

The mass estimation of volatile emission during 1199—1200 AD eruption of Baitoushan volcano and its significance

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Abstract On the basis of the study of volcanic products during 1199—1200AD eruption of Baitou Mountain (Baitoushan), the released volatile content was estimated by comparing Cl, F, S, H₂O concentrations of undegassed glass inclusions with those of degassed matrix glasses. The calculations show that volatile yields, released from the melt, are 109.88×10^6 ton of HCl, 196.80×10^6 ton of HF, 1477.84×10^6 ton of H₂O, 23.14×10^6 ton of SO₂, which could have formed 35.43×10^6 ton of H₂SO₄ aerosol in the atmosphere. They could have substantial effect on paleoclimate and paleo-environment.

Keywords: Baitoushan volcano, glass inclusion, H₂SO₄ aerosol, volatile.

Plinian volcanic eruptions could inject a large amount of volatiles and aerosols into atmosphere, even stratosphere, leading to climate and environment changes. Tambora volcano, for example, erupted in April, 1815, which had caused the “year without summer” because of injections of a large amount of volcanic sulfide volatiles^[1]. The TOMS satellite observations indicate that 1991 eruption of Mt. Pinatubo has injected “HCl+H₂SO₄ aerosol+H₂O vapor” association into the stratosphere, which may be a potential cause to enlarge the area of the Antarctic ozone hole in the fall of 1992^[2].

The previous studies of composition and content of volcanic volatiles focused on the eruptions associated with plate subduction, whose volcanic products are in chief composed of cal-alkaline volcanic rocks and volatiles are characterized by high-S-release content^[3]. Recently, due to the growing interest in the importance of volatile elements for the effects of volcanic eruptions on global climate change, it is recognized that eruptions of intermediate-acidic per-alkaline lava, far from subduction zones, could yet lead to destruction of the stratospheric ozone layer^[4] besides causing the surface’s temperature to decrease due to the erupted H₂O- and HCl-rich magmas.

Baitoushan volcano is far from the subduction zone of Pacific plate toward Eurasia plate, which has erupted many times in history^[5]. One of the largest eruptions occurred in 1199—1200 AD^[6] (see the age determination below). Product of the eruption has clear outcrops, obvious volcanic stratigraphic sequence and fresh phenocryst and matrix glass, which is the ideal object of studying compositions of volcanic volatiles. Previous work mainly studied volcanology, geo-

chemistry and geophysics^[5–9], this paper estimates the compositions and masses of volatiles and H₂SO₄ aerosol, based on the systematical collection samples in remote and poorly studied field of China and North Korea, which is requisite for estimating total masses of volatile release.

1 Geological background

Baitoushan volcano is located in Cenozoic Changbaishan volcanic active region of the eastern Asia continental rift system^[7] (fig. 1). The composite stratocone composed of Pleistocene trachyte and comendite^[5,7] is situated on Pliocene basaltic “Gaima Plateau”. Holocene volcanic eruptions caused a caldera on top of the cone, which was filled with rainwater and formed the famous Tianchi (Heaven Lake) Crater Lake. The largest eruption of Baitoushan volcano in history consists mainly of Plinian pumice fallout and semi-welded pyroclastic flow, which were followed by a small volume of trachytic welded pyroclastic flows. Thickness of gray fallout and pyroclastic flow is from 3 m to 82.5 m within a radius of 35 km around the cone^[7,9], which comprise comenditic pumice (more than 98%) and lapilli and lithic fragments (approximately 2%). Grain sizes of the pumice gradually decrease from the cone to distal sites. Pyroclastic flow related with collapse of Plinian column is principally distributed in the vicinity area around the volcanic cone. Many charcoal fragments and burnt trunks have been found in the proximal products^[7,9]. The determination of age and duration about this eruption has drawn many volcanologists’ attention. Since 1974, ¹⁴C dating results of more than 40 burnt trunks *in situ* in the proximal fallout and pyroclastic flow have indicated that the eruptive age is between 910 and 1435 aBP^[5,7]. Liu et al. (1998)^[9] suggested that the eruptive age be 1215 ± 15 AD, based on systematically ¹⁴C dating from core to rim of one large trunk near Yuanchi (fig. 1). Recently, Cui et al. (2000)^[6] found convincing historic records associated with this eruption and thought that eruptive age is from June, 1199 AD to May, 1200 AD with several eruptive intervals during this period. This eruptive age is accepted in this paper.

