks are dense lavas containing phenocrysts of plagioclase, pyroxene, and hornblende (up to 27%). The texture is seriate porphyritic, occasionally aphyric; the groundmass texture is hyalopilitic intersertal, occasionally doleritic, intersertal or intersertal doleritic. Phenocrysts contain plagioclase up to 1.5–2 mm across; the pyroxene is monoclinic (rare single crystals up to 0.1–0.5 mm across) and rhombic (up to 0.2–0.3 mm across, with concentrations of $FeSiO_3$ between 30 and 35); titanomagnetite is present in amounts that occasionally reach 20%; hornblende is very rare, it is up to 1–1.5 mm across. The lava groundmass consists of glass, plagioclase, and pyroxene, occasionally including hornblende and titanomagnetite.

The Dvuglavy Dome is situated in the southwestern slope of the volcano at altitude 1700 m. The dome is elongate east–west, in map view it has the shape of an ellipse that is narrower in its western part. Its relative height is 250 m. The Dvuglavy northern slope has been heavily eroded; it gradually merges with the volcano's slope, while the other slopes are steep. The dome summit consists of two hills separated by a small depression. Its southern and eastern slopes are fairly well exposed, while the summit and the other slopes contains bedrock lava in two or three exposures only. The flow structure is poorly expressed in the lava. The layering is emphasized by columnar jointing; this is thin, a few millimeters to 4–5 cm. The dome is largely composed of dark grey, dense, pyroxene andesite. The mean concentration of SiO_2 is 60.56% (3 samples) (Braitseva et al., 1990; Almeev et al., 2013). The rock texture is mostly aphyric, more rarely porphyritic: there are plagioclase phenocrysts (no more than 0.2–0.3 cm across) with a low amount of pyroxene; in other cases the phenocrysts consist of plagioclase only; small hornblende crystals are encountered occasionally. The groundmass texture is intersertal. The lava groundmass consists of glass, plagioclase, pyroxene, and ore minerals, and occasionally of hornblende as an extra member of the association, or instead of pyroxene. Titanomagnetite is found in concentrations of 1–2%, but those varieties where magnetite is present contain ore minerals in concentrations of ~10%.

The Kulich Dome is on a branch of Kamen Volcano near the western foot of Bezymianny. The rocks in this dome are mostly hornblende andesites with some amount of pyroxene andesite. The concentration of SiO_2 is 57.86% (Braitseva et al., 1990). The rock structure is porous, the textures are porphyritic with intersertal and occasional intersertal doleritic groundmass texture. The amount of phenocrysts varies between 5 and 70%, the phenocrysts consist of plagioclase, hornblende, pyroxene, and ore minerals (titanomagnetite and magnetite with concentrations between 0 and 30%, the average being 10).

The third set includes the Ekspeditsiya and Pobochny domes whose ages are in the range 3300–5500 years (Braitseva et al., 1990). Their summits and steep slopes are hilly, are crowned with monoliths, obelisks, and pointed ridges; the greater part of slope area is covered with scattered variously sized blocks which are agglomerate mantles of the domes. The lavas are hornblende andesites. The phenocrysts are dominated by coal black hornblende with a glassy luster forming elongate crystals a few tenths of a millimeter to 2 cm across; as well, there are plagioclase phenocrysts up to 0.5 cm across.

The Ekspeditsiya Dome stands on the southern slope of the volcano at altitude 1450 m. Its relative height is 280 m. The dome is elongate east–west, its summit is crowned with monolithic blocks, obelisks, and pointed ridges; the slopes are mostly covered with debris. The dome is composed of grey hornblende andesites saturated with homeogenic inclusions. The mean concentration of SiO_2 is 61.05% (3 samples) (Braitseva et al., 1990; Almeev et al., 2013). The rock structure in the extrusion is porous, the texture is porphyritic, the texture of the lava groundmass is hyalopilitic and intersertal. The amount of phenocrysts in the rocks varies between 5 and 80% (25–30% on average). The phenocrysts mostly consist of hornblende and plagioclase; with occasional pyroxene, or else pyroxene is present instead of hornblende. The groundmass (glass, plagioclase, hornblende, and titanomagnetite) also contains occasional pyroxene, or else the latter is present instead of hornblende. The concentration of titanomagnetite varies between 3 and 8% (5% on average).

The homeogenic inclusions occurring in obelisks to be found in the lower parts of the dome can reach 20 cm across, very rarely the size is 40 cm, the mean size being 2–5 cm, and the frequency of occurrence is 5–6 inclusions per 1 m^2. The inclusions are oval in shape, are generally composed of the same minerals as their host rocks, but contain more hornblende and other mafic minerals, which makes for greater basicity in chemical composition. No homeogenic inclusions in lavas have been detected at the dome summit (Gorshkov and Bogoyavlenskaya, 1965).

The Pobochny Dome stands at an altitude of 1800 m; it is a triangular hill of viscous lava that is elongate east–west. Its summit is crowned with obelisks and monoliths. The dome rocks are grey hornblende andesites distinguished by a banding seen as alternating grey and pink andesites of the same composition, with the band width varying between 1.5 and 5 cm. The concentration of SiO_2 is 61.49% (Gorshkov and Bogoyavlenskaya, 1965). The structure of the rocks that compose the extrusion is porous, the texture is porphyritic, the groundmass texture is hyalopilitic, occasionally intersertal. The phenocrysts consist of hornblende and plagioclase (between 5 and 35%). The groundmass consists of glass, plagioclase, hornblende, and ore minerals (as well, magnetite and titanomagnetite in concentrations reaching 3–10%).

There occasional cases in which no hornblende has been detected.

The fourth set includes the youngest domes related to the growth of Bezymianny Volcano (they are within and on its edifice): Lokhmaty, Pogrebenny, Vysoky, and Novy.

The Lokhmaty Dome is on the southern slope of the volcano at an altitude of 1800 m. Its relative height is 250 m, and its age is 1000–1350 years (Braitseva et al., 1990). Judging by the morphology and petrographic habit of the rocks, it is similar to the Ekspeditsiya Dome. Lokhmaty is composed of grey hornblende andesites that contain numerous homeogenic inclusions. The mean concentration of SiO_2 is 62.19% (7 samples) (Braitseva et al., 1990; Ivanov, 2008; Almeev et al., 2013). The rock texture is porphyritic, occasionally aphyric; the groundmass texture is intersertal or, very rarely, hyalopilitic intersertal. The amount of phenocrysts in different lava samples varies between 15 and 50%, with the mean being 30%. The phenocrysts consist of hornblende and plagioclase, the groundmass contains glass, plagioclase, hornblende, and ore minerals (magnetite and titanomagnetite whose concentrations vary between 1 and 50%).

