INCLUSIONS IN VOLCANIC ROCKS AND A MECHANISM FOR TRIGGERING VOLCANIC ERUPTIONS

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In this study examples of eruptions of two different types of porous inclusions (cumulative and magmatic) in volcanic rocks are considered, and the process of their formation and flotation as a driving force of eruption from shallow magmatic chambers is investigated. The low densities of both types of inclusions, a result of the porosity of their interstitial glass, allows us to suggest that porous inclusions are capable of floating to and concentrating in the upper portion of the chamber (at or near the exit). This process is evidenced by (1) the characteristics of their distribution, (2) the concentration of inclusions on top of lava flows and domes, and (3) the independent overbursts of the inclusions during the initial stages of some eruptions. Lifting of the inclusions, accompanied by expansion of volatiles, involves an increase of the liquid pressure in the chamber in accordance with the gas-lifting mechanism and volcanic eruption results.

INTRODUCTION

The most probable cause of volcanic explosions is believed to be the process of gas release and lifting (Anderson, 1976; Sparks *et al.*, 1977; Sparks, 1978; Steinberg *et al.*, 1989a–c; Michaelides, 1989). In addition to the traditional model of gas-bubble formation (vesiculation) as a cause of volcanic eruptions, the gas-bubble lifting model has also been proposed during recent years (Steinberg *et al.*, 1989a; Michaelides, 1989). Studies on some reported eruptions imply that gas lifting is the mechanism by which the fluid pressure increases enough to initiate eruption (Steinberg *et al.*, 1989b,c).

This process seems rather effective and rapid for low-viscosity basic magmas (comparable in time with periods between eruptions); however, it seems unlikely for high-viscosity siliceous and intermediate magmas. In addition, calculation of mass exchange between magma and the gas bubble lifting shows that even though an increase in fluid pressure exists its quantitative effect is negligible (Steinberg *et al.*, 1989c).

A more promising mechanism is believed to be the lifting of gas bubbles and their surrounding melt ("magma parcel") (Michaelides, 1989) because of the much higher velocity of lifting and the absence of mass exchange. It is believed that different types of porous inclusions in volcanic rocks provide the key to use realization of the proposed mechanism.

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INCLUSIONS IN VOLCANIC ROCKS

A number of cognate inclusions in volcanic rocks from some recently active volcanoes in the Kuril-Kamchatka island arc were studied. At first, inclusions were studied petrographically for their genetic classification. Field measurements of their sizes and the characteristics of their distribution were also made. Xenolites were excluded from further consideration. Finally, the densities of the inclusions and of their host rocks were measured for comparison. The following two types of inclusions have proved to be the most abundant:

1. Cumulate segregations of different stages of fractional crystallization. These inclusions are peculiar to rocks with different composition but occur more often in the siliceous and intermediate rocks.
2. Porous magmatic inclusions of basalt–andesite composition with chilled groundmass. These inclusions occur only in siliceous and intermediate rocks.

The abundance of these types of inclusions seems to reflect the fact that two main processes of petrogenesis are responsible for their generation: (1) fractional differentiation of magma in the chambers, and (2) periodical refilling of these chambers by new pulses of hot basic magma from below (Arculus and Wills, 1980; Bacon, 1986). Similar types of inclusions occur in intrusive bodies (Vernon, 1984) showing that they have been formed in magma chambers.

The sizes of most of the inclusions studied were in the range of 1 to 20 cm; the maximal observable inclusion reached a size of 1 m. The shape of inclusions varied from ellipsoid to irregular. Magmatic inclusions are often surrounded by a thin (0.1–1 cm) chilled margin with unusual hollow and dendritic microlites, proving supercooling due to fast crystallization (Lofgren, 1974).

