

Distribution of Felsic-Mafic Intrusive and Extrusive Rocks in the Earth's Crust: Correlation with Magma Viscosity Regularities

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Received 27 August 2018; accepted 5 February 2019

Abstract—New regularities of the viscosity of near-liquid felsic, medium, and mafic hydrous magmas have been established in a wide range of thermodynamic parameters and the Earth's crust depths (1–30 km). The study was carried out using our new structural and chemical model of reliable predictions and by calculation of the viscosity of magmas of almost any composition. It is shown that these regularities are actually a quantitative physicochemical basis explaining the cause of the relative distribution of intrusive and effusive felsic and mafic rocks in the Earth's crust. This confirms V.S. Sobolev's idea of the relationship between the relative distribution of intrusive and effusive felsic, medium, and mafic rocks in the Earth's crust and the laws of changes in the viscosity of hydrous magmas in a variable P – T field.

Keywords: viscosity, hydrous magmas, granite, andesite, basalt, Earth's crust, regularities, structural and chemical model, rhyolite, diorite, gabbro, temperature, pressure

INTRODUCTION

The knowledge of the average values and range of changes in the volume ratios of intrusive and effusive rocks (I:E) in the Earth's crust is important for establishing the nature of magmatic activity in different geotectonic zones of the Earth and in different geologic epochs. It is also helpful for approaching the correct solution to the problem of the origin of igneous rocks in general. However, the I:E coefficients are difficult to estimate accurately, because plutonic rocks can be buried under sediments, or volcanic rocks can be destroyed, or the relationship between volcanic and plutonic rocks is uncertain. Seismic, geodetic, and electromagnetic methods can yield the size of the partial- or full-melting regions beneath the volcanoes. However, the size of a magma source formed during a single melting period in the Earth's crust, compared to a longer period of the Earth's history, cannot be a valid indicator of the total intrusive volume (White et al., 2006). The calculations made by Soloviev (1970) for the territory of the Soviet Union and by Daly (1933) for the territory of the United States give an idea of the relative prevalence of the main types of igneous rocks within the continents. The researchers found that granites and granodiorites, making up more than 84% of the area occupied by intrusive rocks, are the most common among intrusive rocks within the Earth's crust. Among the main mafic plutonic rocks, the most developed were rocks close in

composition to gabbro. Among the effusive formations, to a lesser extent, the bulk belongs to basalts and then to andesites, which together occupy more than 85% of the total area of development of effusive rocks. The next are rhyolites, and a very insignificant role is played by alkaline effusions. However, the difficult task of establishing strict quantitative ratios of plutonic and volcanic rocks in the Earth's crust remains controversial to this day (Winrker, 1962; Harris et al., 1970; Shaw, 1975; Crisp, 1984; Christiansen, 2001; White et al., 2006; Glazner et al., 2015; Lundstrom and Glazner, 2016). For example, the relationship between acidic volcanic and plutonic rocks has long been debated by geologists, because a significant set of studies in petrology, geochemistry, geochronology, thermal and thermodynamic modeling, and geophysical methods leads to conflicting interpretations, discussed in detail in a number of works (Lipman, 1984; White et al., 2006; Glazner et al., 2015; Lundstrom, Glazner, 2016).

The main factors that correlate with the volume ratio of plutonic and volcanic rocks observed in nature in the Earth's crust are as follows: the composition of magma; its degree of crystallinity and fluid saturation; oxygen potential $f(\text{O}_2)$; crustal thickness; tectonic setting and regional stresses, (Winkler, 1962; Harris et al., 1970; Lukanin, 1985; Di Genova et al., 2017). The ratios of intrusive and extrusive volumes are typically around 5:1 for the oceanic crust and 10:1 for the continental crust. This difference seems to reflect the unequal rate of magma rise associated with different crustal thicknesses and magma compositions (Winkler, 1962; Harris et al., 1970; Marsh, 1981). Note that in very few areas of the Earth the main parts of both volcanic and

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associated plutonic rocks are preserved and exposed. A typical example of acidic rocks is the Yellowstone supervolcano. Geophysical studies indicate that a volume of approximately $32,800 \pm 4,200 \text{ km}^3$ of granite plutonic rock is contained there (Crisp, 1984; Christiansen, 2001). The volume of volcanic rocks formed in Yellowstone during the last 2.2 Ma is from 3550 to 7250 km^3 . Comparison of intrusive with extrusive volumes (I:E) for the Yellowstone field gives a ratio between 4:1 and 10:1 (Persikov, 2019). In the review paper (White et al., 2006), based on an analysis of the volume of volcanic and plutonic rocks of more than 170 provinces of the Earth, a ratio (I:E) of 5:1 is given, which the authors take as the average value for most magmatic systems, while emphasizing the significant uncertainty of this estimate. Based on the data obtained, the authors rightly note a systematic and significant correlation between the ratio (I:E) and the composition of magma, and hence its viscosity. It is known that the viscosity of magmas largely determines the nature of the movement of magmatic melts in the Earth's crust and upper mantle, textural features of intrusions and effusions, and many other features of magmatic rocks (Zavaritsky and Sobolev, 1961; Sobolev, 1973; Persikov, 1984, 1991). Relying on physicochemical analysis of the fusion diagrams of silicate–water systems and petrological analysis of magma–water systems in the Earth's crust and upper mantle, Sobolev proposed a general scheme of vertical movement of magmas in the Earth's crust and upper mantle, formed at different values of P_{lith} and $p_{\text{H}_2\text{O}}$, and proved the impossibility of outpouring of magmas with water content in them $X(\text{H}_2\text{O}) > 1\text{--}2 \text{ wt.}\%$ (Sobolev, 1973). A little earlier Sobolev had proposed (oral report, 1971) to ex-

plain relative prevalence of intrusive and effusive rock masses of acidic, intermediate, and mafic compositions in the Earth's crust based on the understanding of the laws of viscosity of hydrous magmas in a variable field of temperatures and pressures. Alas, in those years it was not possible to solve this problem, because experimental and theoretical studies of the viscosity of such melts at high pressures were just beginning.

