

# **Prediction of Eruptions Using Changes in Composition of Volcanic Gases**

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## **Abstract**

During observations on the dynamics and on the regime of fumarolic activity of some active volcanoes of Kamchatka and Kurile islands, a very close relation was noted between the S/Cl ratio in the fumarolic gases and in waters and the state of the volcano. The S/Cl ratio increased prior to the eruptions of Sheveluch, Bezymianny, Kluchevskoi, Zavaritsky and Ebeko volcanoes.

## **Introduction**

The criteria for the prediction of eruptions using any method, the geochemical included, should be based on a detailed study of the dynamics of volcanic activity for each volcano individually. In the case of geochemical prediction, data on the composition and temperature of volcanic gaseous products — eruptive and fumarolic gases, steam jets, hot springs — are used. Gases represent a mobile part of a magma; they quickly respond to any change in the endogenetic and exogenetic factors. Magmatic and volcanic gases, when they reach the zone of hypergenesis, become very unstable, and are subjected to a regular differentiation as the result of reactions with atmospheric gases, ground water and surrounding rocks. For this reason, it is very complicated to determine the gas and water parameters which would only in the least possible be affected by surface factors.

In studying the volcanic activity in Kamchatka and in the Kurile Islands a close relation has been established between the variations of the S/Cl ratio (on the basis of changes in temperature, pH and F content) in fumarolic gases, condensates, fumarolic waters, and the

state of a given volcano. Recently TONANI (1971) published our data on the geochemical prediction of the eruptions of Kamchatka volcanoes (MENYAILOV and NIKITINA, 1967) for a period of time up to 1965. This paper is based on the same data with the addition of data obtained from 1965 to present.

### **Eruptive Cycle of Active Volcanoes**

A great amount of substantial data has been accumulated up to now on the composition of the fumarolic gases of the active volcanoes of Kamchatka and the Kurile Islands. More or less extensive routine observations are still going on for the most active of these volcanoes.

For active volcanoes, it is advisable to distinguish several eruptive periods, each being characterized by a definite composition and temperature of gases:

1. Eruptive period;
2. Post-eruptive period;
3. Inter-eruptive period;
4. Pre-eruptive period.

These periods, taken together, form one closed eruptive cycle, its beginning and end being, according to ПИП (1956), a catastrophic (culmination) eruption. The length of each eruptive period is, probably, individual for each volcano and depends upon the properties of the magmatic melt and upon other causes affecting the volcanic activity (tectonic, cosmic, etc.).

The *eruptive period* consists of one or several eruptions and moments of relative calm in between — from several days to several months. For the Sheveluch volcano, for instance, the eruptive period consisted of one gigantic eruption of the « directed blast » type that lasted for just about one hour (GORSHKOV and DUBIK, 1969). For the Kliuchevskoi volcano, the eruptive period in 1966 consisted of a summit and of an adventive eruption of Vulcanian-Strombolian type, lasting, however, for about three months (KIRSANOV, 1968). For the Bezymianny volcano, the eruptive period began in 1955 and is still lasting; it consists of a dozen eruptions of « directed blast », Vulcanian

and Peléan types with intervals between them from one month to a year (GORSHKOV and BOGOYAVLENSKAYA, 1965; DUBIK and MENYAILOV, 1969).

The *post-eruptive period* is brief and poorly characterized, owing to scanty information. Its features are the same as those of the stages of relative calm between eruptions during the eruptive period.

*Inter-eruptive period.* For different volcanoes it lasts from several years to centuries. It is characterized by an absence of magma shown as a juvenile material, and by a fumarolic activity of the type of solfatara, mofettes and hot springs. Sometimes it is interrupted, however, by a more intense fumarolic activity or even by a phreatic eruption (Ebeko volcano in 1962-1969).

*Pre-eruptive period.* It is characterized by an intensification of the activity of the volcano indicated by a change in the fumarolic, seismic or other regimes. This period ends with an eruption. It is difficult to distinguish the pre-eruptive period from an intensification of the activity of a volcano in the inter-eruptive period.

