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GLASS INCLUSIONS: AN INDICATOR OF GEOTHERMAL HEAT SOURCE

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ABSTRACT

Many geothermal fields are located in the terrains where volcanic rocks are dominant. These rocks are considered to be products prior to the present geothermal activity on a series of magmatism. In the Kirishima geothermal field, southwestern Japan, many glass inclusions are found in phenocrysts of plagioclase, pyroxene and olivine of the volcanic rocks. At present, most of them consist of a bubble and a clean or devitrified glass with or without daughter and/or trapped minerals. Each inclusion should have consisted of a silicate melt and trapped minerals when it was isolated, and a bubble and daughter crystals were formed during the cooling and solidification process of the melt. The homogenization temperature at which a bubble disappears, therefore, gives an information concerning the temperature of trapped magma. The glass inclusions homogenize at temperatures ranging from 800°C to 1400°C. The values may suggest that the present temperature of geothermal heat source in the Kirishima geothermal field is 800°C at the highest.

INTRODUCTION

A magma reservoir is always illustrated as a heat source in every schematic diagram showing geology of a geothermal field. Any report does not, however, reveal not only the occurrence but also the character of the magma. In order to understand a geothermal system, and to evaluate accurately the potentiality of the resource, however, it is necessary to know the occurrence and the character of the magma. Do we have any key to resolve the problems? The answer is partially "yes", because we have a probable key to clarify the magmatic character. It is glass inclusions trapped in phenocrysts of volcanic rocks.

Many geothermal fields are located in terrains where recent volcanic rocks are predominant. The rocks are products prior to the present geothermal activity derived from the same magmatism. Glass inclusions occur frequently in phenocrysts of the volcanic rocks. They are considered to have been silicate melt, that is magma itself, trapped during the growth of host crystals. Keeping original amounts of volatile components, glass inclusions, although tiny, might have more valuable informations concerning the magmatic activity than groundmass of volcanic rocks. This implies that glass inclusions suggest the character of deeply sited magma, which controls the characteristics of the geothermal system.

The Kirishima geothermal field is one of the most potential areas in Japan. The field is located on the western flank of Kirishima volcanoes, southern Kyushu, southwestern Japan (Fig. 1). Accordingly, this field is the best for glass inclusion studies.

KIRISHIMA VOLCANOES

The geology of Kirishima volcanoes (Fig. 2) is outlined by Kobayashi et al. (1981).

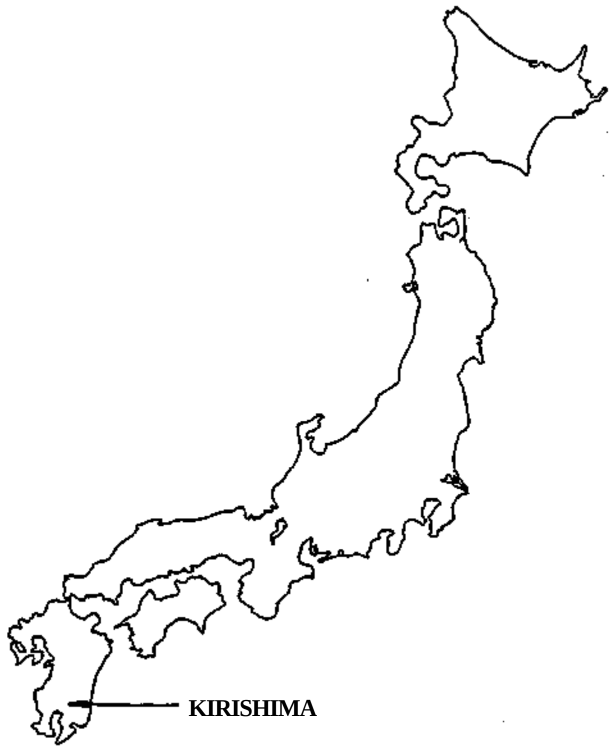

Fig. 1: Map showing the location of Mt. Kirishima.

Mt. Kirishima consists of a group of Quarternary volcanoes occupying an area of about 20x30 km^2 in the northwest-southeast direction. More than 20 eruption centers, which are recognized as peaks or lakes (Fig. 3), have been active from late Pleistocene age. The basement rocks are siltstone, sandstone, conglomerate, chert and minor amount of basalt of Cretaceous to Paleogene ages.