The Pogrebenny Dome (Ekstruzivny Greben) stands in the middle of the volcanic edifice on its west–southwestern slope. The rocks of the dome are mostly pyroxene andesites. The mean concentration of SiO_2 is 60.83% (2 samples) (Braitseva et al., 1990; Almeev et al., 2013). The rock structure is porous, the lava texture is porphyroblastic, while the groundmass texture is hyalopilitic. The amount of phenocrysts is ~55%, they consist of pyroxene and plagioclase, occasionally in association with hornblende. The groundmass consists of glass, plagioclase, pyroxene (pyroxene may be occasionally absent), and ore minerals (mostly titanomagnetite, occasionally with magnetite, with concentrations below 5%).

The Vysoky Dome is to the east of Pogrebenny and somewhat higher. The dome is composed of hornblende andesite. The concentration of SiO_2 is 63.22% (Ivanov, 2008). The lava structure is porous, the rock texture is porphyritic, or occasionally aphyric; the groundmass texture is hyalopilitic and intersertal. The amount of phenocrysts varies between 1% and 30%, they consist of plagioclase and hornblende. The groundmass contains glass, plagioclase, occasionally hornblende, and ore minerals that mostly consist of magnetite with an occasional titanomagnetite (below 3%).

The Novy Dome is being formed in the explosive crater that was produced in the Bezymianny edifice during the catastrophic eruption of March 30, 1956. The dome rocks are mostly pyroxene andesites with a fraction of hornblende andesite; these rocks contain homeogenic inclusions. The mean concentration of SiO_2 is 59.01% (10 samples) (Gorshkov and Bogoyavlenskaya, 1965; Braitseva et al., 1990; Ivanov, 2008). The lavas have a porous structure, their texture is porphyritic, and the groundmass texture is hyalopilitic. The phenocrysts that occur in the lavas are largely composed of pyroxene and plagioclase, with an occasional hornblende. Their percentage varies between 20 and 70% (50% on average). The lava groundmass consists of glass, plagioclase, pyroxene, and ore minerals, with an occasional admixture of hornblende. The ore minerals are titanomagnetite ad magnetite whose total concentration varies between 5 and 30%.

THE PETROGRAPHY OF ROCKS IN THE EXTRUSIONS

With regard to chemical composition, the lavas of all domes are moderately alkaline rocks. The concentration of silicic acid in these varies between 52.67 (Plotina) and 68.03% (Pestrye Khrebtiki), while the rocks that compose, e.g., the Novy Dome show a narrow range of variation, between 57.85 and 60.11% (Fig. 3).

The dacitic lavas of the older domes contain the least amount of magnesium oxide (between 0.87 and 1.24%) and of total ($FeO + Fe_2O_3$) ferric oxide (between 3.19 and 4.33%). The greatest amounts of magnesium oxide and ferric oxide are noted in rocks of the Plotina Dome (3.85 and 9.71%, respectively) and of Stupenchaty (3.65 and 8.25%, respectively), which is due to higher concentrations of mafic and ore minerals. The $MgO–CaO$, $MgO–SiO_2$, and $SiO_2–K_2O$ concentration relationships are best expressed for lavas in the younger domes (sets 3 and 4) (see Fig. 3).

The structures of all lavas in the Bezymianny extrusions considered here are porous. The rock textures of all extrusions are generally porphyritic, with the only exception being Dvuglavy, Stupenchaty, and Vysoky, which occasionally (Dvuglavy and Stupenchaty in most of the cases) have aphyric textures as well. The groundmass textures are different, not only in different domes, but also within a single extrusion. Of the 13 extrusions considered here, six mostly have intersertal texture of the lava groundmass, in four it is hyalopilitic, with the rest being dominated by hyalopilitic intersertal texture. The rocks of the oldest domes typically have intersertal groundmass textures, while the Pravilny lavas also (but very rarely) show hyalopilitic intersertal and hyalopilitic textures. For the tuya domes situated near the foot of the volcano the groundmass textures vary between hyalopilitic and intersertal doleritic, including all intermediate varieties; for rocks of the youngest domes situated within the edifice and in the slopes of the volcano, the dominant textures are hyalopilitic, intersertal, and occasionally hyalopilitic intersertal and aphyric. Comparison between andesites having hyalopilitic and intersertal textures did not reveal any significant differences; however, there is the tendency of decreasing degree of crystallization (increasing amount of glass) in the groundmass going from older to younger extrusions.