2 Sample collection and analytical methods

Samples were taken mainly from the proximal Plinian fallout and pyro-

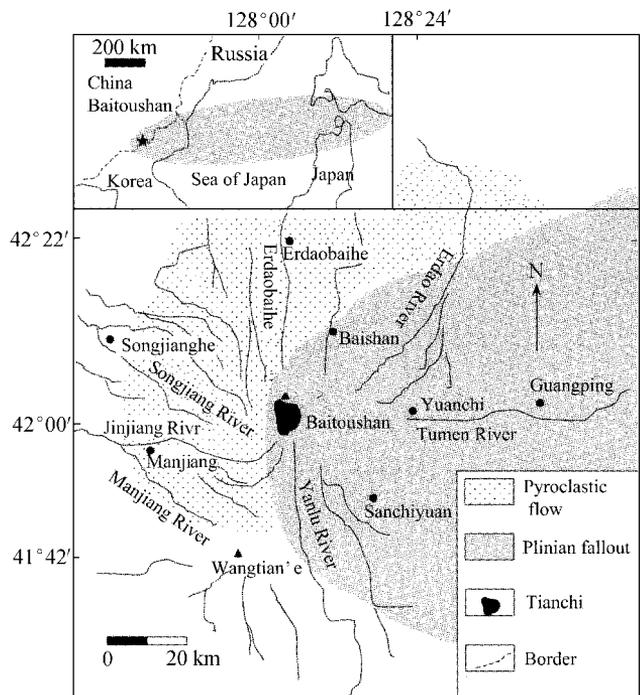


Fig. 1. Distribution of Plinian pumice fallout and pyroclastic flow of Baitoushan (modified from ref. [8]).

clastic flow in China and North Korea (fig. 1 and table 1). Products of 1199—2000 AD eruption consist of highly vesicular comenditic pumice as described above. Phenocryst minerals mainly comprise fayalite, hedenbergite, Fe-Ti oxide, anorthoclase and quartz. The pumice clasts were gently crushed and fresh phenocrysts were separated by handpicking using binocular microscope. The phenocrysts with glass inclusions and pumice chips (or bubble wall) were mounted in epoxy resin and then were carefully polished to expose glass inclusions in order to carry out wavelength dispersive electron microprobe analyses. The analytical conditions were 15 kV accelerating volt-

Table 1 Electron microprobe analyses of representative primary glass inclusions in phenocrysts (GI) and matrix glasses (MG) (wt %)^{a)}

No.	98-328	99-518	99-109	00-203	98-628 [*]	98-201
Site	Yuanchi	Tianwen Mountain	Baiyan Mountain	Sanchiyuan, N. Korea	Huangsong-pu	Qixiangzhan
Name	GI(Ol)	GI(Ol)	GI(Cpx)	GI(Cpx)	GI(Anor)	GI(Anor)
SiO ₂	67.51	65.98	66.71	69.36	72.36	71.06
TiO ₂	0.27	0.18	0.23	0.31	0.28	0.33
Al ₂ O ₃	12.46	13.96	13.46	12.53	10.82	11.52
TFeO	5.78	6.08	5.19	4.35	4.12	4.41
MnO	0.10	0.07	0.16	0.09	0.06	0.06
MgO	0.02	0.05	0.03	0.01	0.02	0.02
CaO	0.65	0.29	1.00	0.34	0.21	0.43
Na ₂ O	5.89	6.31	5.97	5.34	4.30	4.65
K ₂ O	4.82	4.69	4.79	4.68	4.51	4.28
P ₂ O ₅	0.03	0.09	0.24	0.02	0.03	0.03
S	0.06	0.08	0.05	0.04	0.04	0.03
Cl	0.26	0.21	0.25	0.29	0.41	0.35
F	0.24	0.18	0.21	0.27	0.31	0.38
Total	98.09	98.17	98.29	97.63	97.47	97.55
H ₂ O	1.91	1.83	1.71	2.37	2.53	2.45
99-203	00-628	98-364 [*]	99-508	99-203	99-109	00-312
Tianwen Mountain	Huishan, N. Korea	Erdao-bai River	Yuanchi	Tianwen Mountain	Baiyan Mountain	Jiangjun Mt., N. Korea
GI(Anor)	GI(Anor)	GI(Qz)	GI(Qz)	MG	MG	MG
73.42	71.86	72.36	73.12	73.51	75.02	74.64
0.24	0.23	0.21	0.23	0.19	0.23	0.27
10.59	11.06	10.14	10.36	11.19	10.29	10.34
3.75	3.86	3.46	3.64	4.10	3.87	3.91
0.13	0.01	0.08	0.06	0.07	0.12	0.09
0.01	0.02	0.02	0.02	0.02	0.01	0.02
0.24	0.23	0.19	0.02	0.41	0.21	0.20
4.28	4.61	4.45	4.28	4.68	4.19	4.66
4.11	4.53	4.06	4.01	4.20	4.13	4.21
0.06	0.05	0.02	0.03	0.02	0.03	0.02
0.03	0.03	0.02	0.02	n.d.	0.02	n.d.
0.49	0.38	0.51	0.56	0.26	0.38	0.35
0.46	0.46	0.48	0.45	0.19	0.26	0.17
97.81	97.33	95.99	96.80	98.84	98.75	98.88
2.19	2.67	4.01	3.20	1.16	1.25	1.12