In the early stages of the volcanic activity, a large pile of andesite lava flows was formed by the successive eruption. The activity continued to the eruption of andesitic rocks forming several stratovolcanoes overlying the older lava pile. The younger volcanoes are either pyroclastic cones or small stratovolcanoes. They are divided into three groups by the two widespread pyroclastic deposits (Fig. 3). The older key bed is I to pyroclastic flow from the Aira caldera (21-22 ka), while the younger one is Akahoya ash fall from the Kikai caldera (6 ka).

Onami-ike, Karakuni-dake, Ohachi all retain the fresh morphology of scoria cones with large top craters. Crater lake occupies the center of Onami-ike. Stratovolcanoes such as Takachihono-mine and Shinmoe-dake are also mainly composed of pyroclastic materials with a little amount of lava flows. Mi-ike is a maar filled with water. It was formed by a Plinian pumice eruption

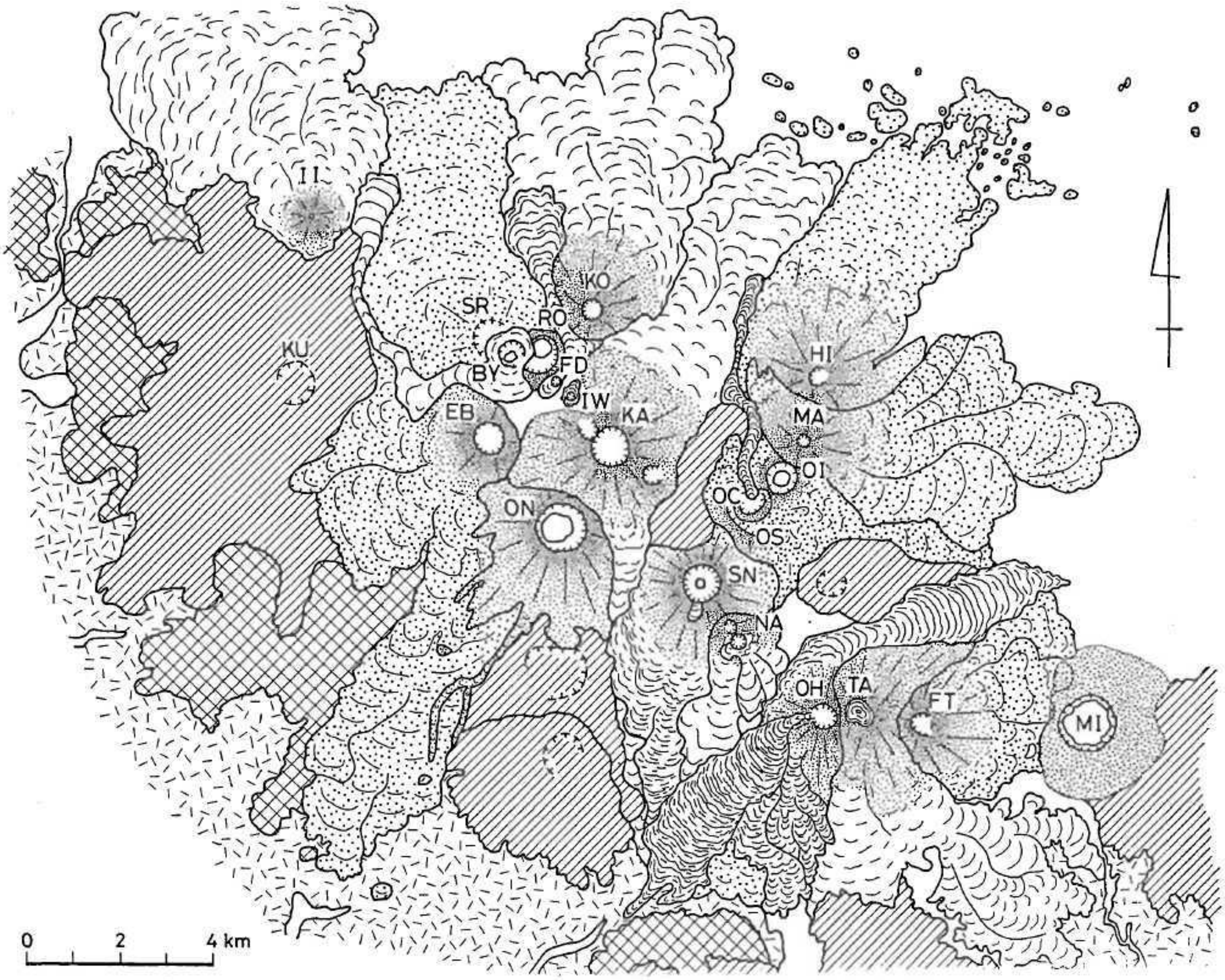