## Gas Composition during the Different Stages of an Eruptive Cycle

### ERUPTIVE PERIOD

*The composition of eruptive gases* (« magmatic gases ») is being studied during different eruptions by means of various methods. During Hawaiian eruptions the gases are sampled directly from a lava lake. During Strombolian eruptions the sampling of gases is made from moving lava flows and at isolated gas boccas. Gases of Hawaiian and Strombolian eruptions have been studied by SHEPHERD (1936), FINLAYSON *et al.* (1968), HEALD *et al.* (1963), SIGVALDASON and ELLISON (1968), IWASAKI *et al.* (1963), CHAIGNEAU *et al.* (1960), MENYAILOV quoted in AVDEIKO *et al.* (1974) using chemical methods of analysis. NAUGHTON (1969), DELSEMME (1960), MURATA (1960), CADLE *et al.* (1969) studied these gases using methods of spectrometry, infrared spectroscopy and air chemistry. The composition of gases of Vulcanian and Peléan eruptions have been studied by analyzing the water extracted from fresh ashes (BASHARINA, 1958; DUBIK and MENYAILOV, 1969; KIRSANOV, 1968; STOIBER and ROSE, 1971).

The composition of the eruptive gases for different volcanoes is not always the same, which, apparently, is due to either direct or

indirect causes — first of all it is due to the different methods used for collecting and analyzing eruptive gas samples:

*Basalt volcanoes*

Pacific (Hawaiian Islands)	$H_2O > CO_2 > SO_2 > H_2 > HCl$ (without HF)
Atlantic (Iceland)	$H_2O > CO_2 > SO_2 > H_2 > HCl$ (without HF)
African (Nyiragongo)	$H_2O > CO_2 > SO_2 > H_2$ (without HCl and HF)
Pacific arcs (Japan)	$H_2O > H_2 > CO_2$ (without $SO_2$ , HCl and HF)
(USSR)	$H_2O > H_2 > HCl > HF > CO_2 > SO_2$

*Andesite volcanoes*

Pacific arcs (USSR, Central America)	$H_2O > SO_2 > HCl > CO_2 > H_2$ (without HF)
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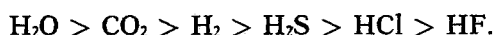
*Order of Emission of Gas Emanations during Volcanic Eruptions*

It has been recorded everywhere that gases of the explosive stage of activity of volcanoes belonging to any type and of any composition differ drastically from gases emanating during the effusive stage of activity; in other words, a differentiation of gases is taking place during an eruption. This is particularly striking for « acid » components — sulfur gases and haloid gases. KRAUSKOPF (1948) indicated that exhalations from a slag cone were rich in sulfur gases, while haloid gases were very abundant in the emanations from a lava flow during the eruption of Paricutin volcano. LOVERING (1957) showed that the first portions of a rhyolitic flow and the explosive outbursts during the eruption of Katmai volcano were characterized by sulfur gases and carbon, whereas the last portions of the flow and of the Novarupta dome were characterized by haloid gases. The same conclusion was reached by BORISOV (1966) for sulfur gases in the fumaroles of a pyroclastic flow of Bezymianny volcano. PИП (1956) and NABOKO (1963) recorded that gases of the explosive activity products of Kliuchevskoi volcano contained relatively more sulfur gases, while haloid gases were predominant in the products of the lava flow. STOIBER and ROSE (1971) demonstrated that gases from the lava flows of Pacaia and Serro-Negro volcanoes were rich in haloids. The closer the fumaroles

were located to the active vent of the volcano, the greater was the role played by sulfur gases in their composition. At Alaid volcano (AVDEIKO *et al.*, 1974), the gases taken at the bocca were very rich in sulfur compounds, whereas the gases from the lava flow contained relatively large amounts of haloids.

Therefore, the data obtained during the eruptions of basaltic, andesitic and other volcanoes in different regions of the world indicate that eruptive gases are enriched in sulfur and carbon compounds as well as in hydrogen to a greater extent than in haloid compounds, which form the bulk of fumarolic gases from the products of the effusive activity.

In the opinion of the majority of the scientists, such a differentiation is the result of the varying capacity of different gases to dissolve in a magmatic melt. Sulfur and carbon gases as well as hydrogen are not so soluble in magma; therefore they are the first to emanate during a volcanic eruption and enrich the gases of the explosive activity. Haloid gases are relatively well soluble in magmatic melts, and are emitted predominantly during the last phases of the eruption and determine the gas composition of the effusive activity products (lava flows, domes etc.). Observations on gas emanations during a volcanic activity coincide with experiments on the solubility of various gases in silicate melts (IWASAKI and KATSURA, 1967; KADIK and LUKONIN, 1973). According to experimental data, gas emanations are released from magmatic melts during an eruption in the following order:



*Order of Emission of Gas Emanations during Eruptive Periods Consisting of Several Eruptions.*

According to the data obtained from direct observations of volcanic eruptions and confirmed experimentally, the order of emission of gas emanations during lengthy eruptive periods is as follows: during separate eruptions, gases belonging to the carbon and sulfur groups and hydrogen emanate; whereas, during the periods of a comparative calm between eruptions, haloid gases emanate from the lava and from the pyroclastic masses produced during the eruptions (ME-  
NYAIILOV and NIKITINA, 1966; STOIBER and ROSE, 1971).

