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INSTALLATION OF PENETRATOR-TYPE THERMOMETERS AND BLASTMETERS FOR DETECTING PYROCLASTIC SURGES DURING ERUPTIONS OF UNZEN VOLCANO, KYUSHU, JAPAN

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ABSTRACT

Pyroclastic flow is one of the most destructive eruptive phenomena and has kept scientists from making direct measurements of its physical properties. We constructed two types of penetrators to measure the temperature, over pressure and particle velocity of a pyroclastic surge accompanied by a pyroclastic-flow eruption. The penetrator-type thermometer measures temperature and duration of a pyroclastic surge based on the change in state of several kinds of metals and thermodyes which melt at specific temperatures during volcanic events. The penetrator-type blastmeter estimates the explosion energy and particle velocity of a pyroclastic surge on the basis of the deformation of a thin metal plate. A helicopter of the Japanese Self Defense Force was used to drop 12 penetrators from a height of 30–45 m at 5 points on Unzen Volcano in Kyushu, Japan, most of which landed erect. Measurements made with this type of penetrator enable us to obtain certain physical properties of pyroclastic surges in dangerous areas during explosive eruptions.

1. INTRODUCTION

A pyroclastic flow is one of the most destructive of eruptive phenomena, containing a mixture of hot lava fragments and gas and descending volcanic slopes at high speed. Pyroclastic-flow eruptions occurred at Unzen Volcano in Kyushu on May 1991, one of which was the largest of Japanese historic pyroclastic-flows since the 1929 pyroclastic-flow eruption at Komagatake Volcano in Hokkaido. Chances to study the physical properties and hazards of pyroclastic-flow eruptions have been few because the frequency of the occurrence of a pyroclastic flow is approximately once in several decades in the case of small-scale pyroclastic-flow eruptions and once in tens of thousands of years in the case of caldera-forming, large-scale pyroclastic-flow eruptions. A pyroclastic flow descends at high speed destroying everytning in its path. The pyroclastic flow from Mount Pelee on 8 May 1902 killed about 28,000 people at St. Pierre 6 km from the crater

KEY WORDS: Penetrator-type thermometer, Penetrator-type blastmeter, Pyroclastic flow, Pyroclastic surge, Unzen Volcano

[1]. The pyroclastic flow at Unzen on 3 June 1991 killed 43 people within a few minutes.

The physical properties of pyroclastic flows must be determined in order to understand the flow mechanism and to reduce disasters. The temperature, dynamic pressure and particle velocity are significant factors with which to determine areas at hazard of pyroclastic flows. Direct measurement of the physical and chemical properties of a pyroclastic flow, however, is rare compared with the monitoring of earthquakes, crustal movements, magnetism and volcanic gases. Chances of studying the physical properties of pyroclastic flows have been limited because they are too dangerous to approach for direct measurement and because instances of pyroclastic-flow eruptions are rare in the history of scientific observations. Previous studies on pyroclastic-flow eruptions have been limited to the measurement of flow velocities.

Taniguchi and Suzuki-Kamata [2] succeeded in directly measuring the over pressure of the volcanic blast at Unzen on 8 June 1991 using a lead-plate blastmeter set up on the ground before the explosion. The over pressure of this volcanic blast was 0.28 bar 2700 m from the crater, the over pressure at 4400 m being less than 0.06 bar. The estimated explosive yield of the eruption that accompanied the blast was 1.1×10^7 kg TNT (5×10^{20} erg). Although this method of measurement was very useful, it proved unrealistic for further use at Unzen because the hazardous areas were enlarged as eruptions continued. A safer method of measurement therefore was needed.

We have developed a penetrator-type thermometer and a blastmeter that measure the temperature, dynamic pressure and particle velocity of a pyroclastic surge. Because the exact time of the occurrence of an eruption can not be predicted and because a pyroclastic-flow eruption is terminated in a few minutes, a penetrator system coupled with the thermometer and blastmeter is essential for obtaining the physical properties of a pyroclastci flow. Penetrator surveys have been planned to obtain seismological data in Antarctic [3] and on the Moon by the Lunar-A mission [4]. Our experiment constitutes the first trial for pyroclastic-flow studies. We succeeded in setting up the penetrators by dropping from a helicopter onto the eastern flank of Unzen Volcano, where a pyroclastic flow was expected in the near future. The thermometer and blastmeter will be withdrawn at the end of pyroclastic-flow eruptions. We here describe the apparatus and the aerial drop experiment done at Unzen Volcano on 4 March 1992.