a) Ol, fayalite; Cpx, hedenbergite; Anor, anorthoclase; Qz, quartz; TFeO, total content of iron oxides. n.d., less than the determined limit (170ppm). Samples with asterisks are pyroclastic flow, the others are Plinian fallout.

age, 6—15 nA beam current, and the electron beams with 1—10 μm (glass inclusion) and 15—20 μm (matrix glass) in diameter. Total water concentrations in glass inclusions and matrix glasses were determined by so called “difference method”^[7,8].

3 Results

Results of electron microprobe analyses (table 1) show that the compositions are homogeneous in primary glass inclusions and matrix glasses, which do not vary with tephra thickness, spatial site and grain size.

3.1 Methods and criteria of component determination of pre- and post-eruption volatiles

Primary glass inclusions in phenocryst minerals are samples of the melt trapped by phenocrysts, from which the crystals crystallized. Original compositions of primary glass inclusions retain the melt constituents with which phenocryst minerals were equilibrated when minerals crystallized; the compositions of fresh matrix glasses coexisting with phenocrysts are the representative of melts suffering from syn-eruptive degassing. The volatile components in matrix glasses are referred to as volcanic gas compositions remaining in post-eruptive melts. In theory, difference of the volatile contents between primary glass inclusions and the coexisting matrix glasses should represent constituents of volatile release during syn-eruptions. However, studies of inclusions in phenocrysts and experimental petrology indicated that some glass inclusions might exchange mass and energy with host minerals and form open magmatic systems after entrapment, which lead to variations of glass inclusion compositions and thus could not represent melt constituents entrapped. Therefore, It is fundamental and critical to select primary glass inclusions in closed magmatic systems so as to obtain melt compositions coexisting with phenocryst minerals before eruptions. The primary glass inclusions in phenocrysts of Baitoushan pumice, which are taken as melt representative of closed magmatic system after entrapment and are analyzed applying electron microprobe analyses, have the features as follows: (i) The shapes of inclusions are regular, including round, oblate, ellipse and negative crystal shapes. There are no fractures in margins of the inclusions. They are not systematically distributed along one direction in the host crystals. (ii) The diameters of inclusions, in general, are 25—100 μm with some reaching 100—150 μm . (iii) The inclusions are colorless. The whole inclusions are filled with undevitrified transparent glasses, which are free of daughter crystal and bubble. Some inclusions contain minor bubbles, however, with the volumes less than 5%. (iv) Analyses of electron microprobe, with an electron beam in less than 2 μm diameter, indicate that the compositions of whole inclusions are homogeneous, showing no composition variations from core to rim. (v) The analyses done by Laser Raman Spectrometry Microprobe (LRSM) show that the bubbles, if any, in inclusions are derived from different expansion coefficients between crystals and filled glasses, belonging to shrinkage bubbles from quenching other than evolved bubbles. (vi) Major element compositions of the selected glass inclusions are coincident with those of the coexisting matrix glasses. These

preclude influence of “boundary layer effect” upon the chemical compositions of glass inclusions. The glass inclusions with the above characteristics are believed to be the result of quenching in closed systems after direct entrapment melt during mineral crystallizing, which preserve the original undegassed magma compositions coexisting with phenocryst minerals. Therefore, on the basis of selecting proper host crystals (see the criteria for host crystal selection below), this kind of glass inclusion could represent immediately pre-eruptive melt compositions.