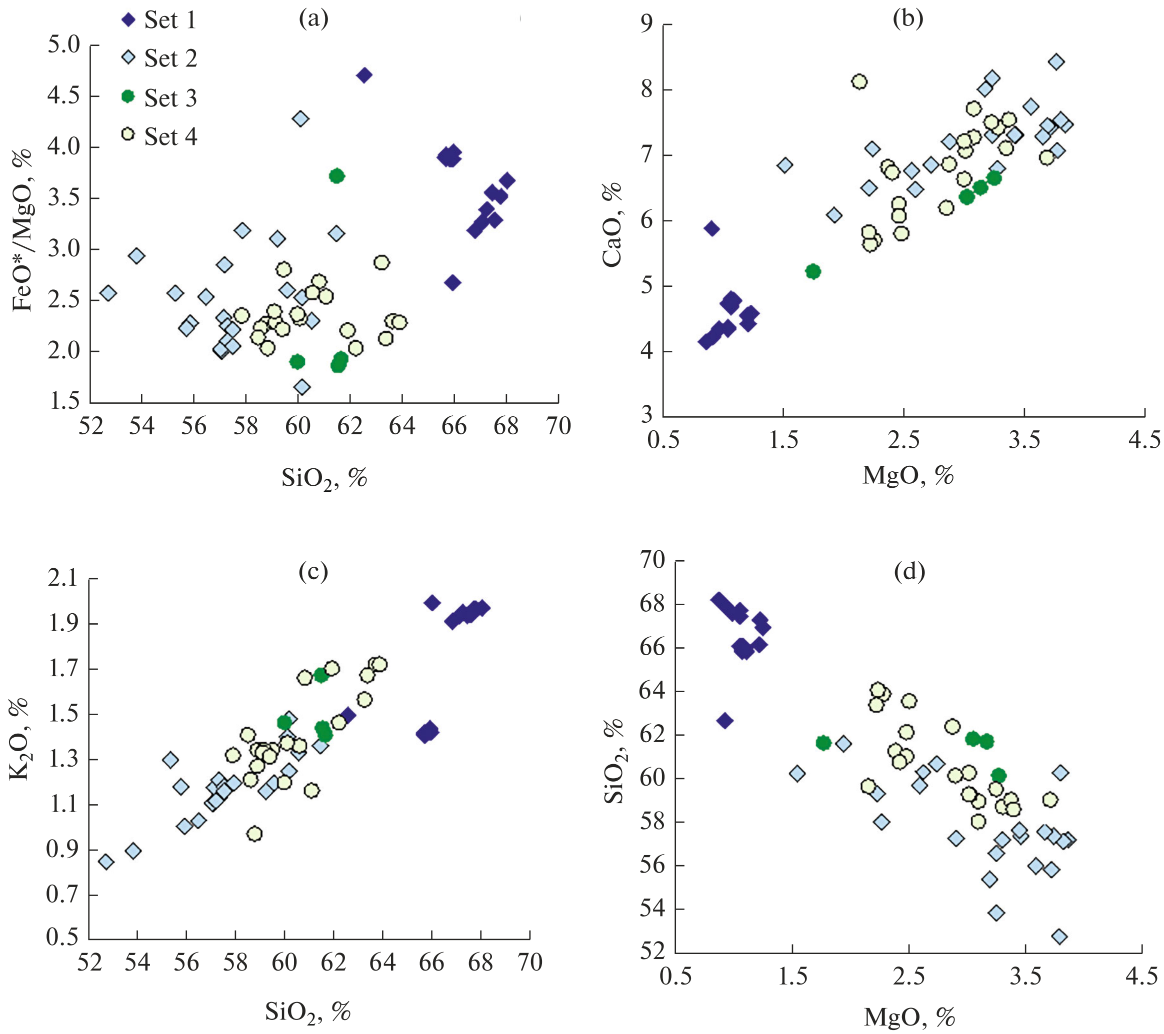

Fig. 3. Variations in the chemical composition of the rocks sampled from extrusions on Bezymianny (using materials from Gorshkov and Bogoyavlenskaya, 1965; Ermakov, 1977; Braitseva et al., 1990; Ivanov, 2008; Almeev et al., 2013). The concentrations of major oxides have been converted to dry basis.

The phenocrysts show the following compositional pattern: the rocks of the older domes (the first set) contain phenocrysts consisting of plagioclase and hornblende, while the lavas of younger domes (the second set) also contain hornblende, but this is not invariably the case, with pyroxene being detected either instead of, or in association with, hornblende. As an example, Dvuglavy and Stupenchaty (the second set) more frequently contain pyroxene, but occasionally hornblende too, with not infrequent aphyric textures. The phenocrysts in the Plotina and Ekspeditsiya lavas exhibit a mixed phenocryst composition, but more frequently there are plagioclase and hornblende again, occasionally in combination with pyroxene; some rare phenocrysts consist of plagioclase alone or pyroxene alone. The Novy phenocrysts mostly consist of plagioclase and pyroxene, but hornblende sometimes appears.

Ore minerals in the lavas of the old extrusions are in amounts of ~5–10%, and they consist of titanomagnetite; their concentrations in the rocks of the intermediate-age extrusions are 3–6% (with titanomagnetite too), occasionally reaching 20% in some varieties (those which contain magnetite). Titanomagnetite in the lavas of the young extrusions is contained in amounts of a few percent, but the concentration of ore minerals occasionally reaches 30% in magnetite-bearing varieties. To some approximation one can note a decreasing concentration of titanomagnetite in the lavas and an increasing concentration of magnetite in the direction from older to younger domes.

As to the groundmass mineral composition, the lavas of all domes invariably contain volcanic glass, plagioclase, and ore minerals, which are "diluted" with hornblende and/or pyroxene in varying ratios. The rocks of the first set contain hornblende; the second set has hornblende and pyroxene in varying combinations; the third contains hornblende, and the fourth has pyroxene and rarely hornblende, occasionally without pyroxene. As to the ore minerals, one notes an incipient tendency of their being accumulated in the matrix toward younger extrusive domes, because their concentration varies between 2 and 10% in the first set of rocks, between 0 and 30% in the second, between 3 and 10% in the third, and up to 30% in the fourth set.

Based on the above, we can arrive to the inference that the rocks in the extrusions mostly differ in the composition and amount of porphyritic phenocrysts and in the concentrations of magnetite and titanomagnetite.

THE PETROPHYSICAL PROPERTIES AND STRENGTH OF THE ROCKS THAT COMPOSE THE EXTRUSIVE DOMES

The rocks that compose the Bezymianny extrusive domes show a wide range of petrophysical parameter values depending on porosity and structural mineralogical features. Considering the mean parameter values, we can state that the rocks are dense (ρ = 2.22 g/cm^3; 114 samples), have an intermediate value of porosity (n = 19%; 47 samples); and have high strength (UCS_d = 84 MPa, UCS_w = 69 MPa; 114 and 77 samples, respectively). The velocities of elastic waves are comparatively low (V_p = 2.79 km/s, $V_{p\,w}$ = 3.58 km/s; 113 and 98 samples, respectively) (Table 1).

Bulk density varies between 1.74 and 2.47 g/cm^3 for andesites having intersertal texture (Ekspeditsiya and Plotina, respectively), and between 1.74 and 2.68 g/cm^3 for those with hyalopilitic texture (Pobochny and Plotina, respectively).

The lava porosity varies between 12.7% for andesites with hyalopilitic texture (Novy Dome) and 28.5% for lavas with doleritic texture (Stupenchaty). Overall, rock bulk density steadily decreases with increasing porosity.

Water absorption varies between 1.3 and 12.4% for andesites with intersertal texture (Pravilny and Ekspeditsiya, respectively) and between 1.9 and 13% for those with hyalopilitic texture (Novy and Ekspeditsiya, respectively). Water saturation is clearly a function of bulk density (Fig. 4a). As the bulk density of a rock increases, the porosity decreases, and so does water saturation.

P-wave velocity in andesites having intersertal texture varies between 1.6 and 4.2 km/s (Lokhmaty and Pravilny, respectively), while for those with hyalopilitic texture the velocity varies between 1.8 and 4.0 km/s (Novy and Plotina, respectively). It is to be noted that this parameter has a low value in andesite. The dependence of P-wave velocity on rock bulk density is poorly pronounced, but one notes relatively higher values of V_p for the lavas of older domes compared with younger ones (see Fig. 4b).