Fig. 2: Geological map of Mt. Kirishima (slightly modified from Kobayashi et al. 1981). Abbreviations of eruption centers: BY=Byakushi-ike, EB=Ebino-dake, FD=Fudo-ike, FT=Futatsuishi, HI=Hinamori-yama, II=Iimori-yama, IW=Iwo-yama, KA=Karakuni-dake, KO=Koshiki-dake, KU=Kurino-dake, MI=Mi-ike, MA=Maruoka-yama, NA=Naka-dake, OC=Ohata-yama central cone, OH=Ohachi, OI=Ohata-ike, ON=Onami-ike, OS=Ohata-yama somma, RO=Rokkan'non-ike, SN=Shinmoe-dake, SR=Shiratori-yama, TA=Takachihono-mine.

Relatively Northwest				Relatively Southeast
Iwo-yama(IW)		Shinmoe-dake(SN)		Ohachi(OH)
Fudo-ike(FD)		Ohata-yama central cone(OC)	Ohata-ike(OI)	Mi-ike(MI)
		Akahoya ash fall (6 ka)		
Byakushi-ike(BY)		Naka-dake (NA)		Takachihono-mine(TA)
Iimori-yama(II)	Koshiki-dake(KO)			
Karakuni-dake(KA)				
		Ito pyroclastic flow (21-22 ka)		
	Onami-ike(ON)			
Rokkan'non-ike(RO)				
Rokkan'non-ike conglomerate				
		Maruoka-yama(MA)		
Shiratori-yama(SR)		Ohata-yama somma(OS)		
Ebino-ke(EB)	Hinamori-yama(HI)			Futatuishi(FT)
Takaharu conglomerate (28 ka)				
Kurino-dake(KU) amdsite (150-600 ka)				

Fig. 3: Stratigraphy of each volcanic centers (Shoji and Yamada, 1986). Small glossary of Japanese topographic terms: dake=rocky or steep mountain, ike=pond or lake, mine=peak, yama=mountain.

