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ULF oscillations in magma in the period of seismic event preparation

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Abstract

In the period of earthquake preparation, electromagnetic emissions appear over the seismic zones. In this work magma movements are considered as a possible source of ULF electromagnetic emissions over the zones with volcanic activity. Magma movements in the volcanic center are activated in the period of seismic event preparation. Hydrodynamic processes in the moving magma can lead to appearance of waves and vortices in the flow, and the electromagnetic emission induced by ULF flows in the magma is estimated.

The mechanism proposed here allows us to explain some features of electromagnetic emissions in the period of the earthquake preparation: the increase of the electromagnetic emission about 1.5–2 months before an earthquake and a sharp decrease of emission about 1.5–2 days before the earthquake.

Keywords: Magma; Hydrodynamic processes; Magnetic fields

1. Introduction

According to numerous observations the preparation of a seismic event is accompanied usually by electromagnetic emissions at different frequencies (See, for example, Hayakawa, 1999; Hayakawa and Molchanov, 2002; Kopytenko et al., 2002). This phenomenon is explained by changes in the Earth crust in the period before an earthquake. In this work magma is considered as one of possible sources of ULF electromagnetic emissions.

An initial source of magma is located at the depth about 100 km. With the increase in volcanic activity magma moves upward to the Earth's surface through volcano channels, filling intermediate volcanic capacities. The magma capacities are close to the Earth's surface, and their depth can vary from 2 to 20 km. Their radius is about a few kilometers. For example, according to the numerical estimations, there is a capacity at the depth 4 km with radius 3600 m under the volcano Kluchevskii (Fedotov et al., 2000) and a capacity at the depth 20 km with radius 6000 m under the volcano Shiveluch. During the process of the earthquake preparation the movement of magma gets more intensive, and hence waves and vortices can appear in the magma. In the presence of the constant Earth magnetic field these movements induce variable magnetic fields with different periods. These fields contribute their part in the common electromagnetic emission that was observed before the earthquake initiation (Ismaguilov et al., 2001). The aim of the present work is to reveal what are the possible causes of exciting the magnetic fields in the magma and to give an estimation of their values.

2. Hydrodynamic processes in magma

Let us consider three kinds of hydrodynamic processes in the magma that can lead to the electromagnetic emission.

2.1. Lifting of magma in magma channels

During the process of seismic event preparing magma moves in volcano channels to the ground surface. Magma velocity is about 1–5 m/s (Marchinin, 1985; Sliozin, 1998). The electromagnetic fields can be induced by a magma flow in the presence of the constant Earth

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magnetic field. These fields are quasiconstant and the values depend on the velocity of upwelling magma and radius of the volcano channel. Their characteristic time is connected with the period of magma lifting and with a change of the lifting velocity.

2.2. Oscillations at the magma surface

The possible sources of the ULF electromagnetic pulsations are the oscillations that can appear at a magma surface (Fig. 1). It is known that inertial waves appear on the surface of liquid between two media with different densities (Phillips, 1966). The frequency of waves appearing on the magma surface depends on a relative change of density between gas and magma and on the diameter of a channel.

$$\omega^2 = ((\rho_2 - \rho_1)/(\rho_2 + \rho_1))gk, \quad (1)$$

where k is wave number, ρ_2 is magma density, $\rho_2 \approx 2500$–2800 kg/m^3, and ρ_1 is gas density, ρ_1 depends on the temperature and pressure in a magma channel, but does not exceed $0.1\rho_2$. So, relative changes of the density can be estimated as $(\rho_2 - \rho_1)/(\rho_2 + \rho_1) \approx 0.5$.

If magma surface is in the intermediate volcanic capacity with diameter $d \approx 10^3$ m ($k = 10^{-3}$ m^{-1}), then oscillations excited in the magma have frequencies of about $f = \omega/2\pi = 10^{-2}$ Hz ($T = 100$ s). If the magma is in the channel with diameter of about 100 m then oscillations with period of about 10–30 s are excited in the magma. Bubbles of gas disturb the magma surface constantly and support the oscillations on this surface.

An increase in volcanic activity leads to the appearance of new gas bubbles. Gas moves in a channel with velocity that is more than the upwelling velocity of magma (Proussevitch et al., 1993; Sliozin, 1998). A large volume of bubbles accumulates at the magma surface where they create a foam structure. That leads to a decrease in density difference between the magma and gas, and inertial waves become weaker. A decrease in waves intensity must be typical for the period of the earthquake preparation, so much amount of gas at this period is accumulated in the magma.