It should be noted that the first attempt to solve this problem at the semiquantitative level was made earlier on the basis of the experimental and theoretical results obtained at that time on the viscosity of magmatic melts (Persikov, 1984, 1991). It took more than two decades of such studies, the main result of which was the developed physicochemical model of reliable predictions and calculations of the viscosity of heterogeneous magmas of almost any composition from acidic to ultramafic in a variable field of temperatures and pressures of the Earth's crust and upper mantle. The new structural-chemical model for the first time allows calculating and predicting the viscosity of magmatic melts of almost any composition as a function of the following parameters: (1) temperature; (2) total and fluid pressures; (3) melt composition, including volatile components (H_2O , OH^- , CO_2 , CO_3^{2-} , F, and Cl); (4) ratios of cations: $\text{Al}^{3+}/(\text{Al}^{3+} + \text{Si}^{4+})$, $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$, $\text{Al}^{3+}/(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Fe}^{2+})$; (5) volume content of crystals and bubbles (up to 45% by volume) (Persikov, 1998, 2007; Persikov and Bukhtiyarov, 2009; Persikov et al., 2015; and references therein). The characteristic features of this model are as follows: (1) structural-chemical approach; (2) the maximum possible simplicity of analytical dependences; (3) high ac-

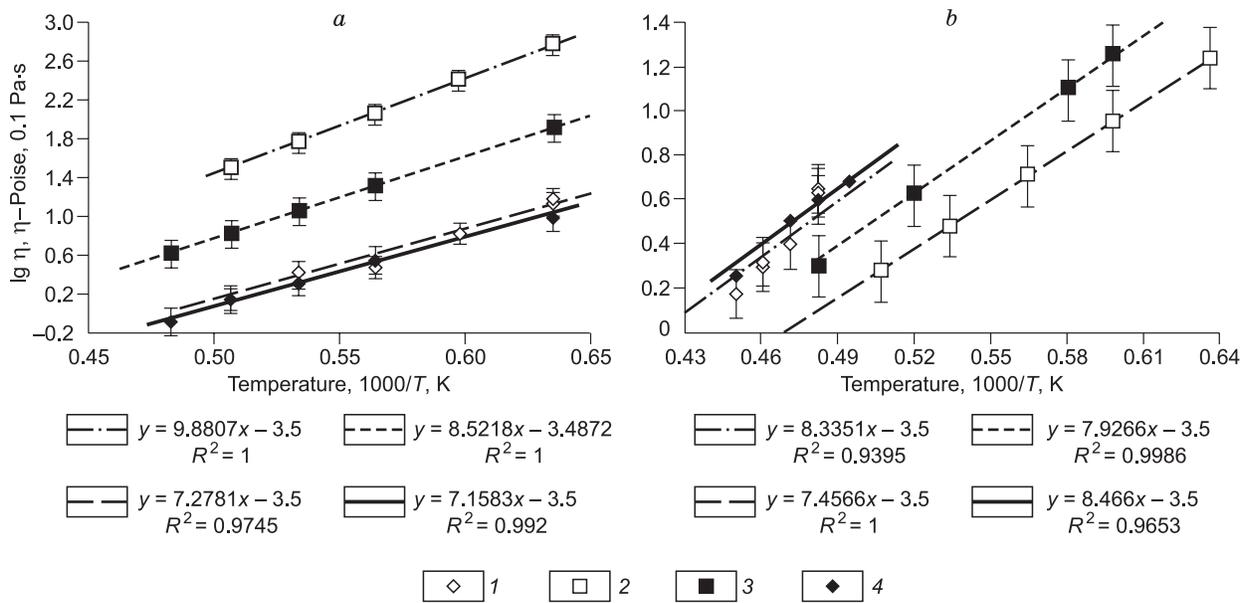


Fig. 1. Temperature dependences of the viscosity of anhydrous and hydrous kimberlite and basaltic melts. The error of experimental and calculated data is $\pm 30\%$ rel.; the experimental data on the temperature dependences of the viscosity of dry melts are taken from (Persikov et al., 2015); *a*, Partial pressure $p_{\text{H}_2\text{O}} = 100 \text{ MPa}$; *b*, lithostatic pressure $P_{\text{lith}} = 5.5 \text{ GPa}$. 1, anhydrous kimberlite melts; 2, anhydrous basaltic melts; 3, water-containing basaltic melts, $X(\text{H}_2\text{O}) = 3 \text{ wt.}\%$; 4, water-containing kimberlite melts, $X(\text{H}_2\text{O}) = 3 \text{ wt.}\%$ (Persikov et al., 2017).