2. THE GEOLOGY AND RECENT ERUPTIVE SEQUENCE OF UNZEN VOLCANO

Unzen is a composite volcano produced by an extensional stress field unlike most Japanese volcanoes whihc are located in compressional stress fields [5]. It is composed mainly of thick lava flows or domes of hornblende-biotite dacite associated with pyroclastic deposits [5,6]. Eruptive activity started about 500,000 years ago in the western part of the volcano and moved eastward [7]. The most recent past eruption occurred at Fugendake, located in the eastern part of the volcano, in 1792. Fifteen thousand people were killed in a debris avalanche triggered by an earthquake associated with this volcanic activity.

The first phenomena preceding the latest eruption were earthquake swarms in November 1989 centered below Tachibana Bay west of Fugendake [8,9]. The eruption began on 17 November 1990 at Fugendake with a steam explosion after 198 years of dormancy [8]. Since the extrusion of the lava domes of hornblende-biotite dacite on 20 May 1991, many pyroclastic flows have originated from gravitational dome collapse up to the present (August 1992). The three largest pyroclastic-flow eruptions occurred on 3 June, 8 June and 15 September, with respective flows from the vent of 3.9, 5.5 and 5.5 km.

Pyroclastic flows are considered to be comprised of a pyroclastic-flow body, a pyroclastic surge and an ash cloud [10,11]. The pyroclastic-flow body is what runs down to a topographically lower area burying any vallies due to its high density. A pyroclastic surge is a dilute flow that first accompanies then detaches from the pyroclastic-flow body. The pyroclastic-surge deposit usually is thin and fine grained in comparison to the pyroclastic-flow body. The pyroclastic surge, however, is destructive in spite of being thin and fine grained, sometimes destroying trees along its route. Volcanic hazard maps, which basically are drawn with reference to ancient volcanic deposits do not usually show pyroclastic-surge deposits, as they are difficult to identify in field surveys of ancient volcanic products because of their being very thin. Therefore it is important to determine the physical properties of a pyroclastic surge in order to chart hazard areas during pyroclastic-flow eruptions.

3. DESIGN OF THE PENETRATOR SYSTEM

Diagrams of the penetrator-type thermometer and blastmeter are shown in Figure 1. As penetrators must stand upright on the ground, we planned its center of gravity to be low at a level and added wings to ensure a straight fall. We designed the wings so that they would detach from the penetrator when it reaches the ground in order to exclude the possibility of the penetrator falling down due to the strong lateral pressure of a pyroclastic surge. The wings are attached to the penetrator with double-sided adhesive tape, selected because of the results of our dropping experiments, in which the wings detatched successfully from the penetrator on the shock of collision