After the magma becomes free of a "foam cap" (for example, when new cracks appear), density difference between the gas and magma restores and inertial waves are initiated at the magma surface again. So, at the frequency of inertial waves we can observe a change of regimes. An increase in ULF magnetic pulsation is replaced by a decrease of oscillation, and this situation points to the volcanic activity increase.

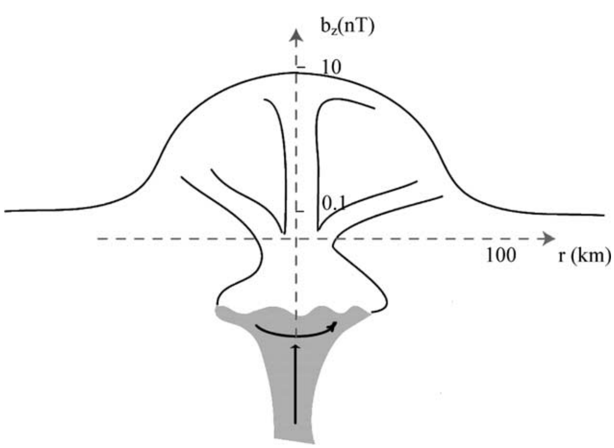

Fig. 1. Oscillations and waves in a volcano capacity. The magnetic field b_z induced by a vortex in the volcano capacity.

2.3. Influence of Coriolis force to the magma movement

Another cause of the ULF movements in magma is connected with vortex structures that appear in the magma flow (see Fig. 1). When the magma is filling a large intermediate volcano capacity, a vortex flow appears in the magma under the action of the Coriolis force. Centrifugal and Coriolis force are in balance, so that

$$v_\varphi^2/R = 2\Omega v_r,$$

where R is vortex radius, Ω is the Earth rotation velocity, $\Omega \approx 7 \times 10^{-5}$c^{-1}, v_φ is vortex rate, and v_r is radial velocity in the volcano capacity. If we assume that v_r is approximately equal to the upwelling velocity of magma in the channel and the radius of volcanic center is about $R = 1000$ m, then liquid rotates with angle velocity 5×10^{-3} rad/s and rotation velocity $v_\varphi = 5$ m/s.

3. Electromagnetic emission induced by hydrodynamic processes in magma

We estimate the magnetic fields induced by processes in the magma described above. The most difficult problem connected with estimation of the electromagnetic fields is to estimate the magma conductivity. Conductivity of basalts is about 10^{-3} S/m at the Earth's surface, but their conductivity depends strongly on temperature. Magma temperature in volcano channels is known to achieve 1000–1300 °C. It is known that if the temperature increases up to the values 500–1000° then the conductivity value increases by 2–3 orders (Vanian and Shilovskii, 1983). According to these data we assume that conductivity of hot magma is about $\sigma = 10^{-1}$ S/m.

3.1. Magnetic fields induced by upwelling magma flow

We consider lifting magma in a channel like a cylindrical flow of the conducting liquid. It is known that the magnetic field induced by the cylindrical flow can be estimated as (Parker, 1979),

$$b_z \approx \mu\sigma B_{0x} R v_z,$$

where B_{0x} is the horizontal component of the Earth magnetic field, and R is a radius of cylinder. If we assume that $\sigma = 10^{-1}$ S/m, $B_{0x} = 2 \times 10^4$ nT, $v_z = 1$–5 m/s and capacity radius is $R = 1000$ m then $b_z \approx 2$–10 nT. The increase of magnetic field in the beginning of the seismic activity can be initiated by the acceleration of the flow.

3.2. Electromagnetic emission induced by inertial oscillations

The vertical component of the magnetic field b_z induced by inertial oscillations can be estimated from the induction equation:

$$\mathrm{rot}_z(\mathbf{v} \times \mathbf{B_0}) = \Delta b_z / \mu\sigma,$$

where σ is medium conductivity, v is oscillation velocity, and B_0 is the Earth magnetic field.

In a cylindrical system of coordinates

$$\mu\sigma(1/r) \cdot \partial(r v_r \cdot B_{0z})/\partial r \approx \partial^2 b_z/\partial z^2.$$

Hence, we can estimate the magnetic field induced by the wave as

$$b_z \approx \mu\sigma B_{0z} k_r v_r / k_z^2, \quad (2)$$

where k_r and k_z are the horizontal and vertical components of the wave vector.