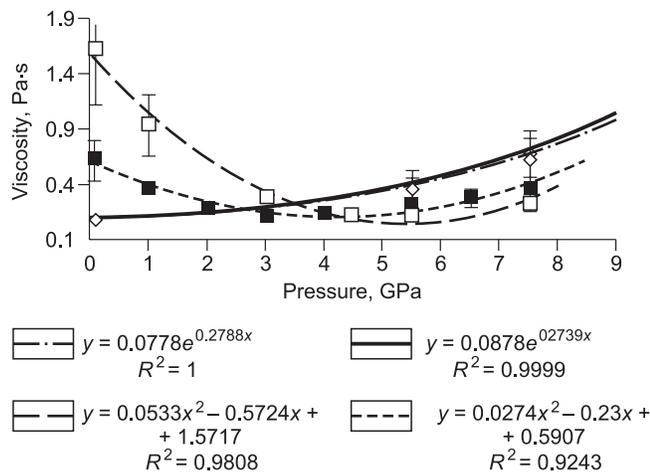


Fig. 2. Isothermal (1800 °C) pressure dependences of the viscosity of anhydrous and hydrous ($X(\text{H}_2\text{O}) = 3$ wt.%) kimberlite and basaltic melts. The error of the experimental and calculated data is ± 30 rel.% (Persikov et al., 2017). For symbols, see Fig. 1.

accuracy of the predict (± 30 rel.%), commensurate with the experimental error of viscosity measurements for such melts at high pressures. The model was developed with the use of experimental and theoretical results of a long-term study carried out by the author and colleagues as well as the entire bank of published experimental data on the viscosity of magmatic melts obtained in many laboratories around the world. A simple and convenient computer program has been developed, which is used in this paper and is recommended for calculations of the viscosity of magmas and water diffusion in them when modeling the processes of origin and evolution of magmas and their dynamics. Applying this model, in the recent work (Persikov, 2019), reliable regularities of the viscosity and structure of near-liquid water-containing granitic magmas were obtained for the first time, at thermodynamic parameters corresponding to a wide range of depths of the Earth's crust (1–30 km). For additional verification of the model-based predictions of magma viscosity, we compare Figs. 1, 2 new experimental and prediction data on temperature and pressure dependences of the viscosity of water-containing and anhydrous kimberlite and basalt melts in a wide range of temperatures (1200–1950 °C) and pressures (0.1–7.5 GPa) in the Earth's crust and upper mantle.

It is obvious that the data on the viscosity of such melts (Figs. 1, 2) obtained from the model correspond very well to the experimental results within the specified accuracy. In this paper, the patterns of changes in the viscosity of near-liquid hydrous magmas of intermediate and mafic compositions were established, which were compared with the previously established patterns of changes in the viscosity of near-liquid hydrous granitic magmas (Persikov, 2019) at T - P parameters of the Earth's crust. These results, along with the physicochemical analysis of the structural features of hydrous magmas in the acidic-mafic series, quantitatively confirm Sobolev's idea of the relationship between the laws

of magma viscosity and the relative crustal prevalence of such intrusive and effusive rocks in the acidic-mafic series.

RESULTS AND DISCUSSION

The modified theoretical Arrhenius-Frenkel-Eyring equation (Persikov, 1998, 2007; Persikov and Bukhtiyarov, 2009; Persikov et al., 2015) was used for calculations of concentration, temperature, and pressure dependences of the viscosity of magmatic melts in the acidic-intermediate-mafic magma range:

$$\eta_T^P = \eta_0 \exp(E_X^P/RT), \quad (1)$$

where E_X^P (J/mol) is the activation energy of the viscous flow, which is a function of:

(1) the composition of the magmatic melt, (2) the concentration of two forms of dissolved water in it (OH^- and H_2O), and (3) the pressure; η_T^P is the magma viscosity at a given temperature and pressure (Pa·s); η_0 is a pre-exponential constant (Pa·s) characterizing the melt viscosity at $T \rightarrow \infty$ ($\log h_0 = -4.5 \pm 0.14$); T is the temperature (K); $R = 8.3192$ (J/mol·K) is a gas constant.

Of all the physical and chemical properties of silicate and magmatic melts, the viscosity has the most complicated relationship with the composition of the liquid and its structure. The degree of viscosity sensitivity to changes in the composition and structure of magmatic melts is clearly characterized, for example, by the following experimental data: In the granite-basalt series, the viscosity of near-liquid melts decreases by a huge amount, approximately by 10^3 times (Persikov, 1984, 1991, 1998). This complex problem was solved quite correctly on the basis of the structural-chemical approach, using theoretical equation (1), which is described in detail in a number of papers (Persikov, 1984, 1991, 1998, 2007; Persikov and Bukhtiyarov, 2009). To characterize the features of the chemical composition and structure of magmas, the parameter $-100\text{NBO}/T$ is used, i.e., the ratio of the amount of nonbridging oxygen in melt ($\text{NBO} = \text{O}^{2-} + \text{O}^-$) to the sum of the network-forming cations of the melt $T = (\text{Al}^{3+} + \text{Si}^{4+} + \text{Fe}^{3+} + \text{Ti}^{4+} + \text{P}^{5+} + \text{B}^{3+})$. This parameter, which we call the degree of depolymerization, or the basicity coefficient of magmas (Persikov, 1984, 1991, 1998, 2007), or the percentage of broken bonds in the melt structure, after (Carron, 1969; Shaw, 1972), reflects the structure and composition of magmas adequately and with the greatest sensitivity. It should be emphasized that for the range of magma compositions from acidic to mafic, this parameter varies from 0 to 100, whereas the similar NBO/T parameter, often used in western literature (Mysen, 1991), changes in the same range of magma compositions only from 0 to 1. This is important because the NBO/T parameter is close to 0 for polymerized granitic melts and therefore cannot reflect the chemistry and structure of polymerized granitic magmas (Persikov, 1984, 1991; Di Genova et al.,

2017). For example, confirming this deficiency of the structural-chemical parameter NBO/T , it is shown in (Di Genova et al., 2017) that the influence of water concentration and the degree of crystallinity of acidic magma alone cannot explain the correlation between the composition of magma and cyclicality of the effusive and explosive nature of volcanic eruptions of acidic rocks of the Yellowstone field. The authors of (Di Genova et al., 2017) proposed three other structural parameters which might be effective in explaining this feature of acidic volcanism of similar composition:

1. $RAI = (Na_2O + K_2O + CaO + MgO + FeO)/(Al_2O_3 + Fe_2O_3)$ – rheological apgaitic index;
2. Molar ratio $K = K_2O/(K_2O + Na_2O)$;
3. Oxidation state of iron in magma ($FeO/(FeO + Fe_2O_3)$).