The character of the distribution of inclusions was log-normal (Figure 1) and rather similar in most volcanoes. The higher proportions of large inclusions led to deviation of the distribution from normal law. Most of the small inclusions (1–2 cm) probably represented the debris chilled margin of the larger ones. This was confirmed by their irregular debris-like morphology and by skeletal microlites.
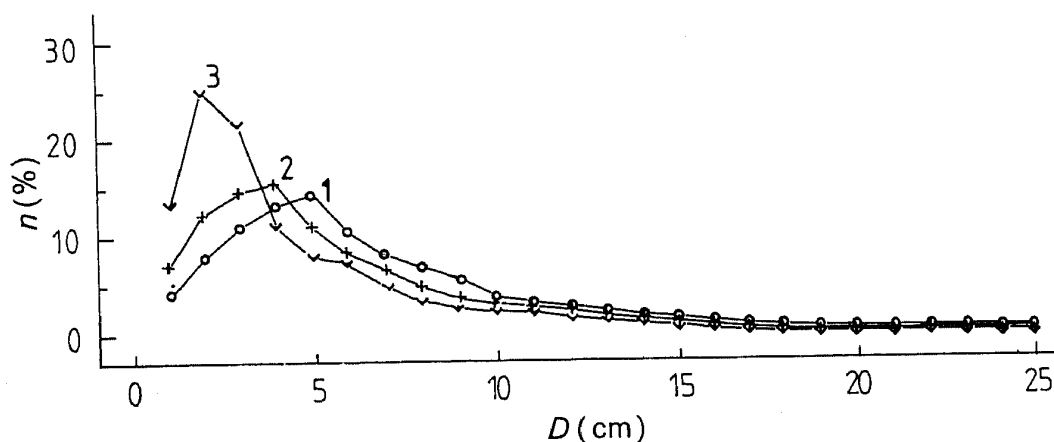

Figure 1   The character of diameter distribution of magmatic inclusions in a series of consecutive eruptions of the Dikii Greben' volcano (southern Kamchatka). Numbers indicate the order of the eruptions.

Magmatic inclusions sometimes concentrate at the heads of extrusive domes and lava flows (Bacon, 1986). Some extrusive domes look like puddings due to the abundance of inclusions.

Petrographically, both types of inclusion consisted of slightly zoned phenocrysts merged into a strongly porous groundmass (Figure 2). The latter is formed by strongly zoned elongated or skeletal microlites with a small amount of interstitial glass. Both types of inclusion are more basic than host and show a much greater degree of crystallinity (80-90%).

The observable proportion of the interstitial glass changes in the range of 5-25%. Amphybole and biotite occur as microlites in the groundmass of inclusions from some volcanoes. This indicates that microlites, groundmass and the inclusions themselves have been formed at water pressure conditions less than the stability field of these H_2O-bearing minerals. Using the results of Eggler (1972) the depth of inclusion formation can be estimated at more than 1.5-4.5 km (0.5-1.5 kbar). It is safe to conclude that inclusions have already been formed in the magma chamber.

The measured density of the inclusions was 0.1-0.3 g/cm^3 lower than that of their host rocks (Table 1) in each of the volcanoes studied. However, the density of the powder of inclusions is always greater than that of host rocks. Therefore, the lower volume density of inclusions is due to the high porosity of their interstitial glass (Figure 1). The lower density of the magmatic inclusions is considered to be the result of vesiculation—gas bubbles being released in the course of rapid crystallization of the hot mafic magma in the cold siliceous host (Eichelberger, 1980). The lower density of cumulate inclusions results from gas
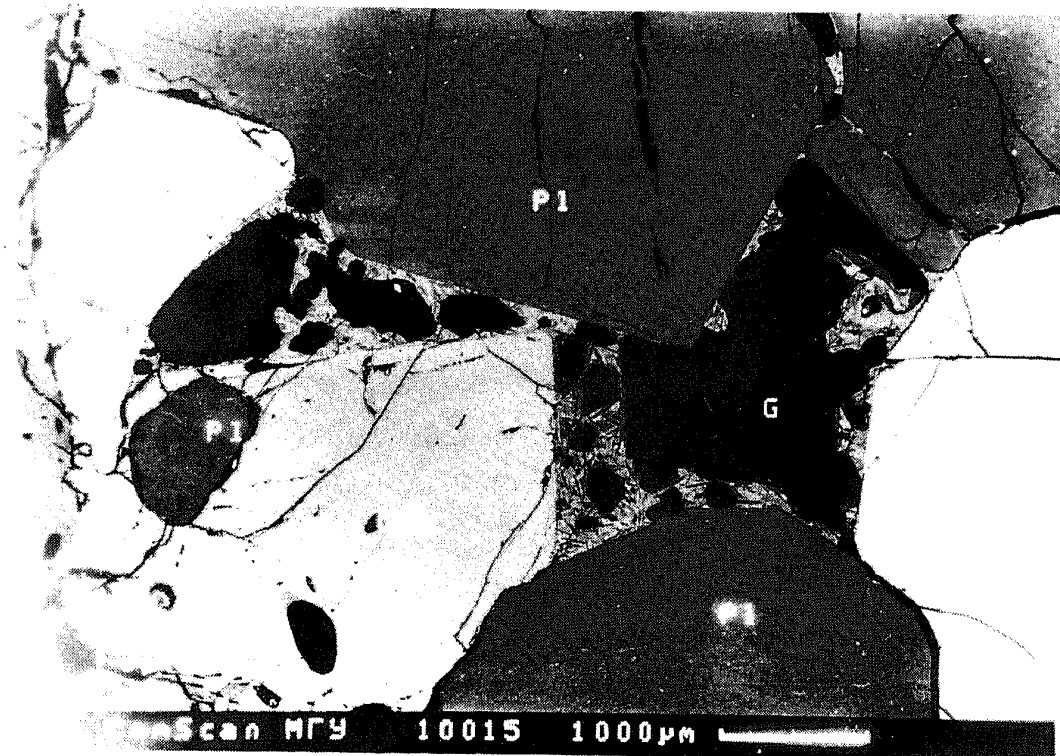