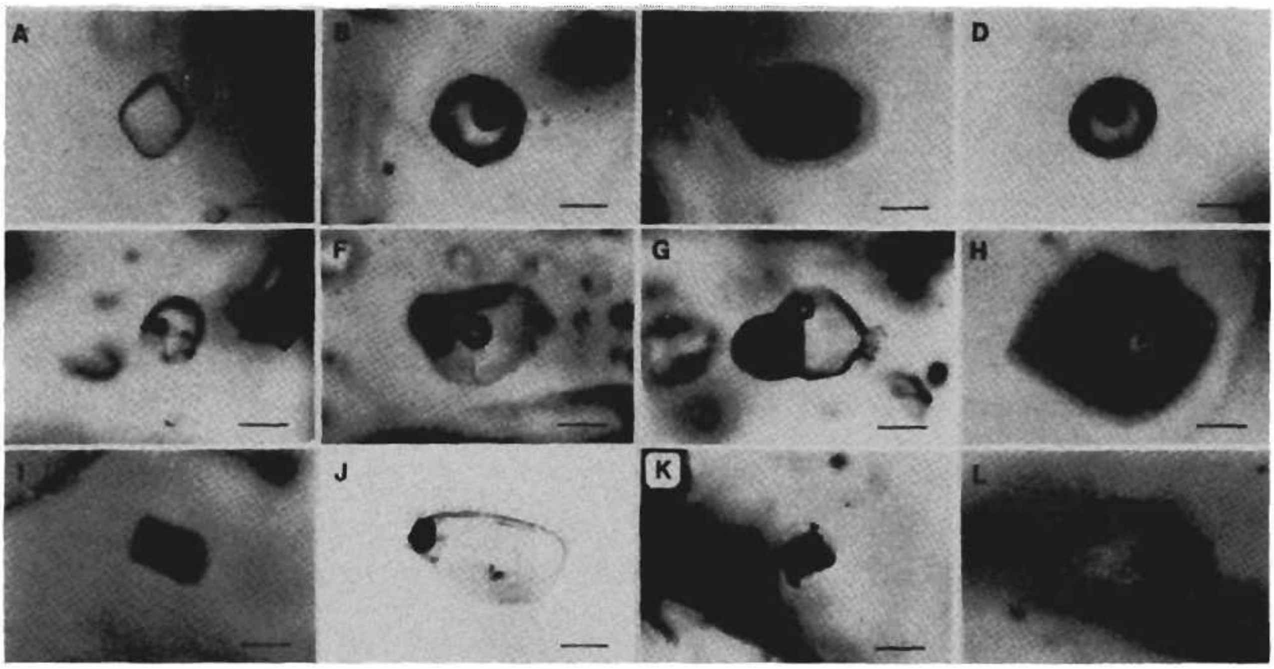

Fig. 4: Various types of glass inclusions occurring in Kirishima volcanic rocks. Alphabets correspond to the type in Table 1. A scale bar is 10 um.

about 3 ka age.

The rocks of older volcanoes are augite-hypersthene andesite with or without a small amount of olivine phenocrysts. The silica contents range from 53 to 59 %. The rocks of younger volcanoes vary from olivine basalt to hornblende-bearing pyroxene andesite through pyroxene andesite with or without olivine. Basalt and mafic andesite are found at Hinamori-dake, Ohachi, Takachihono-mine, and Ohata-yama located in the eastern and southeastern part of Mt. Kirishima.

GLASS INCLUSIONS

If a magma reservoir exists under Mt. Kirishima, the chemistry of magma is expected to be similar to that of the youngest volcanic rocks. For this reason, glass inclusions have been examined using specimens from Shiratori-yama (KR01), Byakushi-ike (KR02), Fudo-ike (KR03), and Ohachi (KR04) lavas. Plagioclase and pyroxene are main phenocryst minerals of the rocks, and olivine is rarely found. Many glass inclusions are observed in the phenocrysts. They occur individually or randomly in host crystals, or along growth bands of host crystals. The occurrences imply that they are primary in origin. Sometimes many inclusions crowd in narrow areas. The origin is not clear. Inclusions are generally less than 30 um in size, though only a few inclusions are 100 um. The inclusions occurring along the growth bands of plagioclase are smaller than a few um.

Fig. 4 shows all types of glass inclusions. On the basis of the constituents, glass inclusions are broadly divided into three types. Inclusions of the first type consists of a single phase of glass (A of Fig. 4). Inclusions of the second type have one or more bubbles besides a glass (B and C of Fig. 4). The third type belonging to a polyphase inclusion is characterized by the presence of one or more crystals (from D to L of Fig. 4). Some of the rystals are acicular, dendritic or granular in shape. The modes of occurrence indicate that they are daughter minerals crystallized after trapped. The species could not be identified because of the small size. Two species of minerals are trapped. The one is transparent and granular. The name is not also determined. The other is opaque and euhedral. The form suggests it is magnetite.

Bubbles are commonly spherical or subspherical in shape. Some bubbles, however, are crooked. Small crystals are frequently formed on the surface of bubbles. Glass of some inclusions is clean, while that of others is devitrified.

In Table 1 are summarized all types of glass inclusions, the constituent phases, and their relation to the species of host minerals. Any significant relation is not found between the inclusion types and host minerals.

HOMOGENIZATION TEMPERATURES

Filling and homogenization temperatures have been measured for inclusions of the second and third types. The measurement procedure is as follows: 1) heating up to a given temperature (every 50°C from 800°C) with a rate of about 500°C/h; 2) holding at the temperature for 8 to 14 h; 3) rapidly cooling in air; 4) observing

Table 1: Types of glass inclusions, the constituent phases, and their relation to host minerals.