The authors refer to the published models of viscosity prediction (Hui and Zhang, 2007; Giordano et al., 2008), which, in their opinion, cannot explain the observed phenomenon. This conclusion is undoubtedly true, but, unfortunately, these authors are apparently not familiar with our model of calculations and prediction of magmatic melt viscosity (Persikov, 2007; Persikov and Bukhtiyarov, 2009; Persikov et al., 2015), in which all these structural parameters are taken into account, along with the $100NBO/T$ parameter (see above and (Persikov, 2007; Persikov and Bukhtiyarov, 2009; Persikov et al., 2015)). The $100NBO/T$ parameter does not have the same drawback noted above for granitic melts, especially water-containing ones, changes significantly (see below), and is used in our model to calculate the activation energy of the viscous flow of magmatic melts. Calculation of the $100NBO/T$ parameter is made based on the chemical composition of the melt, expressed in wt.% oxides, by a simple method (Persikov, 1984, 1991, 1998) using equation (2):

$$100NBO/T = 200 \cdot (O - 2T) / T, \quad (2)$$

where T is the total number of gram-ions of the melt formers in the melt structure $T = (Si^{4+}, Al^{3+}, Fe^{3+}, Ti^{4+}, P^{5+}, B^{3+})$, located in fourfold coordination to oxygen and making up the anionic part of the structure, and O is the total number of gram-ions of oxygen in the melt.

It should be noted that a generalized structural-chemical dependence of the activation energy of the viscous flow of magmatic melts was previously obtained. According to it, the entire range of compositions of natural magmas is divided into four sections, with different degrees of change in the activation energy and, accordingly, viscosity, depending on the composition and structure of magma (Persikov, 1998, 2007; Persikov and Bukhtiyarov, 2009). The range of magma compositions in the acidic-mafic series corresponds to the first two sites:

- (1) fully polymerized acidic magma, $O \leq 100NBO/T \leq 17$;
- (2) partially depolymerized intermediate-mafic magmas, $17 \leq 100NBO/T \leq 100$.

In this range of magma compositions, the fracture points of the dependence $E = f(100NBO/T)$ characterize qualitative

changes in the structure of magmatic melts: At $100NBO/T = 17$, the decay of the three-dimensional framework structure is completed, and at $100NBO/T = 100$, the formation of di- and metasilicate structures in magmatic melts is completed, respectively (Persikov, 1984, 1991, 1998). The initial chemical compositions of the rocks used in this work, along with the degree of depolymerization of their melts, are given in Table 1. The average compositions of granite (rhyolite) and basalt obtained in (Le Maitre, 1976) on the basis of more than 3500 analyses of granite and basalt compositions from almost all regions of the world were chosen as representative compositions of acidic and basic rocks. As a representative composition of intermediate rocks (andesite and diorite), the composition of andesite from Avacha Volcano (Kamchatka) was chosen, the chemical composition of which is close to the average composition of andesites, according to the work (Le Maitre, 1976), and the viscosity of such a melt had been previously studied experimentally at high pressures (Bukhtiyarov et al., 1987).

It is important to emphasize the following:

1. It is now reliably established, on the basis of a significant amount of experimental-theoretical data, that from a wide range of compositions of the fluid of acidic, intermediate, and mafic magmas (H_2O , CO_2 , HCl , $NaCl$, HF , NaF , and H_2S), water dissolving in magmas in two forms (chemical (hydroxyl OH^-) and physical (molecular H_2O)) has a

Table 1. Chemical composition (wt.%) and structural-chemical parameters ($100NBO/T$) of the starting granite, andesite, and basalt

Component	Granite*	Andesite**	Basalt***
SiO ₂	72.82	58.56	49.06
Al ₂ O ₃	13.27	18.98	15.67
Fe ₂ O ₃	1.48	3.96	3.84
FeO	1.11	3.9	7.31
B ₂ O ₃	0	0	0
MnO	0.06	0.16	0.20
MgO	0.39	3.48	6.82
CaO	1.14	6.17	9.47
Na ₂ O	3.55	3.24	2.91
K ₂ O	4.3	0.92	1.10
TiO ₂	0.28	0	1.82
P ₂ O ₅	0.07	0	0.34
Li ₂ O	0	0	0
H ₂ O (molec.)	1.1	0	0.93
OH ⁻ (basic)	0.31	0	0.42
OH ⁻ (acid)	0	0	0
CO ₂	0.08	0	0.11
CO ₃ ²⁻	0	0	0
F	0	0	0
Total	99.65	100.00	100.00
100NBO/T	5.93	21.2	56

* Average composition of granite (Le Maitre, 1976).