Uniaxial compressive strength in rocks varies between 29 and 179 MPa for andesites with intersertal texture (Lokhmaty and Pravilny, respectively) and between 22 and 238 MPa for those with hyalopilitic texture (Ekspeditsiya and Plotina, respectively). According to the classification in (*Gruntovedenie,* 2005), the dome lavas are rocks of intermediate strength, high strength, and very high strength.

The dependence of uniaxial compressive strength on density is well pronounced, and the dependence is about the same for andesites with intersertal and hyalopilitic textures. It should be noted that the higher bulk density of lavas in the older domes entails a higher strength of these rocks compared with the rest whose ranges of variation for bulk density and strength vary in wide limits (see Fig. 4c). The least strength occurs in the youngest lavas (Vysoky Dome), the highest in less old ones (Plotina).

Tensile strength varies between 2 and 23 MPa for andesites with intersertal texture (Lokhmaty and Pravilny, respectively) and between 3 and 8 MPa for those with hyalopilitic texture (Pogrebenny and Pobochny, respectively) (see Table 1). Tensile strength is also observed to depend on bulk density, but the dependence is less clearly pronounced than the relationship between compressive strength and bulk density.

Magnetic susceptibility in rocks varies in a wide range, between 0.7 × 10^{-3} SI (Pravilny) and 58.8 × 10^{-3} SI (Kulich) (see Table 1, Fig. 4d). This can be explained by a low concentration of mafic minerals and ore minerals in the dacites of the old extrusions and by high concentrations of these minerals in the andesites that compose younger domes. According to the classification of rocks over values of magnetic susceptibility from (*Gruntovedenie,* 2005), the Bezymianny extrusive features belong to sets I–VI, from "very weak magnetized" to "well magnetized" (0–60 × 10^{-3} SI)

RESULTS AND DISCUSSION

Comparative Petrophysical Characterization of the Rocks that Compose the Extrusive Domes

Overall, the rocks of the older domes (older than 11 thousand years, the first and second sets) possess the highest petrophysical parameter values (see Table 1). When averaged, the petrophysical parameter values for each dome show that the older domes have the greatest lava bulk density reaching 2.39 g/cm^3 (Kulich Dome), the lowest water absorption (2.7–4.5%, except for the Stupenchaty lavas with 7.4%), a medium porosity (15.2–19.1%, except for Stupenchaty with 28.5%), the highest (occasionally average) values of physico-mechanical parameters (Table 2). As an example, the uniaxial compressive strength in rocks in dry condition varies between 75 and 138 MPa, while when saturated with water the variation is between 60 and 111 MPa (Stupenchaty and Pravilny, respectively)

Table 1. Petrophysical properties and strength of Bezymianny extrusive rocks

Sample no.	ρ, g/cm^3	ρ_s, g/cm^3	n, %	W, %	V_p, km/s	$V_{p\,w}$, km/s	UCS$_d$, MPa	UCS$_w$, MPa	BTS, MPa	$\chi \times 10^{-3}$ SI
Gladky Dome (hornblende dacites)										
B-10a	2.29	2.76	17	3.1	2.5	3	113	103	9.7	2
B-10g	2.3	2.76	16.7	4	2.4	3.05	108	97	6.9	7.8
B-10b	2.2	2.76	20.3	4.7	3.15	3.55	86		10.8	8.8
B-10v	2.22	2.76	19.6	5.1	2.3	2.85	92		7.3	20.1
B-10d	2.15	2.76	22.1	5.4	2.45	3.35	87	87	6.5	18
Pravilny Dome (hornblende dacites)										
B-5a	2.35	2.76	14.9	1.3	4.2	4.7	179		23	34
B-5b	2.33	2.76	15.6	2.5	2.6	3.4	130	87	9	20.4
B-5e	2.32	2.76	15.9	3.3	2.6	3.25	130	130	11.6	13.6
B-5v	2.22	2.76	19.6	4	2.95	3.45	127		11.5	24.8
B-5d	2.22	2.76	19.6	4.9	2.3	3.05	94		12.2	5.4
B-5g	2.29	2.76	17	4.1	2.55	3.2	115	115	9	0.7
B-5a	2.35	2.76	14.9	1.3	4.2	4.7	179		23	34
Pestrye Khrebtiki Dome (dacites)										
6 zh	2.26	2.76	18.1	4	2.6	2.7	66	48		20.4
B-20a	2.28	2.68	14.9	4.2	2.4	3	101	81	6.6	23.8
B-20b	2.23	2.72	18	4	2.4	2.9	92	47	4.8	13.6
B-20g	2.32	2.72	14.7	2.7	2.65	3.4	122	105	12	26.9
B-20v	2.4	2.72	11.8	2.1	3.8	4.1	139	125		28.9
B-20zh	2.27	2.72	16.5	4.6	2.75	2.95	100	93	7.1	27.2
B-20d	2.26	2.72	16.9	3.2	2.75	3.3	122	66	12	1.7
B-20z	2.32	2.72	14.7	3.7	2.75	2.75	98		6.3	3.1
B-20e	2.34	2.72	14	3.2	2.5	2.9	108	108	6.9	3.1
Plotina Dome (hornblende andesites and pyroxene andesites)										
B-37a	1.94			9.6	3.1	3.25	22		3.3	28.2
B-37b	2.2			5.4	3.35	3.75	52	48		30.6
B-37b	2.03			8.2	3.15	3.35	45	30		
B-37v	2.28			4.8	2.3	3.5	100	87		41.8
B-37g	2.31			4.6	3.1	3.5	72		7.3	37.4
B-37d	2.34			4.1	3.6	3.85	68	68		40.8
B-37k	2.09			8.1	3.7	4.05	61	26		20.4
B-37n	2.32			4	3.45	3.9	91	84		45.2
B-37p	2.41			3.1	3.3	4.05	115	105	9.5	19.4
B-37r	2.45				4.15		103			11.6
B-37t	2.27			3.5	3.55	3.95	50	37		38.4
B-37yu	2.37			2.8	3.2	4.1	93	72	8.2	40.5
B-37L	2.28			4	3.6	4.25	72	50		31.3
B-37m	2.28			3.9	3.6	4.3	89	44	8.5	31.6
B-37s	2.34			2.1	3.75	4.25	64		6.8	45.2
B-37z	2.68			0.6	4.05	5.3	238			19
B-37i	2.36			3.1	2.75	4.2	79	70	3.4	45.2
B-37o	2.29				3.4		79			36
B-37ch	2.47				3.2		76			
B-37u	2.46			1.9	3.05	4.2	133		8	40.5
B-37f	2.42			2.1	3.4	4.4	142	123	9.6	34
B-37kh	2.47				3.2		76			

Table 1. (Contd.)