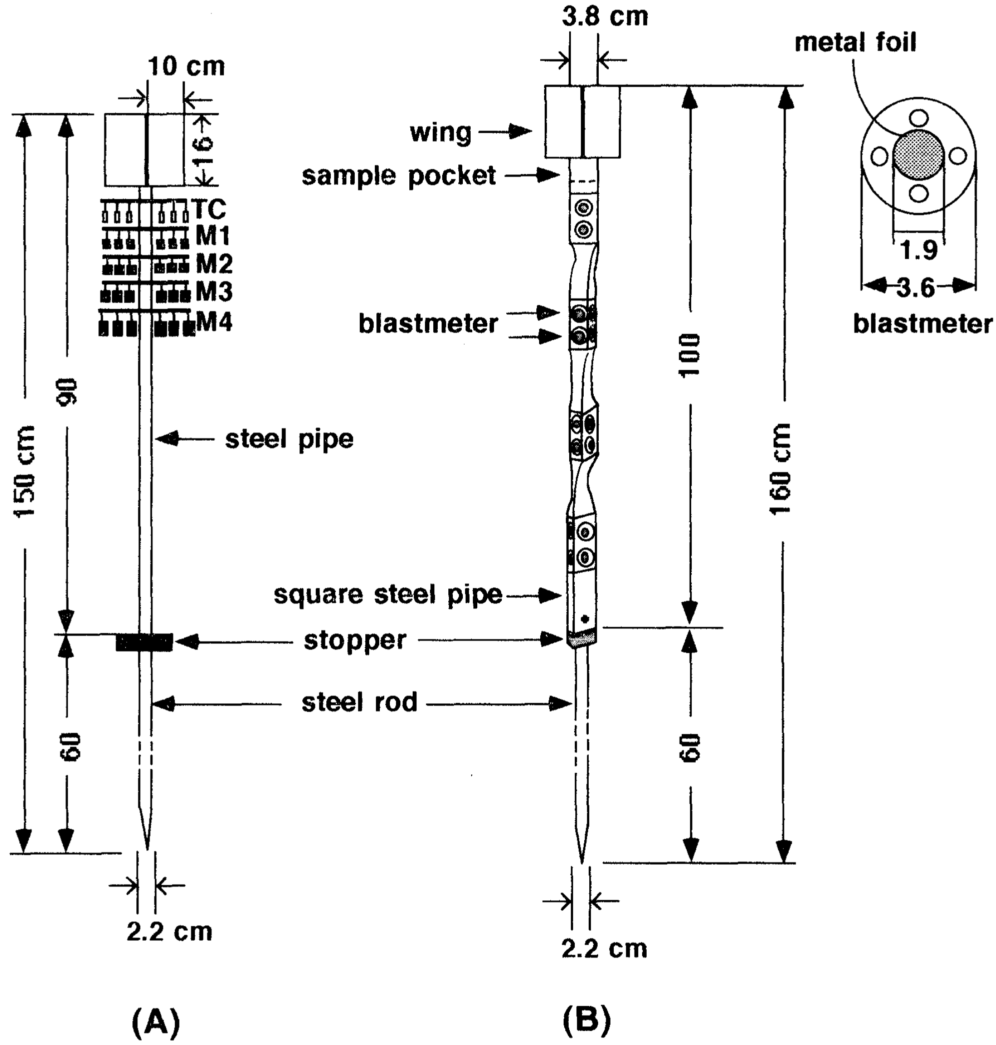

Fig. 1 Diagrams of the penetrators for temperature (A) and the dynamic pressure and particle velocity (B) measurements of a pyroclastic surge and a volcanic blast. M1-M4 and TC respectively are thermometers that use the fusion of metals and thermocrayons.

with the ground.

3.1 *Penetrator-type thermometer*

The thermometer is designed to measure both the temperature and duration of a pyroclastic surge. Sixteen kinds of metal and alloys function as temperature sensors based on their fusion features at various melting temperature. We chose alloys that have a relatively small temperature difference between the minimum liquidus and maximum solidus (Table 1). The melting temperatures range from 100°C to 780°C, the maximum temperature interval being 102°C. All the metals and alloys used are corrosion resistant, as the sensors are desinged to be left for a long time until the withdrawal of the penetrators. We also used thermocrayon, a type of thermodye made by Nichiyugiken Industrial Corporation, that has a melting temperature from 100°C to 793°C (Table 1). Thermocrayon is sealed in a copper tube 2 mm in diameter because it would lose its function if wet. The sensor sizes are 1 mm diameter and 1 mm long (M1 of Fig. 1), 2 mm diameter and 2.5 mm long (M2), 2 mm diameter and 10 mm long (M3) for all 16 metals and alloys; 3 mm diameter and 10 mm long (M4), 5 mm diameter and 10 mm long (M4), 10 mm diameter and 5 mm long (M4), 10 mm diameter and 10 mm long (M4) for the tin, lead, zinc and aluminium devices; and 2 mm diameter and 5 mm long for the thermocrayon (TC of Fig. 1). Results of melting experiments done at 500°C showed that it took 2 seconds for the smallest lead (1 mm diameter and 1 mm long) to melt and about 3 minutes for the largest lead (10 mm diameter and 10 mm long). The sensors are suspended by a nichrome wire 0.02 mm in diameter that is fixed on four bolts of the penetrator (Fig. 2). A nichrome ring 0.35 mm in diameter suspends 16 sensors. The penetrator is composed of a lower steel rod and upper steel pipe connected by a steel stopper (Fig. 2). The thickness of the steel pipe is 2.8 mm. Alminium wings are attached to the penetrator with double-