Figure 2 Micrograph of a porous cumulative inclusion from the Zheltovskii volcano (southern Kamchatka).

Table 1 Density of some types of cumulative and magmatic inclusions in comparison with density of host rocks (depth of chamber is according to the geophysical data of Fedotov et al., 1977; Zlobin, 1987; and Lewis, 1973)

Volcano	Type of volcano	Depth of the chamber (km)	The character of eruption of inclusions	Host rock	Type of inclusions	Average density of rock (g/cm³)	Average density of inclusions (g/cm³)	No. samples	Dispersion (units)
Zheltovskii (Kamchatka)	Caldera	n.d.	Independent overburst	Basalts	c: 01-An-Cpx	2.68	2.46	6	0.025
Ksudach (Kamchatka)	Caldera	n.d.	Pumice overburst	Dacitic rhyolites	c: 01-An	2.42	2.34	5	0.035
Bezymyany (Kamchatka)	Stratovolcano	n.d.	Pyroclastic overburst and extrusion	Andesites	m: Basaltic andesite	2.51	2.10	3	0.01
Avacha (Kamchatka)	Caldera stratovolcano	5	Scoria cone	Andesite	c: 01-Cpx	2.60	2.52	1	–
Dikii Greben (Kamchatka)	Complicated volcano-extrusion	n.d.	Domes and flows	Dacites, rhyolites	m: Basaltic	2.33	2.18	22	0.0004
Zhavaritskii (Kuril Islands)	Caldera	2–3 and 5–6	Independent overburst, pumice overburst	Dacites, rhyolites	c: 01-An	2.46	2.33	6	0.01
Mendeleev (Kuril Islands)	Caldera stratovolcano	8	Lava flow	Basaltic andesites	c: 01-An	2.65	2.52	20	0.02
			Extrusive dome	Dacites	m: Basaltic andesite	2.29	2.16	13	0.009
Golovnin (Kuril Islands)	Caldera	5	Pumice overburst	Dacites	c: 01-An	2.31	2.17	4	0.003
Soufriere (Lesser Antilles)	Caldera	6	Nuée ardente	Andesites	c: 01-Pl	n.d.	n.d.	–	–

n.d., Not determined.
c, Cumulate inclusions (An, anortite; Cpx, elinopyroxene; m, magmatic inclusions; Ol, olivine; Pl, plagioclase).

release in the intercumulus glass during the course of adcumulus growth of cumulus minerals in the cold walls of the magma chamber (Bindeman, 1991). Therefore, both these processes are due to a much earlier release of fluid in the mafic magma (magmatic drops or mafic intercumulus melt), compared to that in the more siliceous host. This fact may be interpreted by the lower solubility of the fluid in the mafic magma.