Sample no.	ρ, g/cm^3	$ρ_s$, g/cm^3	*n*, %	*W*, %	V_p, km/s	$V_{p\,w}$, km/s	UCS$_d$, MPa	UCS$_w$, MPa	BTS, MPa	χ × 10^{-3} SI
Dvuglavy Dome (pyroxene andesites)										
B-26a	2.32		14.1	2.9	2.75	3.7	102	102	11.2	20.4
B-26v	2.31		14.4	3	3.5	3.8	117	97	10.6	8.2
B-26b	2.36		12.6		3.5		140		12.6	31.6
B-26g	2.33		13.7		3.4		142		16.9	16
B-26d	2.25	2.7	16.7	4.2	3.05	3.6	100		12.1	17
B-26e	2.17		19.6		3.4		84			13.9
Stupenchaty Dome (two-pyroxene andesites)										
B-3a	2.24			4.4	3.1	4.15	99	85	8.9	27
B-3b	2.19			5	3	4	89	56	8.3	22.8
B-3v	1.99			11.7	2.7	3.7	59	58	6	24.8
B-3g	2.01	2.81	28.5	9.1	2.9	3.85	45	32	4.4	21.1
B-3d	1.86			13.1	3.7	3.9	33	21	4.9	22.8
B-3L	2.19			4.6	3.85	4.4	99	70	10.3	27.2
B-3m	2.2			6.9	3.7	4.15	61	58	8.7	24.8
B-3e	2.29			2.4	3.35	4.35	100		9.5	27.2
B-3z	1.85			15.9	2.85	3.25	38	26	3.9	22.8
B-3i	2.14			5	3.35	4.1	60		8	22.8
B-3k	2.2			6.7	3.6	4.25	64	59	9.9	24.8
B-3zh	2.22			4.1	3.5	4.2	101	90	5	18.4
B-3n	2.03			9.9	3.35	3.75	42	27	6.8	27.2
B-3o	2.21			6.9	3	3.95	77	73	6.5	26.2
B-3r	2.2			5.3	3	4.05	74	55	5.3	29.6
Kulich Dome (hornblende andesite with some pyroxene andesites)										
B-8a	2.75			1	2.8	4.1	202	213	17	18
1a	2.37			2.8	3.1	3.5	107	65	7.3	37.8
1b	2.21			5.2	2.5	3	74			19.4
1v	2.26			4.7	2.4	3	65	51	17	17.7
B-8b	2.39			2.9	2.8	3.4	102	93	10	58.8
B-8v	2.49			1.6	3.1	4.1	117	124	12	24.8
B-8g	2.49			0.8	3.8	4.7	184	178	15	54.1
B-8d	2.15			5.7	2.8	3.6	69	62	10	18
Ekspeditsiya Dome (hornblende andesites)										
5a	1.91		29	9.5	2.35	3.2	35	35	2.3	3.4
5b	2.24		16.7	7.5	1.7	2.45	67	54	3.8	34
B-4a	1.95		27.5	8	2.3	3.35	46	38	4.3	30.6
B-4g	2.15	2.69	20.1	4	2.35	3.6	87	80		6.8
B-4g	2.05	2.69	23.8	7	2.15	3.5	45			6.8
B-4d	2.45	2.75	10.9	2.8	1.7	2.9	126	90	6.6	23.8
B-4d	1.77	2.75	35.6	13	2.1	3.1	22	15	3.3	
B-4zh	1.92		28.6	8.7	1.95	3.4	36	29		30.6
B-4b	1.74		35.3	12.4	2.25	2.75	19	12		27.2
B-4V	2.17		19.3		3.1		84		7.5	23.8
B-4e	2.48		7.8	2.3	2.2	3	100	75		27.2
B-4z	2.16		19.7	4.7	2.7	3.75	63	50	5.5	13.6
Pobochny Dome (hornblende andesites)										
6z	2.32			5	2.5	3.1	123	92	7.8	29.6
6i	1.97			6.9	2.55	3.8	80	45	6.6	24.5
6k	2.3			4.4	1.4		60	49		9.5
B-12a	1.94			6.7	3.6	4.3	73	69	8.3	27.2
B-12v	1.83			10.5	2.5	3.7	41	26		7.8
B-12v	1.74			11.1	2.45	3.7	23		5.5	
B-12b	1.85			9.8	3.3	3.95	49	29	4.2	24.5

Table 1. (Contd.)

Sample no.	ρ, g/cm^3	$ρ_s$, g/cm^3	*n*, %	*W*, %	V_p, km/s	$V_{p\,w}$, km/s	UCS $_d$, MPa	UCS $_w$, MPa	BTS, MPa	χ × 10^{-3} SI
Lokhmaty Dome (hornblende andesites)										
6-d	2.07			6.9	1.7		45	19	3.6	5.8
6-e	1.97			7.6	1.6		39		3.3	11.9
B-21g	2.17			2.9	2.55	3.7	68	57	3.6	10.9
B-21d	1.97			6.2	2	2.85	38	28	2.1	8.5
B-21v	2.02	2.61	22.6	5.7	2.4	3.7	40		3.1	19
6g	1.94	2.82	31.2	10.2	2	2.8	29			30.6
B-21a	2.28	2.63	13.3	2.4	2.8	4.3	100		6.6	37.4
B-21b	1.89			8.2	2.05	2.65	40	25	4.4	22.8
Pogrebenny Dome (pyroxene andesites)										
B-24a	2.3				1.95		50			38.4
B-24a	2.23				1.9		40		3.2	38.4
B-24g	2.19				2.05	2.45	43	43	3.5	35.4
B-24b	2.37				2.5		105			34
B-24b	2.32						47			34
B-24v	2.25			2.7	2.6	4.25	84	37	4.9	29.6
Vysoky Dome (hornblende andesites)										
B-23e	2.31			3.7	3.2	4.05	110	100	7.1	36
B-23d	2.27	2.66	14.7	3.5	2.1	2.6	77	77	4.5	5.4
B-23zh	1.68	2.66	36.8		2.05		10			22.8
Novy Dome (pyroxene andesites with some hornblende andesites)										
831011-12	2.4	2.75	12.7	2.3	1.8	2.4	102	100		29.2
831011-12	2.37			2.8	1.8	3.25	100		7	35.7
831011-13	2.41	2.76	12.7	1.9	2.15	3.3	77	72		7.1
B-38b	2.36			3.3	1.8	3.4	79			6.8
B-38b	2.26			4.7	1.65	2.55	60	51		6.8
B-38a	2.48			2.5	1.95	3.4	111	83		17

The names and notation for the parameters can be found in main text

(see Table 2). P-wave velocities, hence elastic parameters, are also at the maximum for the rocks of the older domes, Plotina, Stupenchaty, and Dvuglavy (V_p = 3.35–3.40 km/s).

