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Resistivity and self-potential changes associated with volcanic activity: The July 8, 2000 Miyake-jima eruption (Japan)

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Abstract

The Miyake-jima volcano abruptly erupted on July 8, 2000 after 17 years of quiet and gave birth to a crater, 1 km in diameter and 250 m deep. This expected unrest was monitored during the years 1995–2000 by electromagnetic methods including DC resistivity measurements and self-potential (SP) surveys. Beneath the 2500 yr old Hatcho-Taira summit caldera audio-magnetotelluric soundings made in 1997–98 identified a conductive medium, 200–500 m thick (within the 50 Ω m isoline) located at a few hundred metres depth. It was associated with the active steady-state hydrothermal system centred close to the 1940 cone and extending southward. A DC resistivity meter set in a Schlumberger array with 600, 1000 and 1400 m long injection lines evidenced strong resistivity changes between September 1999 and July 3, 2000 in the vicinity of the newly formed crater. The apparent resistivity has reached about three times its initial values on the 1400 m long line and has lowered to about 20% on the 600 m line. Just prior to the July 8, 2000 eruption SP mapping made inside the summit Hatcho-Taira caldera revealed negative anomalies where positive ones had occurred during the previous tens of years. The largest negative anomaly, −225 mV in amplitude, mainly took place above the 1940 cone which collapsed in the crater formation. A permanent 1 km long SP line across the caldera suggests accelerating changes during the 3 months preceding the eruption. On a larger scale, the comparison between 1995 and 2000 surveys has shown a global increase of the hydrothermal activity beneath the volcano. Its source could have been 250 m to the south of the crater. These observations suggest that the hydrothermal system was slowly disturbed in the months preceding the eruption while drastic changes have occurred during the 2 weeks before the summit collapse when tectonic and volcanic swarms have appeared.

Keywords: eruption monitoring; hydrothermal systems; eruption mechanisms; magnetic and electrical methods

1. Introduction

Miyake-jima is one of the seven volcanic islands belonging to the Izu-Bonin arc in Japan. Two major caldera-forming eruptions took place dur-

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ing the building of the volcano. Following the 7000 yr BP eruption a several kilometres large caldera, called Kuwanoki-Taira, was formed (Fig. 1). The second produced a 1.5 km diameter caldera, called Hatcho-Taira, and is dated around 2500 yr BP [1]. Summit eruptions and flank fissure eruptions have since occurred.

No noticeable volcanic seismicity was recorded between the last eruption in 1983 and June 26, 2000 when seismic swarms began to occur beneath the volcano summit. These volcanic events quickly disappeared and strong seismic swarms moved to the west of the island towards Kozu-shima and Nii-jima islands [2]. From this time ground deformations appeared [3]. In early July new earthquakes again appeared beneath the summit. Gravimetric surveys done a few days before the eruption showed the formation of a void beneath the volcano summit [4]. During the July 8 eruption, although no strong volcanic earthquakes were recorded, a new crater encompassing O-Ana and O-Yama craters and a part of Hatcho-Taira caldera occurred within 4 min (Fig. 2). This crater, of about 1 km diameter and 250 m depth, continued to enlarge during the next months. The volcanic activity became sporadic during July and was accompanied by a progressive enlargement of the newly formed caldera. The largest event was a hydro-magmatic explosion on August 18, generating an ash plume of more than 8 km height. The ash falls covered the island. Hereafter the activity receded although large SO_2 emission continued. In September 2000 the size of the newly formed caldera was as large as the Hatcho-Taira caldera: 1.4 km in diameter.

The more or less regular pattern of Miyake-jima activity led us to start electromagnetic studies on the volcano in 1995. Continuous magnetic monitoring [5,6], telluric field monitoring, long-baseline self-potential (SP) measurements, as well as SP surveys [7], audio-magnetotelluric and resistivity soundings were progressively implemented on the volcano.

In this paper we will focus on results obtained by audiofrequency-magnetotelluric (AMT) soundings implemented during the inter-crises 1983–2000 period, by DC resistivity soundings made during the year preceding the collapse of the summit as well as by SP surveys and by a permanent 1 km long SP line crossing Hatcho-Taira caldera.

2. State of the resistivity structure during the 1983 eruption

Some ELF–VLF magnetotelluric soundings at 8, 14, 21 Hz and 21 kHz were made before, during and after the October 1983 fissure eruption, which mainly occurred on the south slope of the volcano (Fig. 1) [8,9]. In October 1980 a small aquifer (40 Ω m) was evidenced near the fumarole area (M6 sounding in Fig. 2) between 700 and 100 m in altitude. One month after the October 1983 eruption the resistivity decreased (4 Ω m). The narrow frequency range of the soundings did not permit to estimate the thickness of the different structures. Only M26 sounding revealed a three-layer resistivity structure, with a substratum estimated to be at 150 m in altitude. Utada et al. [8,9] associated the result at M26 to the eastern limit of the hydrothermal system.

Between 1983 and 1985 the 8 Hz frequency was used to monitor the resistivity changes at M6, M25, M26 sites [9]. At M6 the apparent resistivity decreased from 100 Ω m before the eruption, to 4 Ω m 8 months after, and then slowly went back to higher values. This pattern was observed, with a smaller amplitude, to the east (M26) with a time delay of about 3 months. It was interpreted by a warming up of the aquifer, which shifted to an altitude of about 400 m [9].