Both types of inclusions often erupt at the first stages of eruption (nueé ardente and lithic blocks of Soufriere, 1902; Mont-Pelee, Bezymyanni, 1956; etc. (Hay, 1959; Gorshkov and Bogoyavlenskaya, 1965; Lewis, 1973; Gourgand et al., 1989; Bindeman, 1991). Independent explosions are very typical of olivine–anorthite cumulates, which are formed at great depths (on the chamber floor) under high water pressure conditions (Arculus and Wills, 1980; Frolova et al., 1989). For example, the nueé ardente of Soufriere is composed of 59% cumulative crystals and inclusions (Hay, 1959). When the products of pyroclastic overbursts in the Zheltovskii and Ksudach volcanoes (southern Kamchatka), which form the directed blast, were observed approximately 40–50% of bombs contained porous cumulative inclusions (Figure 2).

These geological observations provide evidence of concentration of the inclusions on the chamber's roof before eruption.

DISCUSSION

The place and condition of density inversion

The existence of amphybole and biotite in groundmass of some inclusions suggests that inclusions have already been formed in the magma chamber. The fact that inclusions have fewer density than host rocks makes us look for an answer to the question: At what depth do inclusions become less dense and buoyant? Figure 3 shows density changes during the course of retrograde oversaturation of cumulates with an initial proportion of basaltic intercumulus melt equal to 40%, changing to 20% at a temperature of 900°C. For this calculation data on the $P-V-T$ properties of water and carbon dioxide (Burnham et al., 1969; Shmulovich, 1988) and on the solubility of these components in basaltic liquids (Kadik et al., 1971; Shilobreeva and Kadik, 1985) were used. Also it was assumed that gas bubbles do not escape from cumulates after oversaturation.

Similar diagrams for the lowering of densities of mafic magma during the course of retrograde oversaturation were presented earlier by Eichelberger (1980).

As shown in Figure 3, the decrease in density occurred only at low pressure conditions. This effect rapidly reduces with depth. Therefore, only shallow magmatic chambers and chambers on intermediate depths can produce floating inclusions. These conclusions are consistent with Table 1, which indicates that inclusions occur on caldera volcanoes and volcanoes with shallow chambers.

Flotation of inclusions

The lower density of the inclusions permits their lifting, according to Stoke's law, through the convective or stagnant host melt. Simple calculations show that the most
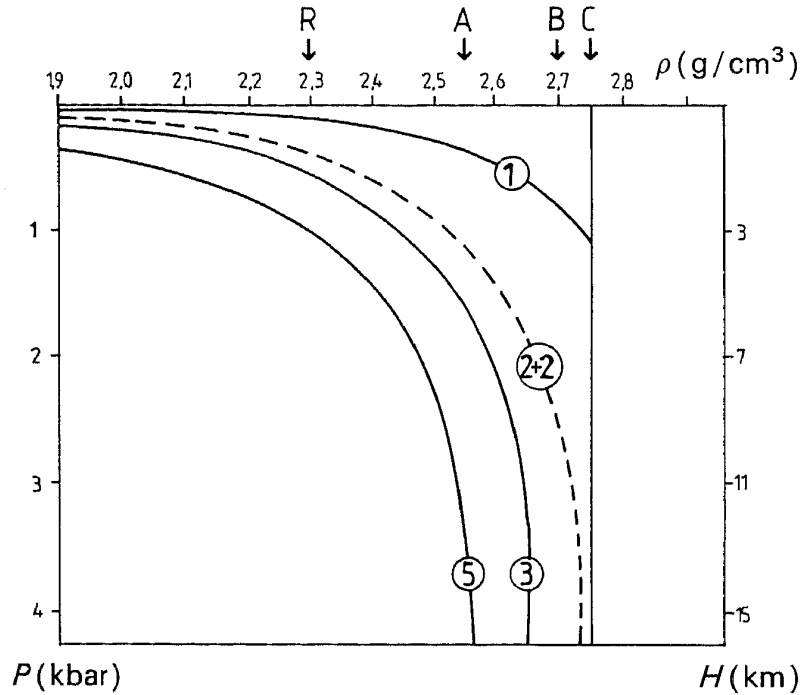
Figure 3 Density change of cumulate due to retrograde oversaturation. Initial density of cumulates is 2.75 g/cm^3, initial proportion of intercumulus melt of basaltic composition is 40% volume, final proportion is 20% volume at final temperature 900°C. Solid lines show the influence of water, where the numbers are the weight fraction of water in the basaltic intercumulus melt, and dashed line shows the influence of 2 weight % water ans 2 weight % carbon dioxide. R, A, B and C are the densities of rhyolite, andesite, basalt and cumulates, respectively. See text for further explanations.