Due to variations of compositions of the crystal and coexisting melt during the magma evolving, constitutes of volatiles in glass inclusions trapped in different phenocrysts will correspondingly vary (fig. 2). As mentioned above, determination of volatile concentrations of immediately pre-eruptive magmas necessitates selection of proper host crystals, which contain closed system inclusions. In comparison with those of crystallizing phenocryst minerals in early stage, temperature and constituent gradients are relatively low between glass inclusions of crystallizing minerals in late stage and immediately pre-eruptive magmas, whose duration of the diffusive re-equilibration^[10] is relatively short. Moreover compositions of glass inclusions in late stage minerals are not influenced by early phenocryst crystallization, which contain volatiles in the crystal lattices (for example, amphibole, biotite). Consequently, compositions of primary glass inclusions in the latest crystallizing minerals approximately represent those of immediately

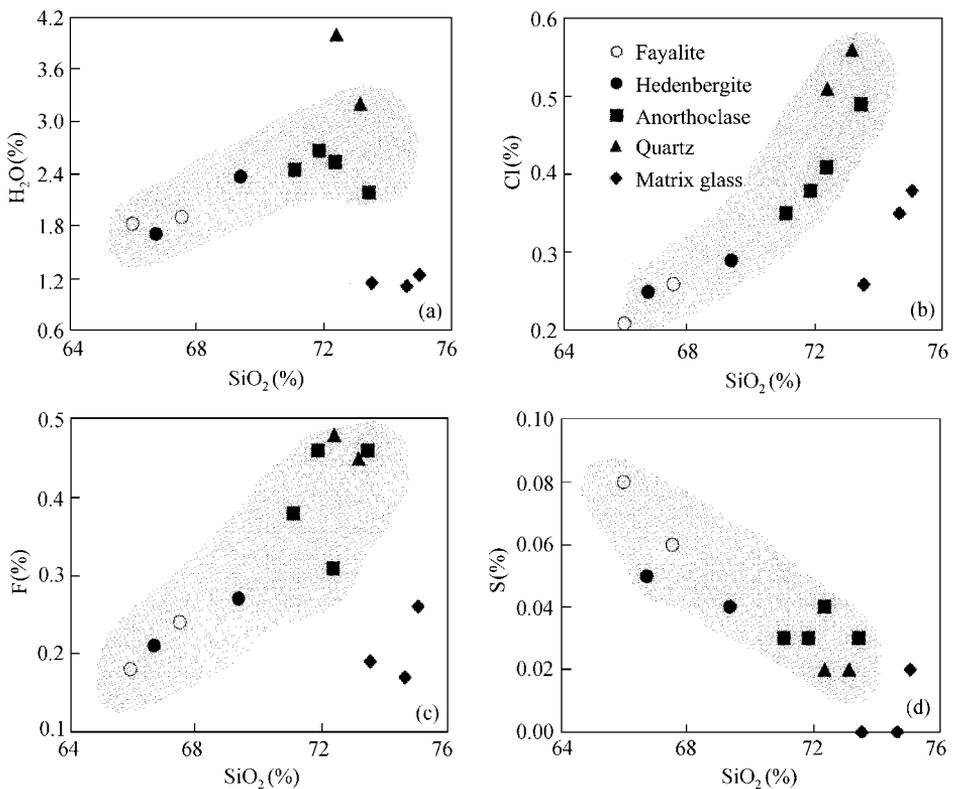


Fig. 2. Variation diagrams of volatiles (H₂O, Cl, F, S) versus SiO₂ (wt %). Shaded areas cover the variations of volatiles and SiO₂ in the glass inclusions.

pre-eruptive magmas. Observations under microscope show that crystallizing order of the major phenocryst minerals in Baitou Mountain is fayalite (Fe-Ti oxide) > hedenbergite > anorthoclase \approx quartz. Thus, we take volatile compositions of glass inclusions in anorthoclase and quartz phenocrysts as that of immediately pre-eruptive magma (tables 1 and 2). Meanwhile, volatile constituent of the post-eruptive melt might be represented by that of partially degassed matrix glass, which coexists with anorthoclase and quartz phenocrysts. Difference of the volatile compositions between pre- and post-eruptive melts is taken as syn-eruptive released volatile concentrations.