#### POST-ERUPTIVE PERIOD

This period is characterized by high temperatures and by the haloid composition of fumarolic gases typical also of the stage of relative calm between eruptions during the eruptive period (BASHARINA, 1963; NABOKO, 1959). Depending upon the amount, thickness and composition of the ejected silicate material, the post-eruptive period lasts a varying time. For instance, a high temperature and a haloid composition of the fumarolic gases were recorded for the post-eruptive period of Kliuchevskoi volcano during several months (with a few exceptions). For the andesitic Sheveluch volcano the post-eruptive period lasts much longer owing to the great mass of the cooling Suelich extrusive dome.

#### INTER-ERUPTIVE PERIOD

It is advisable to divide the inter-eruptive period into several stages depending on the temperature and composition of fumarolic gases: stage of solfatara activity, stage of mofette activity and stage of hot springs activity.

The *stage of solfatara activity* is characterized by the activity of fumaroles of the solfatara type. The gas temperature ranges from 80 to 250° C. In addition to water vapour and CO<sub>2</sub>, sulfur gases have a prominent place in solfatara gases, and an abundant sulfur formation rather stable during a lengthy time, as indicated by IWASAKI *et al.* (1962). In Kamchatka and the Kurile Islands a stable solfatara activity characterizes at the present time the inter-eruptive period of Sheveluch volcano (from 1964 to 1972) (BASHARINA, 1958; BORISOV, 1966; MENYAILOV and NIKITINA, 1964; KIRSANOVA and KIRSANOV, 1971), of Kizimen volcano (PETROV, 1970), of Avachinsky volcano (KIRSANOV *et al.*, 1964), of Mutnovsky volcano (SERAFIMOVA, 1966), of some volcanoes of the Kurile Islands (VORONOVA and SIDOROV, 1966; BASHARINA and KHRAMOVA, 1971; CHIRKOV *et al.*, 1972). The stable solfatara activity of some volcanoes has been interrupted by phreatic eruptions (Ebeko, Mutnovsky, Zhupanovsky and some others).

The *stage of mofette activity* is characterized by low temperatures and a carbon dioxide composition of mofette-type fumarolic gases. At the present time a mofette activity is characteristic of the Komarov volcanoes (Petrov, Skripko, 1971), of the Ksudach caldera (DUBIK and

MENYAILOV, 1969) and of some volcanoes of the Kurile Islands (CHIRKOV *et al.*, 1972).

*The activity stage of hot springs* is characterized by an absence of steam-gas emanations in the form of fumaroles. The gases exhale spontaneously from hot springs.

#### PRE-ERUPTIVE PERIOD

This period is decisive in the prediction of volcanic eruptions. The main fundamental problem is to make a distinction between the pre-eruptive period and an intensification of the solfatara activity; for instance, in the inter-eruptive period. The pre-eruptive period can interrupt the inter-eruptive period during any of its stages. The beginning and development of the pre-eruptive period is controlled by changes in the magmatic vent (particularly, of the physico-chemical conditions of the magmatic melt). On the surface this is reflected in a rise in temperature and in a change in the composition of fumarolic gases. There appear components characteristic of eruptive gases and not characteristic of the gases of the solfatara and mofette activity during the inter-eruptive period of volcanic activity. For solfatara gases these are  $H_2$ ,  $HCl$ ,  $HF$ , for mofette gases these are  $H_2$ ,  $SO_2$ ,  $HCl$ ,  $HF$ . Thus in fumarolic gases of the inter-eruptive period an appearance and an increased amount of  $H_2$ ,  $SO_2$ ,  $HCl$ ,  $HF$  are recorded. However, inasmuch as the rôle of sulfur gases and hydrogen — poorly soluble in magmatic melts — is greater in eruptive gases, these gases enrich primarily the fumarolic gases of the pre-eruptive period. Thus, on the background of a general increase of temperature and of the amounts of  $H_2$ ,  $H_2S$ ,  $SO_2$ ,  $HCl$  and  $HF$ , there is a special increase in the ratio of sulfur gases and haloid gases — the S/Cl ratio or hydrogen-haloid gases ratio —  $H_2/Cl$ .