Type[1]	Constituent Phases[2]						Host Minerals[3]		
	B	Go	Gd	Gx	Mt	Mo	pc	px	ol
A		+					c	c	
B	+	+					c	c	
C	+		+				c	c	
D	+			+			r	c	r
E	+	+			+		r	c	
F	+	+				+	c	c	
G	+	+			+	+	r	c	
H	+		+		+		c	c	
I	+		+			+	c		
J	+			+	+		c	c	
K	+			+		+	c	c	
L	+			+	+	+		c	

[1] Alphabets orrespond to Fig. 3.
[2] Abbreviations:
B=bubble, Go=clean glass, Gd=devitrified glass, Mt=transparent mineral (probably trapped), Mo=opaque mineral (probably trapped).
[3] Abbreviations:
pc=plagioclase, px=pyroxene, ol=olivine; c=common, r=rare.

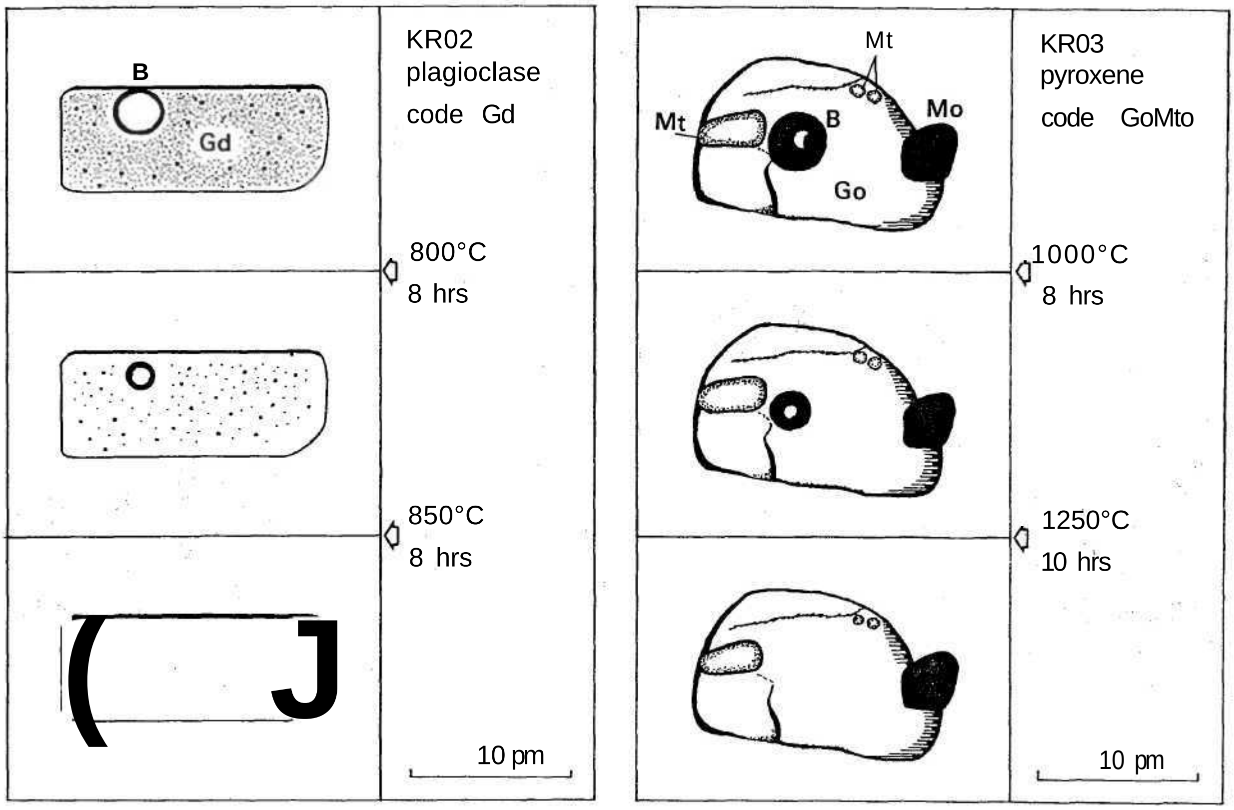

Fig. 5: Illustrations showing change of glass inclusions by heating.

constituent phases and their proportion; 5) heating again up to a temperature 50°C higher than the former run, when the inclusion is not homogenized.

All devitrified glasses become clean by 850°C. All daughter minerals disappear by 1050°C. On the contrary, any trapped minerals do not disappear up to 1400°C. Bubbles disappear at temperatures ranging from 800°C to 1400°C. The illustration of Fig. 5 shows schematically the change of two typical glass inclusions by heating. All inclusions except ones containing trapped crystals are homogenized by the disappearance of bubble. That is, each homogenization temperature is equal to the filling one. The homogenization temperatures are summarized in Fig. 6.