3.2 Estimations of pre- and post-eruptive volatile contents in Baitoushan volcano

The variation diagrams of SiO_2 and H_2O between glass inclusions in phenocrysts and matrix glasses (fig. 2(a)) show increasing H_2O contents when SiO_2 concentrations increase in glass inclusions, indicating more evolved magmas tending to high water content. Therefore, H_2O contents in glass inclusions entrapped in anorthoclase and quartz phenocrysts are regarded as those in immediately pre-eruptive magma.

The Cl contents in the glass inclusions are similar to those of Mayor Island^[4], and higher than those of Tambora (2110 ppm)^[11,12], Krakatau (2380 ppm)^[12] and Pinatubo (880—1060 ppm)^[4,8]. With magma evolving, F and Cl contents increase irregularly, parallel to the increase of SiO_2 concentrations in glass inclusions (fig. 2 (b) and (c)), which lead to Cl in the melt from under-saturation to over-saturation (fig. 3). The released coefficients, which are generally regarded as ratio of released volatile mass to total one, of halogen (30%—50%) and water (57%) are approximately identical. The most plausible explanation is that halogen released from Baitoushan volcano mainly came from erupted melt, and the vapor fluid phase contributions were minor^[8,10,13]. So, the halogen contents in glass inclusions entrapped in late crystallizing phenocrysts might be believed to indicate those of F and Cl in immediately pre-eruptive magma. In view of concentration scatter of F and Cl (fig. 2 (b) and (c)), average contents of F and Cl are calculated as the pre-eruptive contents (table 2).

The S contents in glass inclusions show the reverse correlation with SiO_2 concentrations (fig. 2(d)), indicating that S solubility in magma is controlled by magma differentiation process because of occurrence of the S-rich fluid inclusions^[8]. So, average sulfur content in six highly differentiated glass inclusions is postulated to represent S contents in the immediately pre-eruptive magma. The compositions of coexisting matrix glasses with anorthoclase and quartz phenocrysts, which represent those of post-eruptive magma, are listed in table 2.

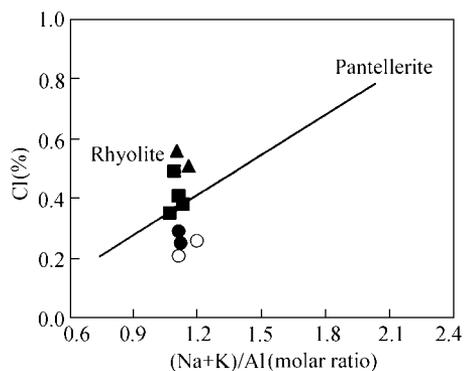


Fig. 3. Variation diagram between Cl (wt %) and [(Na+K)/Al] (molar ratio). Solid line indicates the Cl saturation from rhyolite to pantellerite following ref. [13]. Legend see fig. 2.

Table 2 Average volatile contents in glass inclusions (GI) and coexisting matrix glasses (MG)

	GI (%)	MG (%)	δ_v (%)
S	0.03	0.017	0.013
Cl	0.45	0.33	0.12
F	0.42	0.21	0.21
H ₂ O	2.84	1.18	1.66

δ_v is difference of GI and MG.

3.3 Total volume estimation of the eruptive products in Baitoushan volcano

Investigation in the field work showed that the products erupted in 1199—1200 AD mainly comprise Plinian pumice fallout and pyroclastic flow, thus total volume is the sum of Plinian fallout and pyroclastic flow. After measuring 24 Plinian fallout sections in the field work, based on thickness calculation of the Plinian fallout in proximal area and the tephra sediments in distal deposits from the Sea of Japan and Russia (fig. 1)^[14], total volume of the Plinian fallout was estimated to be $135.2 \pm 7.8 \text{ km}^3$ following the two-line model^[15]. The pyroclastic flow was principally distributed in proximal area within 40 km radius around the cone. Average value of the largest thickness around the cone is about 12 m. Thus, the volume of pyroclastic flow is $1/3 \times \pi \times 1600 \times 0.012 = 20.1 \text{ km}^3$ if pyroclastic flow body was taken as a circular cone shape.