The rocks of the present-day Novy Dome have, in spite of their relatively high bulk density, extremely low P-wave velocities: 1.85 km/s when air dry and 3.05 km/s when saturated with water (see Table 2). This fact calls for further study. Our hypothesis is that this may be due to the least degree of groundmass crystallization in present-day andesites and to the presence of micro cracking which impedes the passage of elastic waves through the rock.

The rocks of Ekspeditsiya and Pobochny, which are in the third set (3300–5500 years), and of Lokhmaty, which is a member of the fourth set (1350–1000 years), are characterized by low bulk densities (2.00–2.08 g/cm^3), medium water absorption (6.3–8.3%), higher porosity (22.4–24.0%), low P-wave velocities (2.10–2.50 km/s when dry and 3.20–3.65 km/s when saturated with water), and medium uniaxial compressive strength (50–65 MPa when dry and 32–52 MPa when saturated with water) (see Table 2).

Although we have classified Lokhmaty as belonging to the fourth set, since it stands on the Bezymianny edifice, and its age was estimated as 1000–1350 years (Braitseva et al., 1990), the parameter values for its lavas are very similar to those for rocks in the third set (see Tables 1, 2). It was pointed out in various publications that the Ekspeditsiya and Lokhmaty rocks are similar, judging from structure, from the concentrations of homeogenic inclusions, petrography, etc. (Bogoyavlenskaya, 1957; Gorshkov and Bogoyavlenskaya, 1965; Ermakov, 1977). The similarity is also corroborated by petrophysical parameter values for the lavas of these domes. Ermakov (1977) thought Ekspeditsiya to be older than Lokhmaty. Braitseva et al

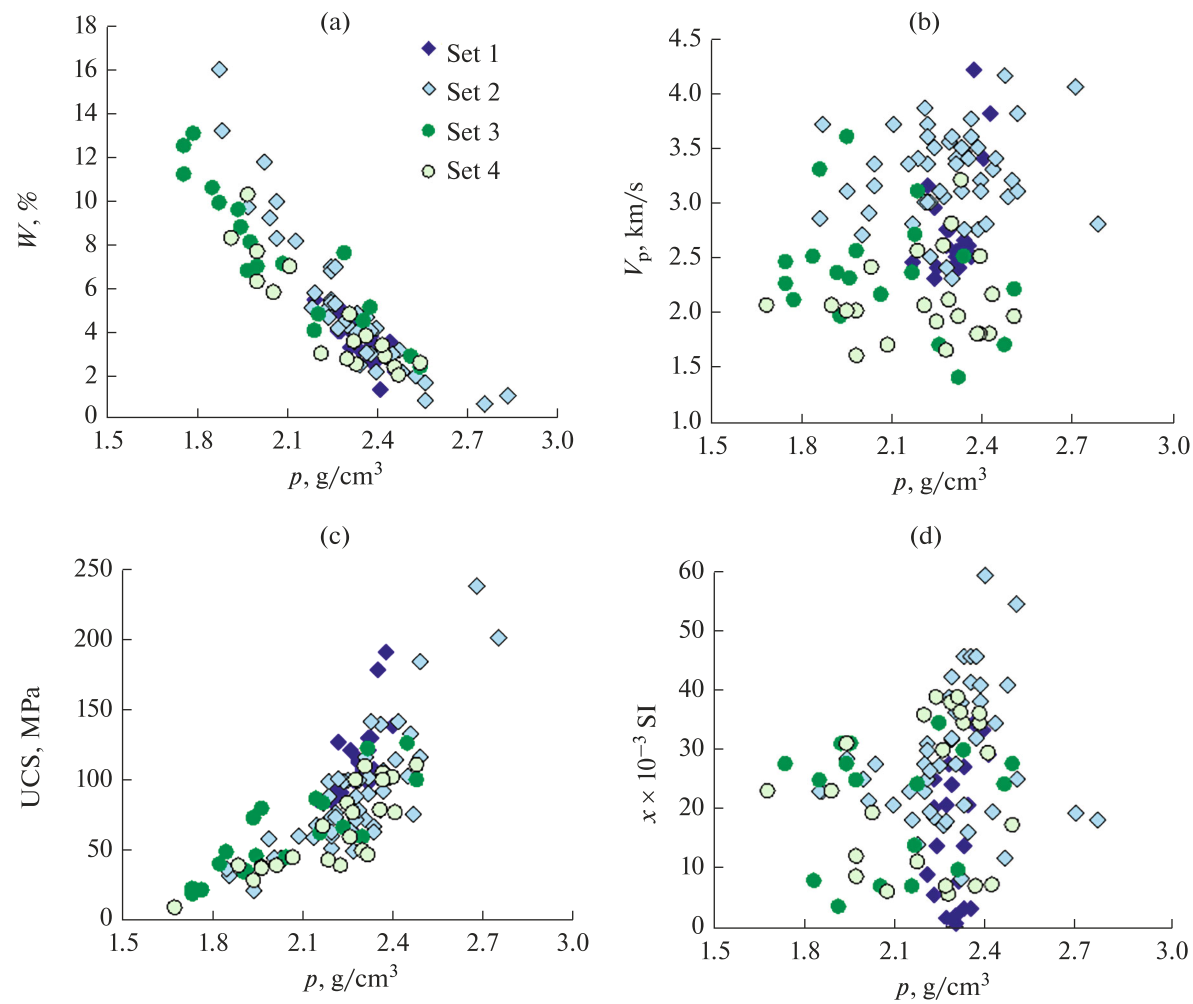

Fig. 4. Various parameters of rocks sampled from extrusions on Bezymianny as functions of bulk density. (a) Water saturation, (b) P-wave velocity in air dry condition, (c) uniaxial compressive strength in air dry condition, (d) magnetic susceptibility.