Table 1 Melting temperatures of the thermometer materials.

	Metal	solidus temperature	liquidus temperature	component		Thermocrayon	liquidus temperature
1	DIA230 (Silver Brazing Filler Metal)	710°C	810°C	Ag(20), Cu(45), Zn(35)	1	M795	795°C
2	BAg-8 (Silver Brazing Filler Metal)	780°C	780°C	Ag(72), Cu(28)	2	M765	765°C
3	BAg-5 (Silver Brazing Filler Metal)	665°C	745°C	Ag(45), Cu(30), Zn(25)	3	M700	700°C
4	BAg-2 (Silver Brazing Filler Metal)	605°C	700°C	Ag(35), Cu(26), Zn(21), Zn(18)	4	M645	645°C
5	Aluminum	660°C	660°C	Al(100)	5	M590	590°C
6	BAg-1 (Silver Brazing Filler Metal)	605°C	620°C	Ag(45), Cu(15), Zn(16), Cd(24)	6	M545	545°C
7	Alumit	580°C	592°C		7	M490	490°C
8	AC2	522°C	522°C	Al(68), Cu(27), Si(5)	8	M460	460°C
9	Zinc	420°C	420°C	Zn(100)	9	M430	430°C
10	Alminum soft solder	360°C	362°C		10	M395	395°C
11	Lead	328°C	328°C	Pb(100)	11	M345	345°C
12	Type lead	260°C	260°C		12	M300	300°C
13	Tin	230°C	230°C	Sn(100)	13	M255	255°C
14	Soft solder	183°C	184°C	Sn(63), Pb(37)	14	M200	200°C
15	Soft solder	143°C	143°C	Sn(51.2), Pb(30.6), Cd(18.2)	15	M150	150°C
16	Termo-fuse	100°C	100°C		16	M100	100°C