In view of cumulating of the pyroclastic flow in paleo-valleys around the cone, for instance, average value on the largest thickness in Erdaobai River, Jinjang River (China) and Qianjunyan (North Korea) is 70—82.5 m, the volume of pyroclastic flow filled in these paleo-valleys is calculated to be 6.3 km^3 , based on thickness measurement of pyroclastic flow in the paleo-valleys and the paleo-valley shapes. Therefore, the total volume of the erupted products is $135.2 (\pm 7.8) + 20.1 + 6.3 = 161.6 \text{ km}^3 \pm 7.8 \text{ km}^3$. The dense rock equivalent (DRE) volume (V_m) of the Plinian fallout and pyroclastic flow is $32.3 \text{ km}^3 \pm 1.6 \text{ km}^3$.

3.4 Estimation of syn-eruptive volatile mass loss

“Petrologic method”^[7,12] assumed to be the best approach to estimate volatile mass especially for historic eruption^[8] shows that total eruptive mass of volatiles is in direct proportion to difference of volatile contents of pre- and post-eruption (δ_v , table 2), melt density (ρ), melt abundance (ϕ) and total volume (DRE, V_m). The relation is as follows:

$$M = \delta_v \times \rho \times \phi \times V_m.$$

The average melt density is calculated to be $2.88 \times 10^{12} \text{ kg/km}^3$ according to the model of Stebbins (1990)^[16], and the major element analyses (table 1). The melt abundance is 96% and the phenocryst abundance is 4%, which is estimated based on microscope observations and statistics. The calculated total mass (M) of volatiles emitted into the atmosphere is $147.784 \times 10^{10} \text{ kg}$ for H₂O vapor, $10.988 \times 10^{10} \text{ kg}$ for HCl, $19.680 \times 10^{10} \text{ kg}$ for HF, $2.314 \times 10^{10} \text{ kg}$ for SO₂ and $3.543 \times 10^{10} \text{ kg}$ for H₂SO₄ aerosol (table 3).

Table 3 The total mass of volatiles and H₂SO₄ aerosol injected into the atmosphere and stratosphere (×10⁶ ton)

	SO ₂	H ₂ SO ₄ aerosol	HCl	HF	H ₂ O
Atmosphere	23.14	35.43	109.88	196.80	1477.84
Stratosphere	3.33	5.10	15.82	28.34	212.81

3.5 Mass estimation of volcanic volatiles injected into the stratosphere

Model calculations of volcanic eruption dynamics^[7] show that the maximum eruption column height is 25—33 km above sea level based on isopleths of the tephra distributions. The tropopause in Baitoushan volcanic cone at 42°N is at approximately 14 km altitude^[8], which indicates the eruption column up into the stratosphere about 11—19 km. Ratio of volatiles injected into the stratosphere is estimated to be 14.4% applying the model of Liu (1998)^[7]. Total mass of the volatiles and H₂SO₄ aerosol injected into the stratosphere is listed in table 3, which suggests that the volatile components in the stratosphere are dominated by HF and HCl.

4 Comparison with other related eruptions of the world

The total masses of erupted products, volatiles and aerosols, released from other typical intermediate-acidic peralkaline volcanoes (VEI>5), are listed in table 4, showing that 1199—1200 AD eruption of Baitou Mountain is one of the largest Plinian explosive eruptions in history, according to estimation of product volumes and halogen masses, and comes second only to 1815 Tambora eruption (table 4).

Table 4 Comparison of 1199—1200 AD eruption of Baitoushan volcano with other related eruptions of the world

Volcano name	Country /area	Age	Volume of products/km ³	Composi-tion	HCl (10 ⁶ ton)	HF (10 ⁶ ton)	SO ₂ (10 ⁶ ton)	H ₂ SO ₄ aero-sol (10 ⁶ ton)
Campanian	Italy	33050BC	23	andesite	6.62*	2.91*	35.95	55.00
Roseau Tuff	Dominica	26050BC	30	dacite	11.51	4.12*	41.68*	69.41*
Santorini	Greece	1500BC	25	dacite	3.01*	2.72*	2.50	3.83
Taupo Plinian	New Zealand	131AD	5.8	rhyolite	1.28	1.13	0.21	0.33
Baitoushan	China/N. Korea	1199/1200 AD	32.3*	comendite	109.88*	196.80*	23.14*	35.43*
Oraefajokull	Iceland	1360AD	2	comendite	0.66	2.36	0.25	0.38
Tambora	Indonesia	1815AD	87	phonolite	216.00	125.00	34.20	52.33
Krakatau	Indonesia	1883AD	10	rhyolite	3.75	1.53*	1.90	2.94
Agung	Indonesia	1963AD	0.95	andesite	3.50	2.04	5.50	11.50
Mt. St. Helens	The USA	1980AD	0.23	dacite	0.11*	0.02	0.05	0.30
El Chichon	Mexico	1982AD	0.35	dacite	4.32	1.09	7.00	20.00
Redoubt	Alaska, USA	1989/90 AD	0.11	rhyolite	0.14	0.05*	0.04	0.24
Pinatubo	Philippines	1991AD	5	dacite	4.63	1.21*	20.00	29.00