** Andesite, Avacha Volcano, Kamchatka (Bukhtiyarov et al., 1987).

*** Average composition of basalt (Le Maitre, 1976).

decisive influence on the viscosity of such magmas: The chemical form depolymerizes the melt and greatly reduces the melt viscosity, and the physical form has no effect on the structure and to a lesser extent reduces the melt viscosity. That is, a pseudobinary magma–water system with a good degree of approximation (Persikov, 1991, 1998). Note also the previously established important results: Limit capacity of melts by chemically dissolved water (hydroxyl OH^-) decreases with increasing degree of depolymerization (basicity) of magmas: granitic magmas ~ 6.4 wt.%, andesitic magmas ~ 4 wt.% and basaltic magma ~ 3 wt.%. (Persikov, 1991, 1998; Persikov and Bukhtiyarov, 2009). It should be noted that the problem of reliable determination of the numerical ratio of the two forms of water dissolved in such melts ($\text{OH}^-/\text{H}_2\text{O}$) at different temperatures and pressures is still debatable (Kadik et al., 1971; Stolper, 1982; Persikov, 1991, 1998; Nowak and Behrens, 1995). Our experimental and theoretical results, as well as data obtained in a number of other works (Nowak and Behrens, 1995), definitely confirm the mentioned limiting capacity of these melts by the amount of chemically dissolved water in them at high temperatures. However, it is known that molecular H_2O prevails in quenched melts (glasses) obtained by isobaric quenching of water-containing melts, especially after experiments at $p_{\text{H}_2\text{O}} \geq 200$ MPa, (Stolper, 1982; Persikov, 1984, 1991, 1998; Nowak and Behrens, 1995).

2. An anomaly of dependence of viscosity of magmas in the acidic–mafic range of compositions on total (lithostatic) and water pressures has been established. Contrary to theoretical assumptions, the viscosity of such magmas decreases with an increase in of both total (lithostatic) pressure and partial pressure of H_2O (Persikov, 1991, 1998). Naturally, these features: the pressure dependence of magma viscosity and the mechanism of water dissolution in magmatic melts are taken into account in this paper (Table 2).

3. Due to the fact that there is no geological evidence of significant overheating of acidic, intermediate and mafic magmas in different facies of the Earth's crust, it is of great interest to estimate the viscosity of near-liquid magmas in the acidic–mafic range of compositions in relation to the structure.

Figure 3 shows a diagram of the viscosity of magma– H_2O systems: granitic melts–water (Persikov, 2019), the andesitic melts–water, and basaltic melts–water at thermodynamic parameters of their near-liquid state ($T = T_{\text{liq}} - 50$ °C), in conditions of almost the full range of crustal depths (1–30 km). In its construction, experimental and theoretical results of studies of the parameters of melting of granite, andesite, and basalt rocks in the presence of water vapor were used (Kadik et al., 1971; Perchuk, 1973; Persikov, 1984, 1991, 1998), and the melt viscosity under these conditions was calculated using our model. Table 2 presents the calculated viscosity values of water-containing granitic (Persikov, 2019), andesitic, and basaltic melts at the parameters indicated in the table: (1) near-liquid temperatures, i.e., temperatures 50 °C lower than the experimentally estab-

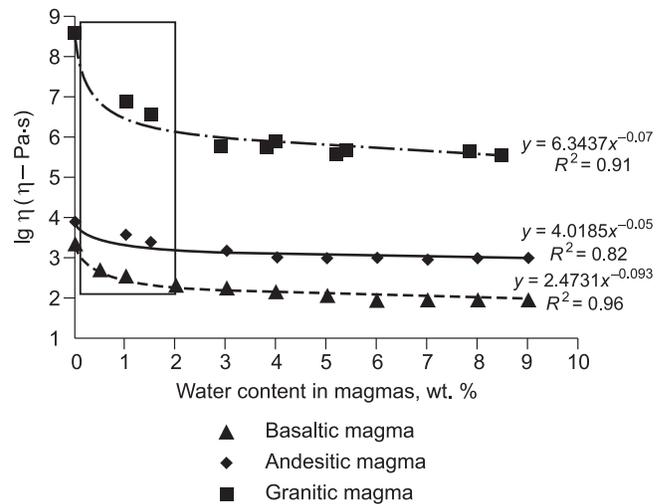


Fig. 3. Patterns of the viscosity of near-liquid ($T = T_{\text{liq}} - 50$ °C) water-containing granitic (Persikov, 2019), andesitic, and basaltic magmas in a wide range of depths of the Earth's crust (1–30 km). $p_{\text{H}_2\text{O}} = 10$ –600 MPa, $P_{\text{lith}} -$ up to 1000 MPa, $T = 680$ –1100 °C (Table 2).

lished corresponding liquidus temperatures (Kadik et al., 1971; Perchuk, 1973; Persikov, 1984, 1991, 1998); (2) pressures (total P_{lith}) and partial pressure $p_{\text{H}_2\text{O}}$; (3) water content in magmas ($\text{OH}^- + \text{H}_2\text{O}$); (4) values of the degree of depolymerization of melts ($100\text{NBO}/T$); (5) volume content of crystals and bubbles in magmas. Analysis of the presented results (Fig. 3; Table 2) indicates the following:

1. **Granitic magma.** The data quantitatively confirm many of the features of granitic rocks, such as homogeneity of huge amounts of granitic batholiths formation, a considerable length of dike varieties of granitic intrusions. Near-liquid granitic magmas with a water content of from ~ 2 to ~ 8.0 wt.% are sufficiently mobile melts in a wide range of thermodynamic parameters and crustal depths (1–30 km). We established the relatively low viscosity of water-containing granitic magmas ($\sim 10^{5.7}$ Pa·s) and, most importantly, the almost complete independence of the viscosity of magmas under these conditions from water content in them (Fig. 3) and, accordingly, from the degree of depolymerization ($100\text{NBO}/T = 17$ –53, Table 2). It is a definite indicator of the real possibility of homogenization of large masses of plutonic granitic batholiths and lopoliths in the Earth's crust at different depth by convection and fluid-magmatic mass transfer. Fundamentally different laws of viscosity of granitic magmas were obtained at low content of magmatic water in them (< 2 wt.% Fig. 3; Table 2). These data reflect many features of acidic magmatism in effusive and subvolcanic facies. With almost complete degassing of granitic magmas, their viscosity increases by three orders of magnitude and reaches $\sim 10^8$ – 10^9 Pa·s, and the degree of depolymerization decreases significantly ($100\text{NBO}/T$ from 19 to ~ 4). At this viscosity, polymerized granitic magmas are not able to flow in the form of lava flows and erupt relatively rarely in the form of extrusions or explosive catastrophic