#### **Increase of the S/Cl Ratio in Fumarolic Gases Before an Intensification of the Activity of Certain Volcanoes in Kamchatka and Kurile Islands**

*Bezymianny volcano* has been erupting since 1955-56. The volcanic activity included « directed blast » eruptions, the formation of deposits of pyroclastic flows and incandescent avalanches, and the extrusion of the intracrateral Novy dome. Closest to the composition of

« magmatic gases » there were the high-temperature fumaroles of the Novy dome. In the gases sampled from the fumaroles of the dome during a period of relative calm of the volcano the value of the S/Cl ratio was about 0.05. During the eruptions of 1962, 1964, 1967 this value increased to 1 (see Fig. 1). The temperature of gases has been comparatively permanent and varied within a range of 450-500° C. In

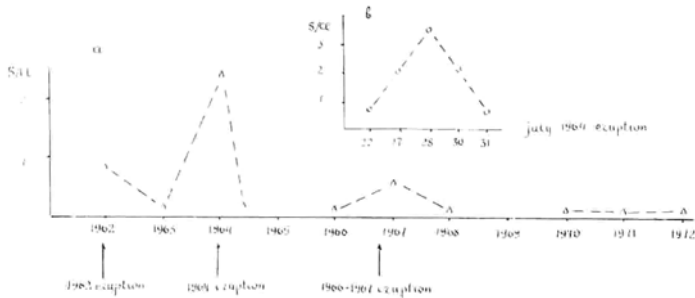


Fig. 1 - a) S/Cl ratio in gases and condensates of the Novy dome, Bezymianny volcano.  
 b) S/Cl ratio in atmospheric sediments sampled near the Novy dome.

1964 the S/Cl ratio in atmospheric sediments collected every day near the Novy dome began to increase four days before the eruption and reached its maximum on July 28<sup>th</sup>, the day of the greatest activity of the volcano.

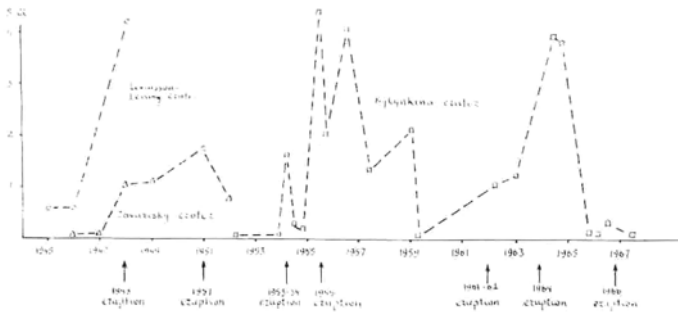


Fig. 2 - S/Cl ratio in fumarolic gases of the Zavaritzky, Loewinson-Lessing and Bylinkina craters on Kliuchevskoi volcano.

*Kliuchevskoi volcano* is characterized by Vulcanian-Strombolian eruptions from the central and the adventive craters. The temperature and value of the S/Cl ratio in fumarolic gases of the adventive Zavaritzky and Loewinson-Lessing (formed during the eruption of 1945)



craters increased in 1948 and 1951. In the first case this increase took place before the eruption of the central crater; in the second case, the increase occurred before the eruption of the adventive crater, at the time when the Bylinkina cone was formed. Later on, on Bylinkina cone, the temperature and the value of the S/Cl ratio sharply increased before the eruptions from the central crater in 1955-1956, 1962 and 1964 (see Fig. 2).

*Sheveluch volcano* had two cycles of activity: a lengthy one in 1946-1951, and a short one in 1964. In the first case the Suelich dome was formed, as well as the pyroclastic flow deposits. During this period of activity the temperature of the fumaroles on the old domes of the volcano rose from 100 to 250° C and the value of the S/Cl ratio

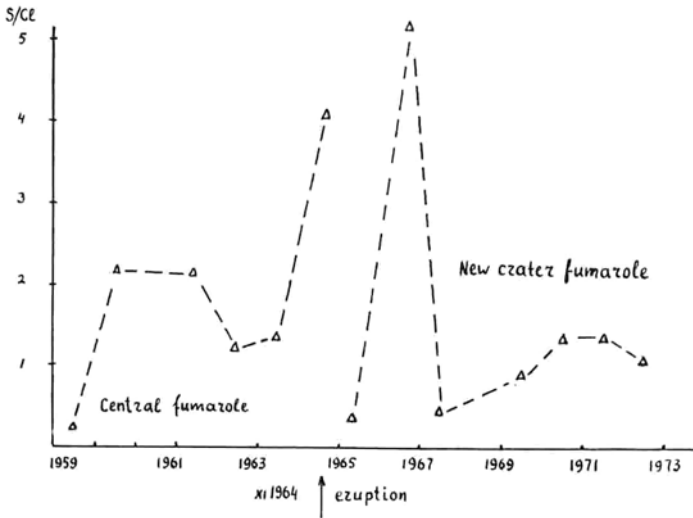


FIG. 3 - S/Cl ratio in fumarolic gases of Sheveluch volcano.