(1990) determined concrete different ages of formation for these domes. Based on a study of the respective petrophysical parameters, we believe that Ekspeditsiya and Lokhmaty were formed at about the same time, that is, have about the same age, viz., 3300–5500 years.

Consider the mean values of petrophysical parameters for the Bezymianny extrusive rocks, with Lokhmaty being treated as belonging to the third set (Table 3). The first set of dome lavas includes dacites, the second mostly consists of hornblende andesites with a small fraction of pyroxene andesite, the third includes hornblende andesites, and the fourth mostly consists of pyroxene andesites with a small fraction of hornblende andesite.

The mean bulk density of dome lavas for the first, second, and fourth sets is the same, while that of the third is much lower (2.28 and 2.05 g/cm^3, respectively). The grain density of the older lavas has a slightly greater than that for younger ones (2.75–2.76 g/cm^3 and 2.70–2.71 g/cm^3, respectively). The mean porosity is approximately the same for rocks of the first and fourth sets (17–19%), and the second and third (22–23%), although the range of its variation is the widest for the lavas of the third set (7.8–35.6%) (see Table 3). The mean P-wave velocities steadily decrease from the older rocks in the first and second sets (2.65 and 3.26 km/s, respectively) toward the youngest andesites of the fourth set (2.11 km/s). The mean uniaxial compressive strength is the greatest in the older dacitic lavas, the least strength occurs in hornblende andesites, although the ranges of strength variation within the second, third, and fourth sets are wide enough, and it is the Plotina pyroxene andesites which have the highest strength. The mean values of magnetic susceptibility can be arranged in a compositional series: dacites (18.3 × 10^{-3} SI), the hornblende andesites (19.9 × 10^{-3} SI), pyroxene-dominated andesites (25.1 × 10^{-3} SI), and the hornblende and pyroxene andesites (27.3 × 10^{-3} SI). It is to be noted that the highest values of

Table 2. The mean values of petrophysical parameters and strength for Bezymianny extrusive rocks

Extrusive dome	ρ, g/cm^3	$ρ_s$, g/cm^3	*n*, %	*W*, %	V_p, km/s	V_p w, km/s	UCS $_d$, MPa	UCS $_w$, MPa	BTS, MPa	χ × 10^{-3} SI
Set 1 (old domes)										
Gladky	2.23	2.76	19.1	4.5	2.40	3.15	97	96	8	13.7
Pravilny	2.30	2.76	16.6	3.4	2.95	3.60	138	111	13	18.8
Pestrye Khrebtiki	2.30	2.72	16.0	3.7	2.60	3.00	101	78	8	22.4
Set 2 (less old domes)										
Plotina	2.32			3.9	3.40	4.05	90	65	8	33.8
Stupenchaty	2.12	2.81	28.5	7.4	3.35	4.00	75	60	8	24.6
Dvuglavy	2.29	2.70	15.2	3.4	3.35	3.70	114	100	13	17.9
Kulich	2.39			3.4	2.95	3.60	103	96	12	32.9
Set 3 (domes aged 3300–5500 years)										
Ekspeditsiya	2.08	2.71	24.0	7.7	2.25	3.20	55	43	4	20.4
Pobochny	2.00			8.3	2.50	3.65	65	52	6	22.7
Set 4 (domes on Bezymianny edifice and inside it)										
Lokhmaty	2.04	2.69	22.4	6.3	2.10	3.35	50	32	4	15.6
Vysoky	2.09	2.66	14.7	3.6	2.65	3.35	94	89	6	36.0
Pogrebenny	2.28			2.7	2.20	3.35	62	40	4	35.0
Novy	2.38	2.75	12.7	2.9	1.85	3.05	88	77	7	17.1

The names and notation for rock parameters can be found in main text

Table 3. Petrophysical parameters and strength for Bezymianny extrusive rocks

Domes	ρ, g/cm^3	$ρ_s$, g/cm^3	*n*, %	V_p, km/s	UCS $_d$, MPa	χ × 10^{-3} SI
Set 1	2.28 (21) / 2.2–2.38	2.76 (21) / 2.68–2.76	17 (21) / 14–22.1	2.65 (21) / 2.3–4.2	112 (21) / 86–179	18.3 (21) / 0.7–28.9
Set 2	2.27 (51) / 1.85–2.75	2.75 (2) / 2.7–2.81	22 (7) / 12.6–28.5	3.26 (51) / 2.3–4.15	95 (51) / 22–238	27.3 (48) / 8.2–58.8
Set 3	2.05 (27) / 1.74–2.48	2.70 (7) / 2.61–2.75	23 (15) / 7.8–35.6	2.30 (27) / 1.4–3.6	58 (27) / 19–126	19.9 (25) / 3.4–37.4
Set 4	2.28 (15) / 1.68–2.48	2.71 (4) / 2.66–2.76	19(4) / 12.7–36.8	2.11(14) / 1.65–3.2	73(15) / 10–111	25.1(15) / 5.4–38.4

The numerator shows the mean value based on the number of samples shown in parentheses; the denominator shows the minimal and maximal values

magnetic susceptibility occur in pyroxene andesites in which the fraction of phenocrysts reaches 50%, while the concentration of ore minerals does not exceed 10% (Kulich).

Overall, the petrophysical properties both for older and for younger extrusive rocks are similar, and so are their respective parameters (see Table 3). However, the factors that control those properties are different for the older and younger rocks.

It is known that extrusive domes have zonal structure (Borisova and Borisov, 1974; Macdonald, 1972). When extrusive lavas came onto the ground surface, their outer layers were probably "frothing", similarly to the present-day lava flows that were extruded out onto the Novy dome slopes (Ladygin et al., 2012). The older extrusions that were formed more than 11 ka B.P. have been gradually losing their outer porous brittle layers, thus exposing their massive and monolithic central rocks (this is supported by the presence of numerous debris and screes on the dome slopes). It was due to this that the rocks of the first and second sets possess higher values of petrophysical parameters. The youngest rocks of the fourth set appeared on the Earth's surface comparatively recently (about 40–1000 B.P.), they have not been subjected to long-continued weathering, and their petrophysical parameters are high too. The rocks of the third set were probably formed 3300–5500 years ago. Sufficient time has elapsed to weaken their rocks and reduce their strength, but the process has not gone as far as to leave only the monolithic parts of these extrusions at the ground surface.