typical inclusions with $\rho = 0.1\text{--}0.2$ g/cm^3 (Table 1), $R = 1\text{--}2$ cm (see Figure 1), float through the viscous melt with $v = 10^6$ poise with the velocity being $68-544$ m/year, whereas the lifting of a gas bubble of $R = 0.1$ mm takes about one thousand years to cover the same distance.

The distribution is direct evidence for flotation of the inclusions. The characteristics of the distribution of the inclusions in a succession of eruption products from the Dikii Greben Volcano (southern Kamchatka) were studied. The results are in good agreement with the fact that large inclusions float faster than small ones (Figure 1) and concentrate at the roof of chamber. The large number of inclusions on the roof of the chamber or in the magmatic column is supported by their higher proportion on the heads of lava flows and domes (observed example and Bacon, 1986).

Inclusions and volcanic eruption

The authors realize that there are many factors related to retrograding oversaturation of magma that cause eruption. The facts discussed above imply that only the lifting of inclusions that comprise expanding volatiles can trigger volcanic eruption. Our calculations pertaining to the increase in pressure in a closed magmatic chamber during flotation of a portion of inclusions with fixed initial distribution (from Figure 1, line 3) support the proposed hypothesis (Figure 4).

At first approximation, the increase of fluid pressure in the closed, absolutely isochoric magmatic chamber of height H, containing magma of density ρ, because
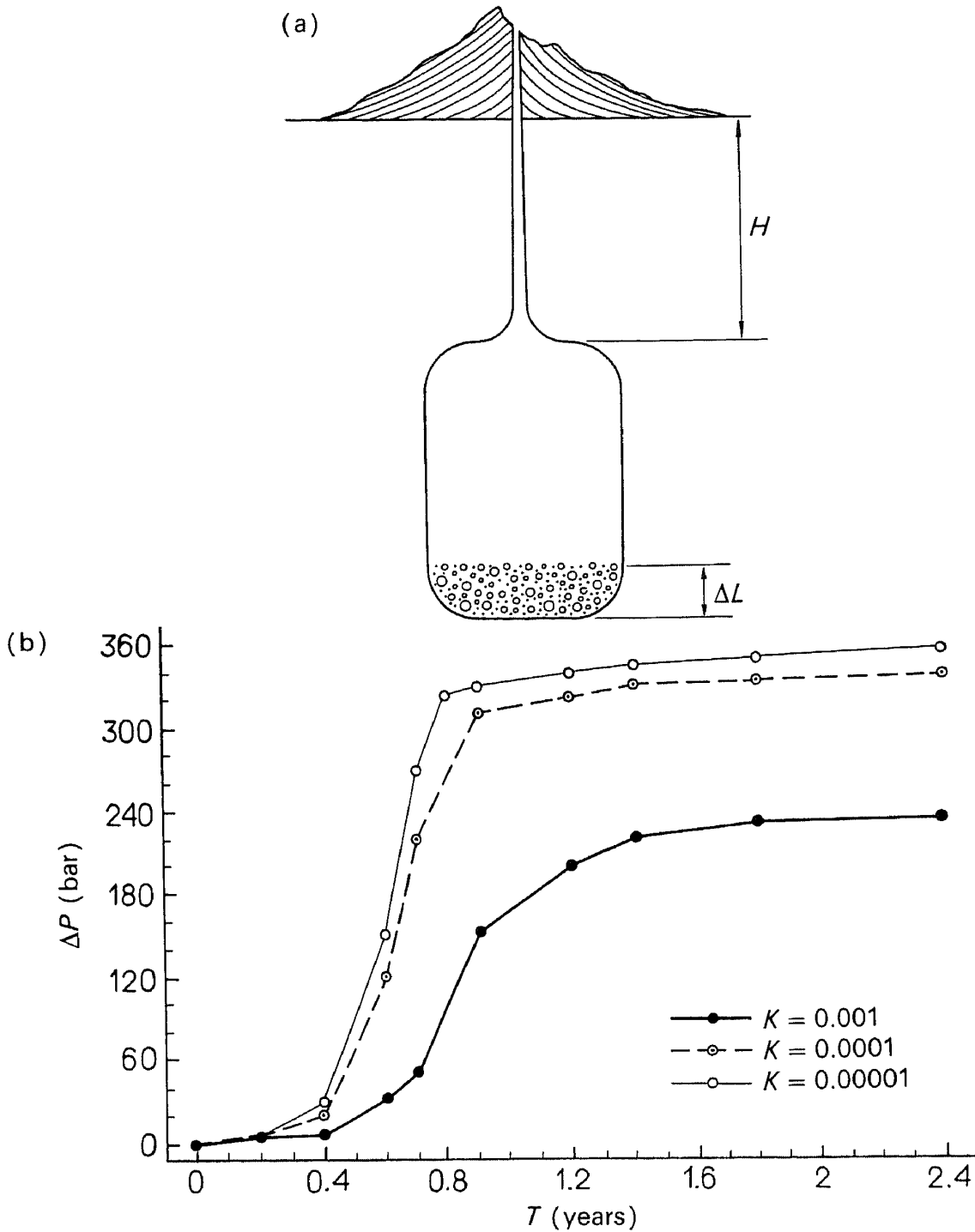
Figure 4 Results of computer modelling of the increase in pressure in a closed magmatic chamber during lifting of the portion of inclusions with fixed initial distribution over size (from Figures 1 and 3). The height of the chamber is 2 km, the magma