Table 2. Viscosity (η_T^P) and structural-chemical parameters (100NBO/T) of water-containing near-liquid granitic, andesitic and basaltic magmas under thermodynamic parameters of the Earth's crust

P_{lith} MPa	$P_{\text{H}_2\text{O}}$ MPa	$\text{OH}^- + \text{H}_2\text{O}$, wt.%	T , °C	100 NBO/T	$V_{\text{cr.}} + V_{\text{bs}}$, vol.%	$\log \eta_T^P \pm 30$ rel. % ($\eta_T^P - \text{Pa}\cdot\text{s}$)
$P_{\text{lith}} > P_{\text{H}_2\text{O}}$; $T = T_{\text{liq}} - 50$ °C (granitic magmas*)						
10	1	0.02 + 0	975	3.5	10 + 10	8.55
50	30	1.0 + 0.1	1000	11.4	10 + 10	6.9
60	40	1.5 + 0.2	925	15.4	10 + 10	6.6
200	50	2.9 + 0.3	850	26.4	10 + 10	5.9
500	100	4.0 + 0.4	750	35.1	10 + 10	5.6
800	200	5.19 + 0.5	720	44.6	10 + 10	5.65
1000	300	6.4 + 1.45	670	54.1	10 + 10	5.8
500	100	3.83 + 0.4	850	33.8	10 + 10	5.64
800	200	5.4 + 0.5	750	46.2	10 + 10	5.6
1000	300	6.4 + 2.45	680	54.1	10 + 10	5.7
$P_{\text{lith}} > P_{\text{H}_2\text{O}}$; $T = T_{\text{liq}} - 50$ °C (andesitic magmas)						
10	1	0.02 + 0	1090	21	30 + 20	3.9
100	30	1.0 + 0.1	1070	30	20 + 20	3.6
200	50	1.5 + 0.2	1050	34	15 + 15	3.4
400	120	3.0 + 0.3	1030	47	15 + 15	3.2
500	200	4.0 + 0.4	1010	57	15 + 15	3.05
600	270	4.0 + 1.0	1000	57	15 + 15	3.0
800	350	4.0 + 2.0	990	57	15 + 15	3.0
700	430	4.0 + 3.0	980	57	15 + 15	3.0
1000	520	4.0 + 4.0	970	57	15 + 15	2.98
1000	600	4.0 + 5.0	965	57	15 + 15	3.0
$P_{\text{lith}} > P_{\text{H}_2\text{O}}$; $T = T_{\text{liq}} - 50$ °C (basaltic magmas)						
10	1	0.02 + 0	1100	56	40 + 40	3.4
100	30	0.5 + 0	1090	60	20 + 20	2.74
100	30	1.0 + 0.1	1070	63	15 + 15	2.6
100	50	2 + 0.1	1060	73	15 + 15	2.4
200	120	3.0 + 0.3	1040	83	15 + 15	2.3
400	200	3.0 + 1.0	1020	83	15 + 15	2.2
600	270	3.0 + 2.0	1010	83	15 + 15	2.1
700	350	3.0 + 3.0	1000	83	15 + 15	2.0
800	430	3.0 + 4.0	990	83	10 + 10	2.0
900	520	3.0 + 5.0	980	83	10 + 10	2.03
1000	600	3.0 + 6.0	975	83	10 + 10	2.02

Note: *granitic magmas (Persikov, 2019).

eruptions. The main mass of such granitic magmas will not reach the Earth's surface, and their formation and crystallization will occur in the plutonic facies. This quantitatively confirms the idea of V.S. Sobolev that the laws of viscosity of such magmas correlate with the relative prevalence of the masses of intrusive (granites) and effusive (rhyolites) rocks in the Earth's crust (Persikov, 2019).

2. Andesitic and basaltic magmas showed rheological patterns, which were similar to each other but fundamentally different from granitic ones. At the T - P parameters of their near-liquid state and the large depth range of the crust, an-

desitic and basaltic magmas with a water content of from ~2 to ~9 wt.% are highly mobile melts in a wide range of thermodynamic parameters and depths of the Earth's crust (1–30 km). We obtained the extremely low viscosity of water-saturated andesitic ($\sim 10^3$ Pa·s) and especially basaltic ($\sim 10^2$ Pa·s) magmas and the almost complete independence of the viscosity of magmas in these conditions from the water content in them and from the degree of depolymerization (100NBO/T = 47–57, andesitic melts; 100NBO/T = 73–83, basalt melts, Table 2). This is definitely indicates the real possibility of homogenization of large masses of andesites