The results with asterisks are from estimation of the authors applying "petrologic method"^[7,12]. The data are from refs. [8, 11, 12]

5 Discussion

The rationale of "petrologic method"^[7,12] applied is conservation of mass, i.e. total mass of

the erupted volatiles from immediately pre-eruptive melt = syn-eruptive volatile mass loss + volatile mass remained in post-eruptive melt. In this model, only magma degassing during syn-eruption is considered, which neglects vapor fluid phase and melted wallrock in conduit (for example, carbonate, gypsum) degassing. Thus, the inherent assumptions in the “petrologic method” are as follows: (i) All volatiles and aerosols released during syn-eruptions were derived only from the erupted magma. (ii) The assimilation process did not happen when magma ascended in conduit. Therefore, the mass of volatiles and H₂SO₄ aerosol determined by the method is the minimum of actual eruptive product. On the other hand, the error of model calculation results yet from unreasonable estimation of some parameters, for example, pyroclastic flow volume, although the departure could be decreased with the detailed section measurements in the field work. Nevertheless, it is the only quantitative model to calculate volatile mass erupted in history, which is prior to the use of TOMS satellite and avoids ice core records, so the method was gradually accepted by petrologists and paleoclimatologists.

How about accuracy of results estimated above? The volatile released from Baitoushan volcano is mainly from decompression exsolution process of the ascending magma, and the volatile released from vapor fluid phase is negligible as mentioned above. This is coincident with the first assumption of the method. Field survey shows that magma from 1199—1200 AD eruption ascends along the same conduit as the previous basaltic, trachytic and comenditic lavas erupted in Pleistocene and Pliocene, which could mantle and melt the inner conduit and crater wall because of their high viscosity. This precludes the contact between 1199—1200 AD lava and wall rock in the conduit, thus eliminating assimilation during the magma ascending. This is in accordance with the second assumption of the method as noted above. Likely, this is why no wallrock inclusion was found in 1199—1200 AD eruption products of Baitou Mountain. In addition, on the basis of section measurements in the field work, we think that departure of the estimated product volume from the actual one is minor. Thus, it is feasible for “petrologic method”^[7,12] to estimate syn-eruption mass of the volatiles and aerosol from Baitou Mountain, and the finally estimated result (table 3) is reasonable.

Atmospheric measurements by TOMS show that final environmental effect of the active volcanic eruptions, whose volatile compositions dominated in “halogen + H₂SO₄ aerosol + water vapor” association, could decrease total mass of atmospheric ozone, and even cause ozone layer depletion and ozone hole in the stratosphere if eruptive columns reach into the stratosphere^[2]. Volatile released from Baitou Mountain and injected into the stratosphere consists also principally of HF and HCl (tables 3 and 4), and the volume of products comes second only to 1815 Tambora eruption. The further work should answer whether the eruption of Baitoushan volcano had a significant effect on climate. In addition, previous studies showed that the positive peaks of SO₄²⁻ and Cl⁻ concentrations are obvious in 1200 AD in Guliya ice core, north Tibet^[17]. In Greenland Ice Core (GISP2), SO₄²⁻ peak in 32ppb was showed in 1205 AD^[18]. Whether those peaks are associ-

ated with 1199—1200 AD eruption of Baitoushan remains unsolved.

6 Conclusion

The products of 1199—1200 AD Baitoushan volcanic eruption dominantly comprise Plinian pumice fallout. Of all the volatiles injected into the stratosphere, HF and HCl are dominant. The total mass of products from Baitoushan volcano comes second only to 1815 Tambora. A large amount of volatiles could have substantial effect on paleoclimate and paleo-environment.

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