density is 2.5 g/cm³ and the initial difference between the densities of host magma and inclusions is 0.1 g/cm³. (a) Initial pattern before the lifting process. ΔL, part of the volume of the magmatic chamber occupied by inclusions before the lifting begins near the bottom; H, depth of magmatic chamber; V, Stoke's velocity of lifting of the inclusions. (b) Plot of ΔP against time t at various given values of parameter $K = ZX$, where Z is the effective compressibility of the magma chamber, X is the average initial gas proportion in magma with inclusions near the bottom of the magma chamber, ΔL is 0.05 and H is 2 km. (c) Plot of ΔP against ΔL at given different values of parameter K, where $H = 2$ km and $t = 1.2$ years. (d) Plot of ΔP against H at given different value of parameter Z, where $\Delta L = 0.05$ and $t = 1.2$ years.
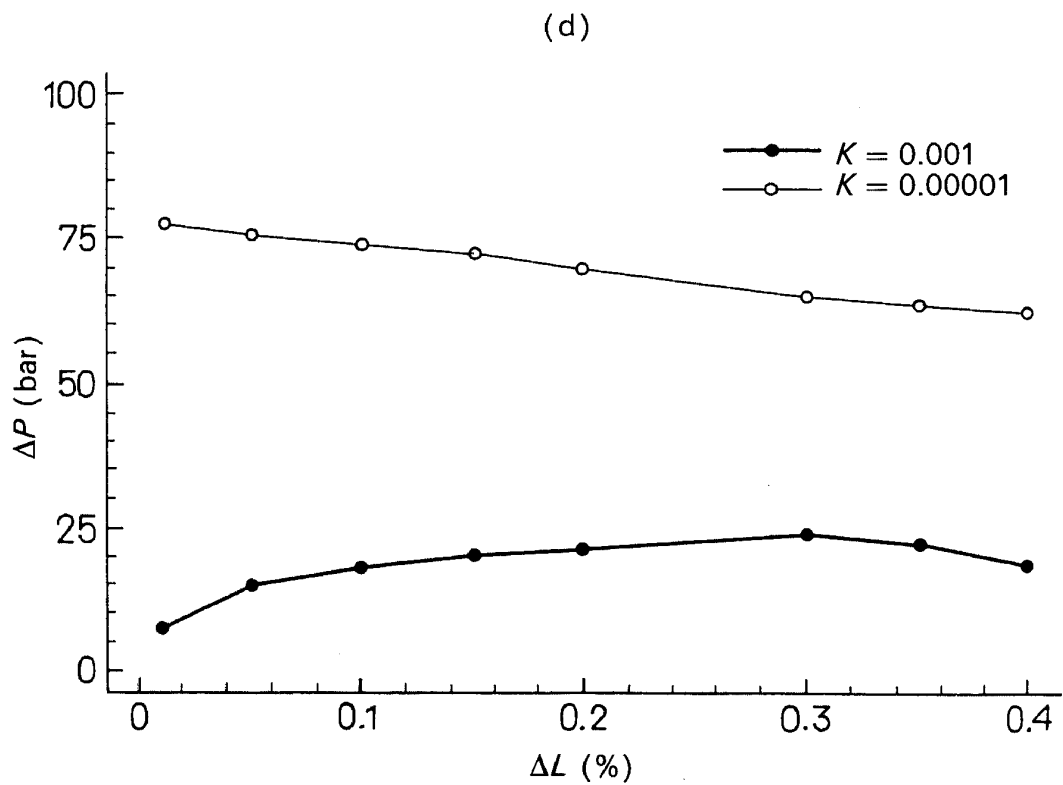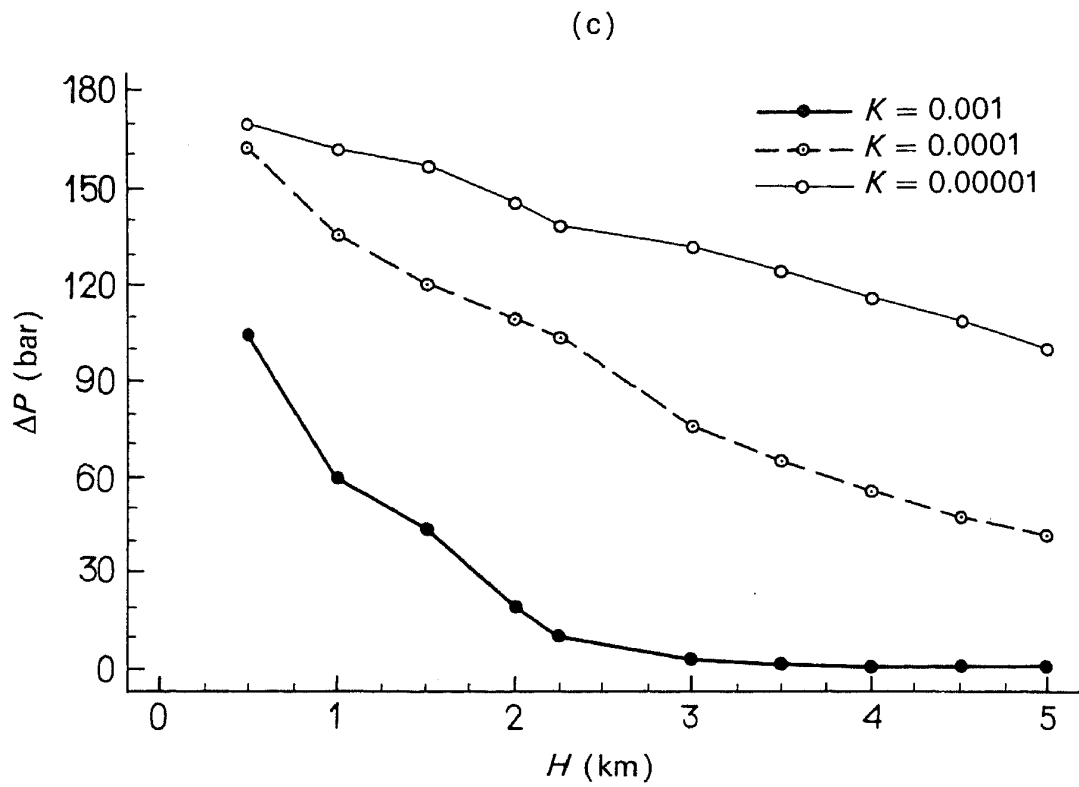
(c)