and basalts in magmatic chambers in the Earth's crust by convection and fluid-magmatic mass transfer. It should be emphasized that the viscosity of the water-saturated andesitic magmas in this range of H_2O concentrations is three orders of magnitude less than the viscosity of water-saturated granitic magma, and the viscosity of water-saturated basaltic magmas is already four orders of magnitude less. However, the ability to rise to the upper horizons of the Earth's crust, up to the volcanoes, will be shown predominantly by andesitic and basaltic magmas undersaturated with water. This conclusion of Sobolev and others (Sobolev, 1973; Yoder, 1976; Persikov, 1984, 1991, 1998) is confirmed by the obtained data. Indeed, low-viscosity near-liquid andesitic and basaltic magmas saturated with water ($X(H_2O) > 2$ wt.%, Fig. 3) will be intensively degassed when they rise to higher hypsometric levels of the Earth's crust due to a decrease in pressure, dumping excess water through diffusion and bubble mechanisms. The crystallization process of such magmas will also develop intensively due to the increase in their liquidus temperature, caused by the decrease in the partial pressure of H_2O and the relatively low viscosity of these magmas (Persikov, 1984, 1991). Water loss and the crystals and bubbles formed in magma will significantly increase the effective viscosity of heterogeneous magma (1000 and more times for andesitic magma and 100 and more times for basaltic magma), and, accordingly, the rate of magma rise will significantly decrease. Moreover, when the threshold degree of magma crystallinity (≥ 60 vol.%) is reached, it becomes impossible for magma to rise to the upper hypsometric levels up to volcanic eruption (Sobolev, 1973; Yoder, 1976; Marsh, 1981; Russell et al., 2012; Persikov et al., 2015). Eventually, such magma will completely crystallize at depth. But unlike the granitic magmas, near-liquid water-unsaturated andesitic and basaltic magma at low concentration of water ($X(H_2O) \leq 2$ wt.%, Fig. 3) remain very mobile melts even when they degas in the effusive facies with a viscosity of $\sim 10^4$ Pa·s (andesitic melt + crystals + bubbles) and $\sim 10^3$ Pa·s (basaltic melt + crystals + bubbles) (Fig. 3; Table 2). The latter is well correlated with the conclusion of the paper (Sobolev, 1973) and estimates of the viscosity of lava flows of the Great Tolbachik Fissure Eruption (1975–1976) by volcanologists of Kamchatka (Andreev et al., 1978). This feature of the rheology of water-unsaturated andesitic and basaltic magmas is the main cause of the relatively wide distribution of andesite masses in the Earth's crust compared to diorites and, accordingly, of basalt masses compared to gabbro.

CONCLUSION

1. The established patterns of viscosity and structure of near-liquid hydrous magmas in the range of acid–intermediate–mafic compositions at thermodynamic parameters of a wide range of crustal depths (1–30 km) confirm, on a quantitative physicochemical basis, the possible ranges and lim-

its of movement of such magmas at different hypsometric levels in the Earth's crust.

2. These patterns of viscosity of near-liquid hydrous magmas within the range of the acidic–mafic compositions confirm, on a physicochemical basis, Sobolev's idea of the relationship between the viscosity of hydrous magmas and the relative crustal abundance of intrusive and effusive rock masses. Thus, a rigorous physicochemical explanation is given for the natural domination of intrusive masses of granites in the Earth's crust compared to the effusive rhyolites (liparite) and, on the contrary, of massive effusive andesites and basalts compared to the intrusive counterparts (diorite and gabbro).

ACKNOWLEDGEMENTS

The author is grateful to P.G. Bukhtiyarov (Korzhinskii Institute of Experimental Mineralogy) for continuous cooperation in experiments, discussion of results, and critical remarks. Also, the author thanks A.V. Girnits and the anonymous reviewer for their valuable comments on the work, which undoubtedly contributed to the improvement of the original version of the article.

The research was performed under science project AAAA-A18-118020590141-4 of the Korzhinskii Institute of Experimental Mineralogy, program no. 8 of the Presidium of the Russian Academy of Sciences.

REFERENCES

- Andreev, V.I., Gusev, N.A., Kovalev, G.I., Slezin, Y.B., 1978. Dynamics of lava flows of the Southern Breakthrough of the Great Tolbachik eruption, 1975–1976. *Bulleten Vulcanologicheskikh Stanziy*, No. 55, 18–26.
- Bukhtiyarov, P.G., Persikov, E.S., Kalinicheva, T.V., 1987. Viscosity of andesitic melts. *Vulcanologiya i Seismologiya*, No. 5, 45–53.
- Carron, J.-P., 1969. Vue d'ensemble sur la rhéologie des magmas silicatés naturels. *Bul. Soc. Franc. Minéral. Cristallogr.* Vol. 92, 435–446.
- Christiansen, R.L., 2001. The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana, in: USGS Prof. Paper, Vol. 729, pp. 1–146.
- Crisp, J.A., 1984. Ratios of magma emplacement and volcanic output. *J. Volcanol. Geotherm. Res.* 20, 177–211.
- Daly, R.A., 1933. *Igneous Rocks and Depths of the Earth*. McGraw-Hill, New York–London.
- Di Genova, D., Kolzenburg, S., Wiesmaier, S., Dallanave E., Neuville, D.R., Hess, K.U., Dingwell, D.B., 2017. A compositional tipping point governing the mobilization and eruption style of rhyolitic magma. *Nature* 552, 235–238.
- Giordano, D., Russell, J.K., Dingwell, D.B., 2008. Viscosity of magmatic liquids: A model. *Earth Planet. Sci. Lett.* 271, 123–134.
- Glazner, A.F., Coleman, D.S., Mills, R.D., 2015. The volcanic-plutonic connection, in: Breikreuz, C., Rocchi, S. (Eds.), *Physical Geology of Shallow Magmatic Systems: Dykes, Sills, and Laccoliths*. Springer International Publishing, New York, pp. 1–22.
- Harris, P., Kennedy, W., Scarf, K., 1970. Volcanism versus plutonism – The effect of chemical composition, in: Newall, G., Rast, N. (Eds.), *Mechanism of Igneous Intrusions*. Liverpool Geol. Soc. Symp., Proc.: Geol. J. Spec. Issue 2, pp. 187–200.