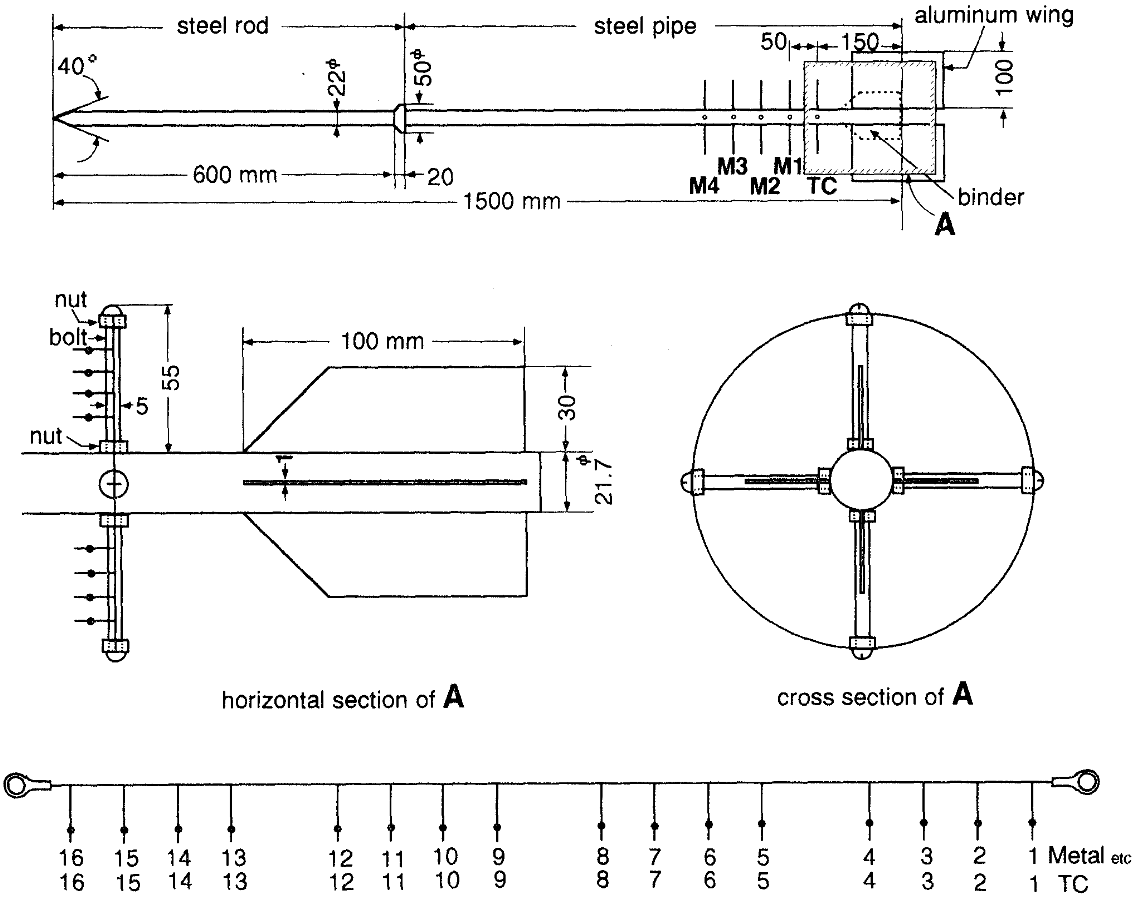

Fig. 2 Plan of the penetrator-type thermometer. M1 denotes the smallest metal and alloy pieces that indicate the shortest duration of a pyroclastic surge. The sizes of the thermometer materials increase from M1 to M4. TC shows the thermocrayon thermometer. Numbers 1 to 16 show placement of the metal and alloy pieces and thermocrayon. These materials fuse at the melting or liquidus temperatures shown in Table 1.

sided adhesive tape just before dropping it. The total weight of the penetrator-type thermometer is 3.5 kg.

3.2 *Penetrator-type blastmeter*

The main frame of the penetrator-type blastmeter is a square steel pipe. It is twisted 22.5° at three points having 16 different orientations for the blastmeter elements (Figs. 1 and 3). This pipe in cross section is 38 by 38 mm and 1.6 mm thick. Blastmeters originally were used to measure the over pressure of a blast in order to estimate explosive effects in the fields of industry and military technology [12]. Taniguchi and Suzuki-Kamata[2] succeeded in measuring the over pressure of volcanic blast using a blastmeter during the earliest stage of the 1991 pyroclastic-flow eruption of Unzen Volcano. The pressure sensor used is a lead plate 0.5 mm thick and 50 mm in diameter. The total weight of the blastmeter is 1.3 kg. We designed a small-size blastmeter for the penetrator because the usual device is too heavy for the penetrator attachment. Lead and aluminium foils 0.1 mm thick that make up the sensor are fixed on a hole 20 mm in diameter with plain washers (2.6 mm thick) attached to a screw on each of 16 faces of the square steel pipe (Fig. 3). Four holes 3 mm in diameter have been drilled to secure the washer screw and to set a bolt in the steel square pipe. Four holes 10 mm in diameter are present in the lower part of the square pipe to avoid increases in the inside pressure due to the volcanic blast and/or pyroclastic surge at the time of eruption. These four holes are covered by a steel-board fence to divert the