(d)

Figure 4   *Continued.*

of lifting of the inclusions from the bottom to the roof, can be given as:

$$\Delta P = \rho g H.$$

For $\rho = 2.5$ g/cm^3, $H = 1$ km, ΔP is equal to 250 bars, sufficient to overcome the safety margins of the rocks (Crosely and Pipling, 1977; Clark, 1966) and open the closed system of the magmatic chamber. Theoretically, one inclusion is enough to increase the pressure of a chamber to the required magnitude.

Real magmatic chambers are not absolutely isochoric and can change their volumes. This is demonstrated by the lifting of the surface of the volcano before eruption (see for example Fedotov, 1984). Thus, a number of inclusions is necessary to start eruption.

The following equations can be used for detailed calculations of the increasing fluid pressure in the quasi-isochoric magmatic chamber with initial distribution of the inclusions over size, occupying the initial volume in the vicinity of the chamber floor (Figure 4a and Table 2):

$$P = P^u + \int_{-z}^{0} (1 - X)\rho g \, dz,$$

$$P^u = P^{u0}\left[1 + k \int_{-H}^{0} (X - X^0) \, dz\right],$$

$$X = N \int_{\alpha1}^{\alpha2} \tfrac{4}{3}\Pi a^3 F(a) \, d\alpha/m^3 \quad \text{for } 0 < a_1 < a_2 < a_{max} \text{ or } X = 0,$$

Table 2 Parameters and their values, used in calculations

Symbol	Parameter	Value
z	Vertical coordinate changing from $-H$ at the bottom of the chamber to 0 at the top	
k	Effective compressibility of the chamber	
$F(a)$	Proportion of the inclusions with the diameter a (m^3)	
a_1, a_2	Minimal and maximal diameter of lifting inclusions at the given z and t	
a_{max}	Maximal diameter of the inclusions at $t = 0$	
Q^0	Volume proportion of the inclusions at $t = 0$	
v	Stokes velocity of lifting	
P^u	Pressure at the chamber's roof	
P^{u0}	Pressure at the roof of the chamber before lifting of the inclusions	
t	Time from beginning of lifting	
l	Distance between the top of the chamber and inclusions at $t = 0$	
X	Volume proportion of the gas	
H	Chamber height	2 km
ρ	Host magma density	2.5 g/cm^3
$\Delta\rho$	Density differences between the magma and inclusions	0.1 g/cm^3
v	Viscosity of the host magma	10^6 poise
g	Acceleration due to gravity	980 cm/s^2
N	Quantity of all inclusions in 1 m^3	800
X^0	Volume proportion of the gas in inclusions at $t = 0$	0.15

$$a_2 = \left[\frac{9zv}{2\Delta\rho gt}\right]^{0.5}, \qquad a_1 = \left[\frac{9(z+l)v}{2\Delta\rho gt}\right]^{0.5} \quad \text{for } z > 1 \text{ or } a_1 = 0,$$

$$X^0 = Q^0 \quad \text{for } -H < z < -1, \qquad X^0 = 0 \quad \text{for } -1 < z < 0,$$

$$Q^0 = N \int_0^{\alpha^{max}} \tfrac{4}{3}\Pi a^3 F(a)\, d\alpha/m^3.$$

The results of computer modelling are shown in Figure 4. As shown in Figure 4(b), a significant increase in pressure ΔP is reached at the first stage of lifting, the stage corresponding to flotation of the larger inclusions to the magma chamber roof. Hence, the time required to overcome the value of ΔP for eruptions and the time necessary for large inclusions to rise are comparable.

The second interesting result is an increase in ΔP with decreasing ΔL (the part of the magmatic chamber volume occupied by inclusions before lifting) for "hard" chambers and a reverse regularity for "soft" chambers (see Figure 4c). Thus, "hard" magmatic chambers, increasing the number of inclusions, involve a decrease in the effectiveness of the gas-lifting mechanism.

The connection between the eruption of a shallow magmatic chamber and a caldera volcano (Table 1) depends on three factors:

(1) The effectiveness of decreasing density due to vesiculation.
(2) Lesser values of the critical fluid pressure for eruption.
(3) The gas-lifting mechanism is more effective with increasing depth (see Figure 4d).

The proposed model can explain the curious facts of independent overbursts of large plagioclase twins (Vesuvius, Etna, Erebus, Tolbachik, etc.) (Tasieff, 1978, 1984; Fedotov, 1984). The complex margins of these crystals can capture gas bubbles from magma leading to flotation and eruption of the twins.

Therefore, the overburst of the inclusions at the initial stages of eruption can be considered as a trigger and dangerous volcanological presage of further possible eruption.

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