For inertial oscillations with $T = 100$ s according to Eq. (2) the induced magnetic field is estimated to be $b_z \approx 0.1$ nT, if $k_r = 10^{-3}$ m^{-1}, $v_r = f/k_r = 10$ m/s, and $k_z = 10^{-2}$ m^{-1}. For inertial oscillations with $T = 10$–30 s the induced magnetic field is about $b_z \approx 0.01$ nT if $k_r = 10^{-2}$ m^{-1}, $v_r = 1/(fk_x) = 6$ m/s, and $k_z = 10^{-1}$ m^{-1}. Let us note that with the increase of oscillation period we expect an increase in the value of the induced magnetic fields.

3.3. The magnetic fields induced by a vortex in an intermediate volcano capacity

It is known that a vortex in the conducting liquid in the presence of the constant magnetic field induces a constant azimuthal magnetic field (Parker, 1979):

$$B_\varphi = \mu\sigma V_\varphi B_{0z} D/2,$$

where V_φ is rotation velocity, and D is depth of the rotating liquid.

A value of the magnetic field induced by magma movements in an intermediate volcanic capacity is about $B_\varphi = 2.5$ nT for the parameters $D = 1000$ m, $v_\varphi = 5$ m/s, and $\sigma = 10^{-1}$ S/m.

The vertical magnetic field b_z over the vortex is calculated as a field of circular current $j_\varphi = \sigma\ (\mathbf{v_r} \times \mathbf{B_{0z}})$:

$$b_z = \mu \int_S \int (j/2r)\, \mathrm{d}S,$$

where S is magma surface. Then the induced magnetic field is estimated to be,

$$b_z = \mu\sigma\pi B_{0z} R_0 v_z. \quad (3)$$

The qualitative estimation gives a value of $b_z \approx 10$ nT.

4. Comparing with the observing data

Let us compare the described mechanism of the magnetic field excitation and the results of measurements. Measurements of ULF electromagnetic disturbances were carried out in Japan before and during a seismic active period (Gotoh et al., 2002; Kopytenko et al., 2002; Ismaguilov et al., 2003). Behavior of the magnetic field before the earthquake has the following stages:

1. The value of the magnetic field starts to increase $\approx$1.5 months before the seismic activity in the frequency band of 0.001–0.01 Hz.
2. On the background of common increase it is observed oscillations of the magnetic field value with the characteristic time of about some days.
3. There is observed a sharp decrease of the magnetic field (1.5–2 days) before the earthquake.

From the point of view of the mechanism described above the increase in magnetic field during the period of the earthquake preparation is connected with lifting of magma to the Earth's surface. Oscillations of the magnetic field can be connected with upwelling and downwelling of the magma level in volcano channels and with inertial waves at the surface of magma in capacities.

A sharp decrease of the magnetic field 1.5–2 days before the earthquake can be explained by slowing of all movements in the magma before the beginning of the earthquake, by the great amount of gas bubbles and/or hard particles that accumulate at the magma surface and create an obstacle to upwelling of magma and wave movements on the magma surface.

The value of the magnetic field can be measured on the Earth's surface. For example, z-component of the magnetic field induced by the vortex in a volcano capacity decreases like R_0^2/r^2 where R_0 is radius of the capacity (see Fig. 1). So, the magnetic field measured at the distance $r = 100$ km from the volcanic center must be approximately 0.05–0.1 nT. The corresponding gradient of the magnetic field is about $\nabla b_z \approx 1$ pT/km.

These theoretical results are confirmed by the measurements. In actuality, the vertical component of the magnetic fields decreases as r^{-n} where $n \approx 1.2$ (Ismaguilov et al., 2001) and the gradient of the magnetic field is 1–5 pT/km.

The observed values of the magnetic fields are found to be about 0.01–0.4 nT, which corresponds to the estimations.

5. Conclusion

We can assume that hydrodynamic processes in magma can be considered as one of possible causes for ULF electromagnetic emission. In this work three possible different mechanisms of the magnetic field exciting were considered:

- magma flow in volcanic channels;
- inertial waves at the magma surface that give their contribution to the magnetic field at the frequencies 0.01–0.1 Hz;
- vortex flows that can appear in magma when magma fills intermediate capacities.

General increase of seismic activity leads to an intensification of the hydrodynamic processes in magma that can be reflected in the change of electromagnetic emissions.

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