- Hui, H.J., Zhang, Y., 2007. Toward a general viscosity equation for natural anhydrous and hydrous silicate melts. *Geochim. Cosmochim. Acta* 71, 403–416.
- Kadik, A.A., Lebedev, E.B., Khitarov, N.I., 1971. Water in Magmatic Melts [in Russian]. Nauka, Moscow.
- Le Maitre, R.W., 1976. The chemical variability of some common igneous rocks. *J. Petrol.* 17 (4), 589–637.
- Lipman, P.W., 1984. The roots of ash flow calderas in western North America: Windows into the tops of granitic batholiths, *J. Geophys. Res.* 89, 8801–8841.
- Lukanin, O.A., 1985. On the causes of bimodal distribution of volcanic series rocks. *Geokhimiya*, No. 3, 348–359.
- Lundstrom, C.C., Glazner, A.F., 2016. Silicic magmatism and the volcanic–plutonic connection. *Elements* 12, 91–96.
- Marsh, B., 1981. On the crystallinity, probability of occurrence, and rheology of lava and magma. *Contrib. Mineral. Petrol.* 78 (1), 85–98.
- Mysen, B.O., 1991. Relation between structure, redox equilibria of iron, and properties of magmatic liquids, in: Perchuk, L.L., Kushiro, I. (Eds.), *Physical Chemistry of Magmas*. Springer-Verlag, New York, Vol. 9, pp. 41–98.
- Nowak, M., Behrens, H., 1995. The speciation of water in haplogranitic glasses and melts determined by in situ near-infrared spectroscopy. *Geochim. Cosmochim. Acta* 59 (16), 3445–3450.
- Perchuk, L.L., 1973. Thermodynamic Regime of Deep Petrogenesis [in Russian]. Nauka, Moscow.
- Persikov, E.S., 1984. The Viscosity of Magmatic Melts [in Russian]. Nauka, Moscow.
- Persikov, E.S., 1991. The viscosity of magmatic liquids: experiment, generalized patterns; a model for calculation and prediction; application, in: Perchuk, L.L., Kushiro, I. (Eds.), *Physical Chemistry of Magmas*. Springer-Verlag, New York, Vol. 9, pp. 1–40.
- Persikov, E.S., 1998. The viscosity of model and magmatic melts under P – T parameters of the Earth's crust and upper mantle. *Russian Geology and Geophysics (Geologiya i Geofizika)*, 39 (12), 1780–1792 (1798–1804).
- Persikov, E.S., 2007. Structural chemical model to calculate and predict the viscosity of magmatic melts in full range of composition and conditions. General Assembly EGU-2007. Vienna. *Geophysical Research Abstracts*, Vol. 9. A-02262. SRef-ID: 1607-7962/gra/EGU2007-A-02262.
- Persikov, E.S., 2019. The relationship between the relative abundance of masses of granites and rhyolites in the Earth's crust with the laws of the rheology of the granitoid magmas. *Petrology* 5, 18–29.
- Persikov, E.S., Bukhtiyarov, P.G., 2009. Interrelated structural chemical model to predict and calculate viscosity of magmatic melts and water diffusion in a wide range of compositions and T – P parameters of the Earth's crust and upper mantle. *Russian Geology and Geophysics (Geologiya i Geofizika)* 50 (12), 1079–1090 (1393–1408).
- Persikov, E.S., Bukhtiyarov, P.G., Sokol, A.G., 2015. Change in the viscosity of kimberlite and basaltic magmas during their origin and evolution (prediction). *Russian Geology and Geophysics (Geologiya i Geofizika)* 56 (6), 885–892 (1131–1140).
- Persikov, E.S., Bukhtiyarov, P.G., Sokol, A.G., 2017. Viscosity of hydrous kimberlite and basaltic melts at high pressures. *Russian Geology and Geophysics (Geologiya i Geofizika)* 58 (9), 1093–1100 (1377–1387).
- Russell, J.K., Porritt, L.A., Lavallée, Y., Dingwell, D.B., 2012. Kimberlite ascent by assimilation-fuelled buoyancy. *Nature* 481 (7381), 352–356.
- Shaw, H., 1975. Links between magma-tectonic rate balances, plutonism, and volcanism. *J. Geophys. Res.* 90, 11275–11288.
- Sobolev, V.S., 1973. Structure of the Upper Mantle and Methods of Magma Formation [in Russian]. Nauka, Moscow.
- Soloviev, S.P., 1970. Chemistry of Igneous Rocks and Some Questions of Petrochemistry [in Russian]. Nauka, Leningrad.
- Stolper, E.M., 1982. Water in silicate glasses: an infrared spectroscopic study. *Contrib. Mineral. Petrol.* 81 (1), 1–17.
- White, S.M., Crisp, J.A., Spera, F.J., 2006. Long-term volumetric eruption rates and magma budgets. *Geochem. Geophys. Geosyst.* 7 (3), 1–20.
- Winkler, H.G.F., 1962. Viel Basalt und wenig Gabbro – und wenig Rhyolith und viel Granit. *Beitr. Mineral. Petrogr.* 8, 222–231.
- Yoder, H.S., 1976. Generation of Basaltic Magma. *Nat. Acad. Sci., Washington*.
- Zavaritsky, A.N., Sobolev, V.S., 1961. Physical and Chemical Bases of Petrography of Igneous Rocks [in Russian]. Gosgeoltekhizdat, Moscow.