DISCUSSION

Glass of a inclusion was originally silicate melt, a part of magma in which phenocrysts were formed. After eruption, the inclusion was cooled together with the host crystal. The volume of silicate melt decreases by cooling and solidification. The inclusion melt should have filled the whole inclusion volume, when it was trapped. The temperature at that time, therefore, was higher than the homogenization temperature.

The cooling process of glass inclusions with bubbles is summarized as follows:

1) the melt was cooled from the trapped temperature to the liquidus one; in this process, a bubble was formed by the shrinkage of inclusion liquid;
2) from the liquidus temperature to the solidus one, the melt changed gradually to the glass, and the bubble grew; if the cooling rate was slow enough, daughter minerals were crystallized;
3) at temperatures below the solidus, the constituent phases scarcely changed.

When the cooling rate is very high, the melt changed immediately to glass, and no bubble appeared. Therefore, a negative pressure to compensate the shrinkage should be produced in a bubble-free inclusion.

Heating a glass inclusion shows the cooling process of the inclusion reversewards. The filling temperature (i. e. homogenization temperature), therefore, corresponds to the temperature at which a bubble began to be formed. Consequently, the trapped temperature should have been approximately equal to but slightly higher than the homogenization temperature. Fig. 6 shows the following facts:

1) glass inclusions of each lava have a wide range of homogenization temperatures;
2) no difference in homogenization temperatures is found among the examined lavas;
3) no difference in homogenization temperatures is also found between plagioclase and pyroxene phenocrysts.

These yield the following conclusions:

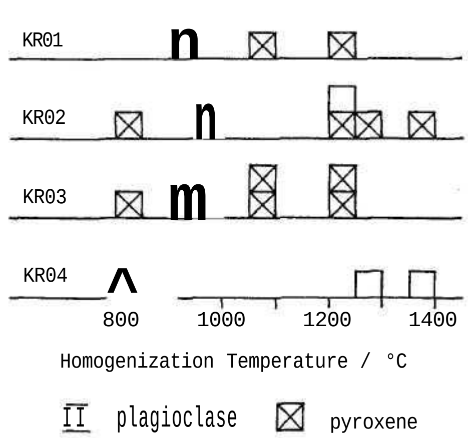

Fig. 6: Homogenization temperatures of glass inclusions.

1) both phenocryst minerals were formed in a wide temperature range from 800°C to 1400°C;
2) four lavas examined here are not products formed on the process of gradual cooling of of a single magma, because no systematic change is found from the oldest Shiratori-yama lava to the youngest Ohachi lava.

The above conclusions suggest two probable models for the magma reservoir. It is assumed in the first model that each lava was supplied from its own magma reservoir. According to the model, it is concluded that many magma reservoirs exist under Mt. Kirishima. On the contrary, if the number of reservoir is single, the high temperature magmas must have been supplied repeatedly into the reservoir from a deeper portion.

The lowest value of homogenization temperatures is about 850°C. This temperature is too low for the melting point of dry andesite magma. The inclusion glass, therefore, seems to contain a remarkable amount of water. The water content can be estimated based on the data of the chemistry and melting temperature of glass. The chemistry of glass inclusion, however, has not yet been determined even by the electron microprobe, because the inclusion is wrapped with a host crystal, and is small in size. If the magma in the Kirishima geothermal field is cooled gradually and continuously, it is inferred that the present temperature is 850°C at the highest. However, the assumption does not agree with the probable models of the Kirishima magma reservoir. The actual temperature of the reservoir, therefore, is estimated to be higher than the value.

CONCLUSION

Many glass inclusions are found in volcanic rocks from Mt. Kirishima. They homogenize at temperatures ranging from 800°C to 1400°C. The wide range of homogenization temperatures yields two models of magma reservoir: 1) each volcanic rock was erupted from its own magma reservoir; and 2) new magmas were supplied repeatedly into a magma reservoir. If the lowest value of homogenization temperatures indicates the present magma temperature, the value is 850°C at the highest. However, both models of magma reservoir suggest that the actual temperature of the magma reservoir is higher than the value.

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