increased several times. Four months before the eruption of 1964 there was a rise in the temperature and a greater value of the S/Cl ratio in the fumarolic gases of the Suelich dome. During this eruption an intense explosion destroyed completely both the old domes and the Suelich dome. After the eruption of 1964 a permanent solfatara activity started in the new Sheveluch crater, the composition of gases and the temperature of fumaroles remaining constant for a long time. In 1967 a higher S/Cl ratio in the solfataras was recorded, although there was no eruption. However, at the same time a high seismic activity was recorded in the region around the volcano (Fig. 3).

*Ebeko volcano* is characterized by an intense solfatara and hydrothermal activity. In 1963-1969 it was interrupted by a series of phreatic eruptions. Their precursor has been a gradual increase in the S/Cl

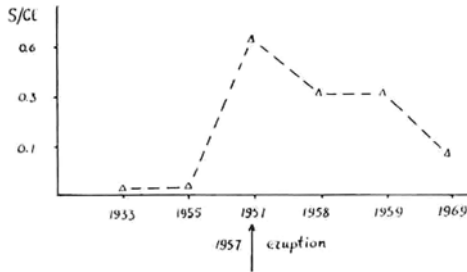


FIG. 4 - S/Cl ratio in the waters of the crateral lake of Zavaritzky volcano.

ratio in the solfatara gases of the North-Eastern thermal field since 1960. Along with this, the S/Cl ratio increased in the solfatara gases before each phreatic eruption in 1965, 1967 and 1969.

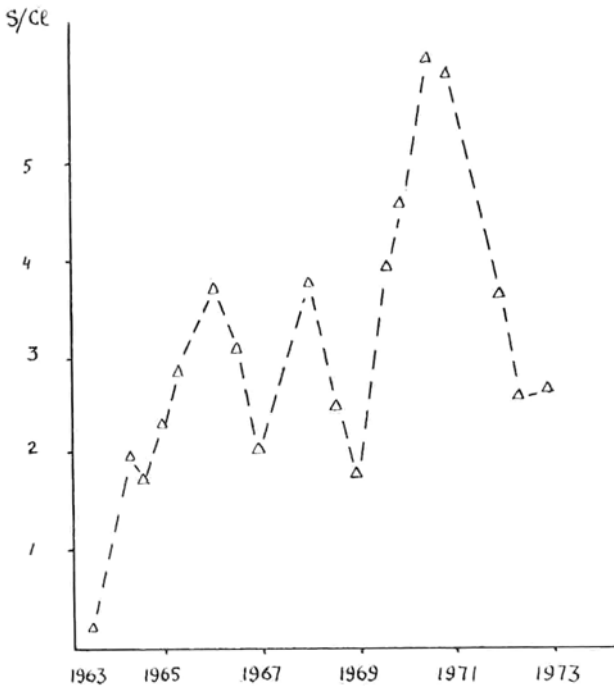


FIG. 5 - S/Cl ratio in fumarolic gases of Avachinsky volcano.

*Zavaritzky volcano* was active in 1957. During the eruption a small dome and a short lava flow formed in the caldera lake. It was recorded that during the eruption the pH in the waters of the lake had dropped, and that the mineralization had increased; especially striking was an increase of the value of the S/Cl ratio.

*Avachinsky volcano* was active for the last time in 1945. Since then, a fumarolic activity is recorded in the central crater. The composition of the gases and the temperature of the fumaroles on the northern scarp have been permanent since 1962. In 1971 there was a drastic increase of the S/Cl ratio (Fig. 5), which was not connected with the eruption. This could, possibly, be connected with a strong tectonic earthquake that took place in Kamchatka in 1971. During the following years this ratio has been the same as in 1969.

### Conclusions

As already mentioned, the greatest difficulty lies in a correct interpretation of the increase of the S/Cl ratio before eruptions, because a drop in volcanic activity also leads to a higher S/Cl ratio — the transition from a post-eruptive to an inter-eruptive state is marked by a replacement of fumarolic gases of haloid nature with solfatara gases. It should be noted that an increase in the S/Cl ratio in fumarolic gases in the inter-eruptive period takes place on a background of a drop in temperature, of a lesser content in the total of « acid » gases, of a lower mineralization and acidity of the condensates. On the contrary, the transition from an inter-eruptive to a pre-eruptive and eruptive state is characterized by an increase in the S/Cl ratio on the background of a higher temperature, of a greater amount of « acid » gases, and of a higher mineralization and acidity of the condensates.

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