Table 4. Petrophysical parameters and strength for Bezymianny rocks of various origin

Relative age	ρ, g/cm^3	$ρ_s$, g/cm^3	*n*, %	V_p, km/s	UCS $_d$, MPa	χ × 10^{-3} SI
Extrusive features						
Old (sets 1–3)	2.21(108) / 1.68–2.68	2.73(32) / 2.61–2.82	19(45) / 7.8–36.8	2.85(107) / 1.4–4.2	84(108) / 10–238	24(103) / 0.7–58.8
Young (Novy Dome)	2.38(6) / 2.26–2.48	2.75(2) / 2.75–2.76	13 (2)	1.85(6) / 1.65–2.15	88(6) / 77–102	17.1(6) / 6.8–35.7
Effusive features (from Ladygin et al., 2012)						
Old	2.43 (53) / 1.49–2.73	2.81(53) / 2.71–2.91	13(53) / 4–45	3.12(53) / 1.75–4.65	115(53) / 18–221	23.1(53) / 3–87
Young	1.94(21) / 1.13–2.47	2.71(21) / 2.67–2.75	28(21) / 8–58	1.81(21) / 1.5–2.1	44(19) / 3–169	18.5(20) / 1.4–47

The numerator shows the mean value based on the number of samples given in parentheses; the denominator shows the minimal and maximal values.

Comparative Petrophysical Characterization of the Rocks that Compose the Extrusive Domes and the Lava Flows

The conditions during the formation of extrusive and effusive rocks on Bezymianny were different: a long-continued extrusion of a viscous melt over an area of 0.1 to 2.12 km^2 (extrusive domes) and a comparatively rapid formation of a lava flow extending for distances of between 300 m and 5 km. Some individual domes on Bezymianny which consist of numerous lava blocks can reach heights of 280 m, while lava flow thicknesses do not exceed 25–30 m. Differences in crystallization conditions (the rate and time of cooling for magma melt, pressure, and the gas component) produce a diversity of resulting textures including porphyritic and aphyric, hyalopilitic and intersertal, less frequently microlithic, which in turn affects rock properties. Probably the leading factor for the distinctive properties of extrusive and effusive rocks consists in different conditions of their generation. As to mineral composition, all rock sets are dominated by volcanic glass and plagioclase, while ore minerals, hornblende, and/or pyroxenes are found in lesser amounts.

The older lava flows have the greatest mean bulk density (2.43 g/cm^3), the young and old extrusive rocks have lower bulk densities (2.38 and 2.21 g/cm^3, respectively), and the young lava flows possess the lowest bulk density (1.94 g/cm^3) (Table 4).

It has been shown by Ladygin et al. (2012) that P-wave velocities are low in the Bezymianny lava flows. This is primarily due to micro cracking of the volcanites arising in its turn from the conditions of cooling and crystallization for these rocks (Ladygin and Nikitin, 1980). We note that the tendency of P-wave velocity increasing from younger rocks to older ones is characteristic of both extrusive domes and lava flows (see Table 4).

The uniaxial compressive strength is higher in older rocks compared with younger ones, independent of whether they are extrusive or effusive (see Table 4). As pointed out above and in (Ladygin et al., 2012), this is due to the weathering of porous outer layers in old extrusive blocks and lava flows as time goes on. Today only their monolithic parts have been left, and these have greater strength.

One peculiar feature of the Bezymianny rocks consists in the fact that the least values of magnetic susceptibility occur in present-day lavas in both extrusions and lava flows, while the greatest values occur in the older rocks of these features dominated by hornblende andesites and pyroxene andesites.

We conclude by discussing one important question that arises in the mapping of volcanogenic features: how is one to determine the genesis of rocks that are similar in composition? The application of petrophysical parameters in rocks to separate volcanogenic features of different genesis is described, e.g., in (Kantsel et al., 1968). Let us discuss whether the Bezymianny rocks of different genesis (extrusive and effusive types) can be distinguished based on their petrophysical properties, all the more so because, according to Borisova and Borisov (1974), neither bulk chemical composition nor mineral composition enable reliable differentiation between the rocks of lava flows and of extrusive domes.

Overall, the petrophysical parameters of rocks in older lava flows (mean bulk density, mean grain density, P-wave velocity, and strength) are higher than the mean values for all sets of extrusive features and young lava flows. In turn, the lavas of young flows have the least parameters among the abovementioned rocks; in addition, the frothed lavas in the upper parts of young lava flows have higher porosity that can reach 58% (see Table 4). It follows that, if andesitic lavas of uncertain origin have extremely low values of all petrophysical parameters and a high porosity, there is a great likelihood that they are young rocks of effusive origin. Conversely, high petrophysical parameters would indicate older rocks of effusive genesis. Whatever their age, extrusive rocks occupy an intermediate position based on their petrophysical properties between young and old rocks in lava flows.

It can thus be said that detailed petrophysical analysis can distinguish between rocks of different genesis that have similar petrographic compositions; this is possible, in particular, for rocks of extrusive and effusive origin.

CONCLUSIONS

(1) The rocks that compose the Bezymianny extrusive domes are dacites, as well as hornblende andesites and pyroxene andesites. The rocks of various domes contain 10 to 80% porphyritic phenocrysts consisting of plagioclase (which has been detected in all rocks), hornblende, pyroxene, and ore minerals (titanomagnetite and magnetite in amounts of 5 to 30%, mostly 10%). The groundmass of all rocks invariably consists of volcanic glass, plagioclase, and ore minerals, which are "diluted" with hornblende and/or pyroxene in varying ratios.

(2) The petrophysical properties of the rocks sampled on the extrusive domes vary in wide ranges depending on mineral composition, texture and structure, porosity, and micro cracking: bulk density varies between 1.74 and 2.75 g/cm^3 (the majority of values, 72%, occurs in the range 2.2–2.5 g/cm^3); P-wave velocity is between 1.4 and 4.2 km/s; uniaxial compressive strength is between 22 and 238 MPa; and magnetic susceptibility ranges between 0.7 and 58.8×10^{-3} SI.

(3) One peculiarity of the dome rocks consists in relatively low elastic wave velocities independent of texture and porosity, which is in overall agreement with the situation for Upper Pleistocene to Holocene volcanic rocks.

(4) We have found a tendency of increasing bulk density, strength, and the velocities of elastic waves from younger rocks to older extrusions. This seems to be related to gradual weathering of outer porous layers of extrusive domes and exposure of their inner parts, which are massive and monolithic.

(5) We show for Bezymianny Volcano that the conditions under which extrusive and effusive processes are occurring affect the petrophysical properties of resulting rocks. The differences among petrophysical parameters of rocks can be used to determine more accurate origins of volcanic rocks that have similar petrographical characteristics.

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