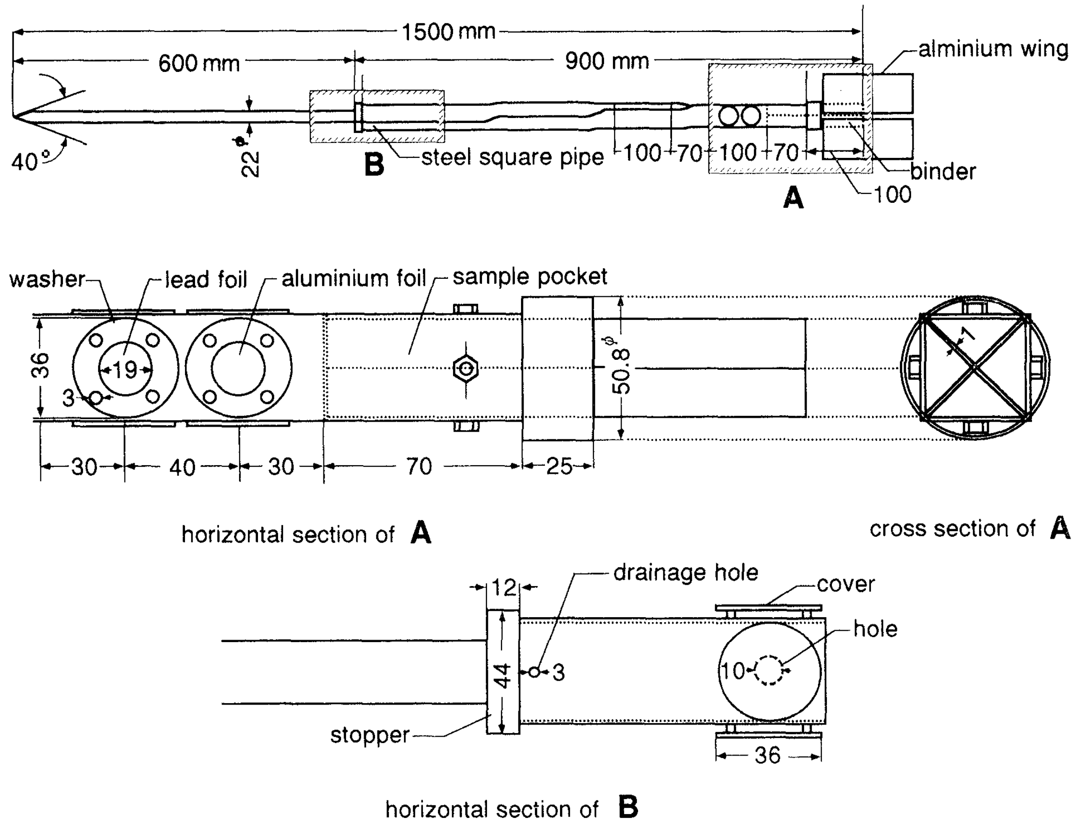

Fig. 3 Plan of the penetrator-type blastmeter that measures dynamic pressure and particle velocity.

direct effects of the flow. Total weight of the penetrator-type blastmeter is 4.1 kg. A trinitrotoluence (TNT) burst experiment is planned to calibrate the blastmeter after the withdrawal of the blastmeter.

The lead and aluminium foils of the blastmeter are used to measure the particle velocity of a pyroclastic surge on the basis of the relation between the impact traces of ash particles and the nature of the metal plate. Particle velocity is calculated by the methods of Baker et al. [13] and of Taniguchi and Suzuki-Kamata [2]. The equation of Baker et al. [13] is given by

$$\frac{\delta h}{a^2} \simeq 0.5 \frac{\rho_p V}{\sqrt{\sigma_t \rho_t}} - 0.035 \qquad (1)$$

where a is the projectile radius (assuming a spherical shape), V the projectile velocity, ρ_p the density of the ash particle projectile, h the thickness of the metal plate, ρ_t the density of that plate, σ_t the yield stress of the plate and δ the permanent deflection of metal plate at the point of impact. This penetrator also has a sample pocket for the collection of pyroclastic materials that are used to estimate the density and size of the ash particle projectiles (Fig. 3). The bulk density of a pyroclastic surge can be calculated from the particle velocity, dynamic pressure and average thickness of the pyroclastic-surge deposit.

4. THE DROPPING OF THE PENETRATORS AT UNZEN VOLCANO

The penetrators were dropped on 4 March 1992 with the cooperation of the Japanese Self Defense Force and the Director of the Shimabara Earthquake Volcano Observatory (Kyushu University), after gaining permission for the experiment from Nagasaki Prefecture, the municipal office of the Environment Agency of Japan and the Forestry Agency of Japan.

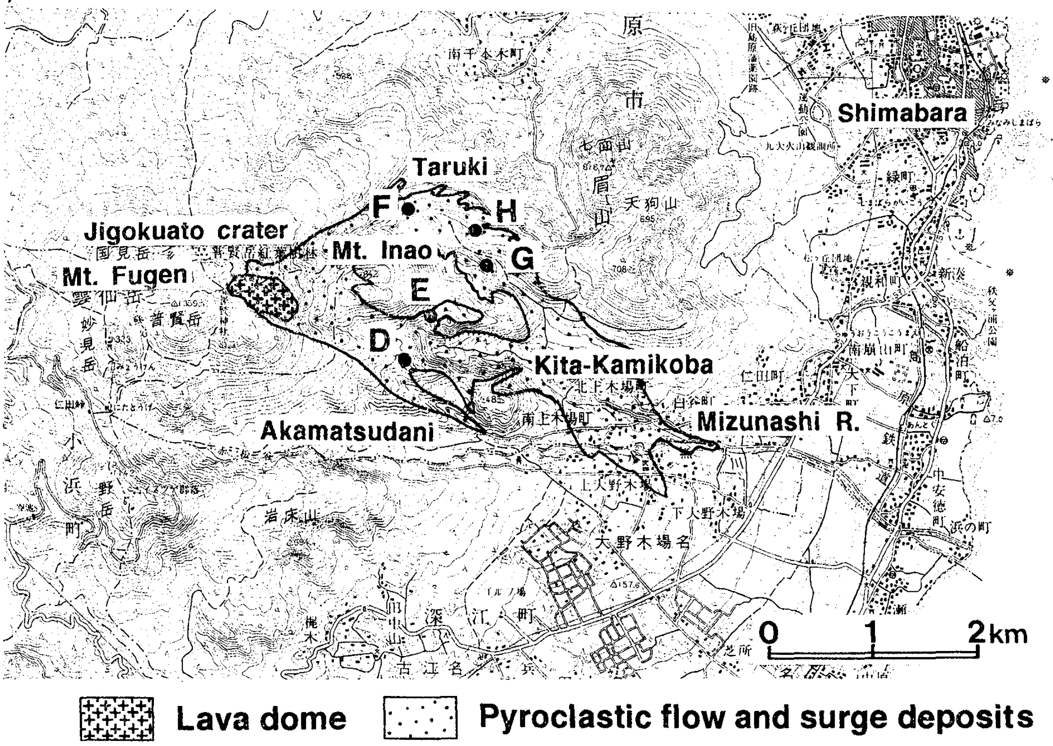

Fig. 4 Landing points (D, E, F, G and H) of the penetrators on the flank of Mount Unzen and the distributions of the lava dome, pyroclastic flow and surge deposits up to 22 September 1992. The topographic map of Shimabara (1 : 50,000 scale) published by the Geographical Survey Institute, Japan, is used.

Japanese Self Defense Force crews dropped 12 penetrators (six thermometers and six blastmeters) from a twin-engine helicopter of the Self Defense Force at 5 points northeast and east of Fugendake (Fig. 4). Another type of medium-sized helicopter was used to monitor the new lava domes at that time for sefety precautions. At each point the penetrators of the thermometer and blastmeter were thrown simultaneously by two people. Because the penetrator is designed to measure the pyroclastic surge of a pyroclastic flow, it was thrown onto broad ridges or gentle slopes where the pyroclastic-flow deposit was less thick. The altitude from which the devices were dropped was 30–45 m above ground surface. The landings of the penetrators were confirmed on board, and pictures taken by the crew. These penetrators made successful nearly vertical landings at four points (Nos. E, F, G and H in Fig. 4). At point No. D, the temperature penetrator made a successful landing but the blastmeter penetrator broke against the surface rocks. It took about one hour to drop the 6 pairs of penetrators.

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