3. 1997–98 AMT soundings

In 1997 and 1998 AMT soundings were performed inside the Hatcho-Taira caldera and in its vicinity. An antenna of 400 A m^2 was used in the frequency band 70–1 kHz to generate an artificial electromagnetic field in two orthogonal directions. For each sounding the antenna was placed far enough from the receiver to ensure a planar electromagnetic wave. From 1 kHz to 0.1 Hz only the natural field was used for soundings. The receiver was composed of two orthogonal horizontal magnetic coils (H_x, H_y) associated

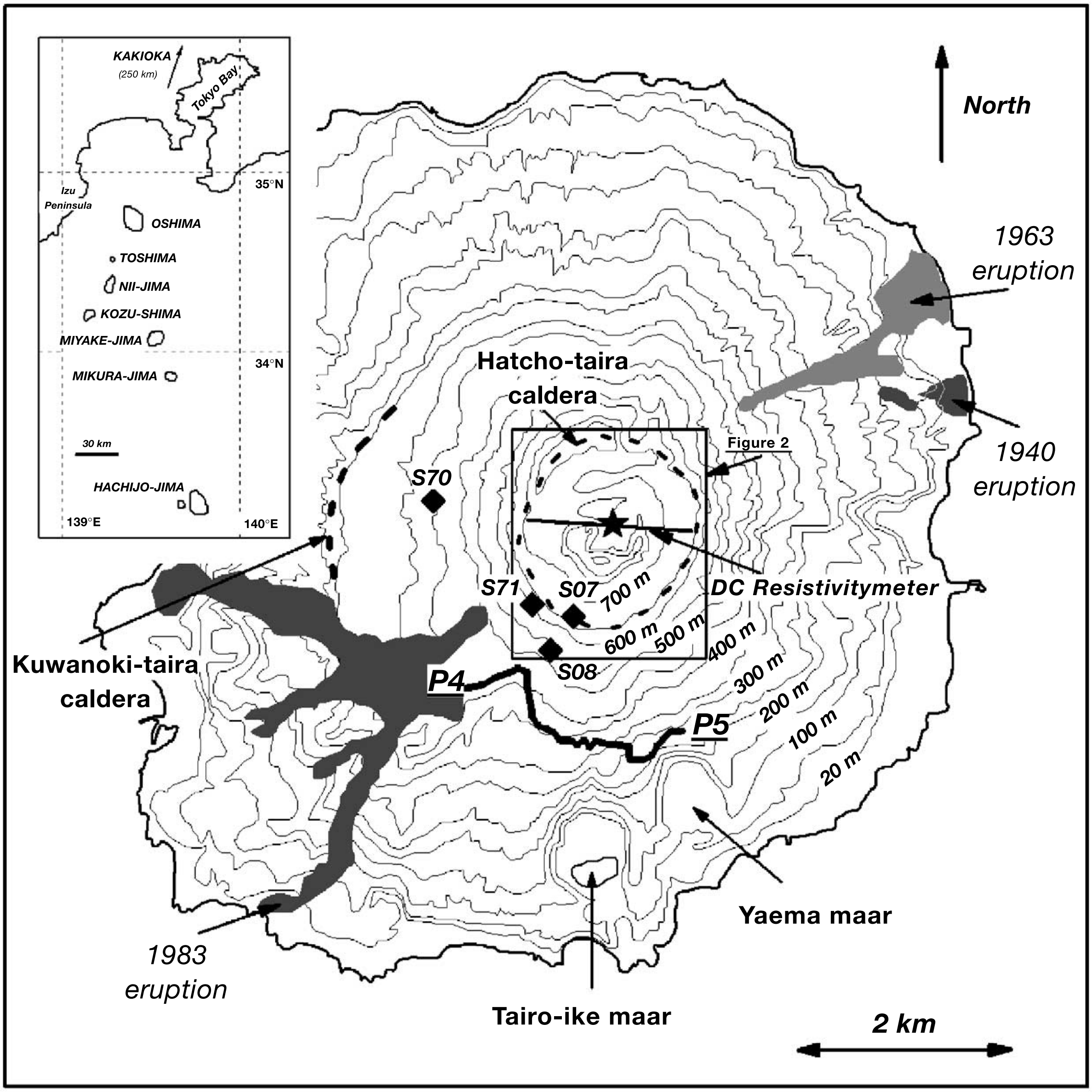


Fig. 1. Miyke-jima Island sketch. 1940, 1963 and 1983 eruptions are in grey. Location of the continuous DC resistivity meter (heavy line). Diamonds indicate 1997–98 AMT soundings not located in Fig. 2.

with two orthogonal electric field lines (E_y, E_x). For each sounding, several data sets were collected to check the quality and the validity of the data. E_x was installed in a N50°E direction (Figs. 1 and 2). The static shift effect was not significant for the AMT stations located in the Hatcho-Taira caldera [6].

One-dimensional (1D) invariant inversions along an approximate N–S profile (stations S08, S07, S11, S38 and S67) and a NW–SE profile (stations S70, S66, S38 and S68) are presented in Fig. 3. Both inversions show a low-resistivity structure, less than 50 Ω m, centred beneath the 1940 cone and the western part of the O-Ana crater (Figs. 2 and 3). This structure most probably corresponds to the one evidenced in 1983

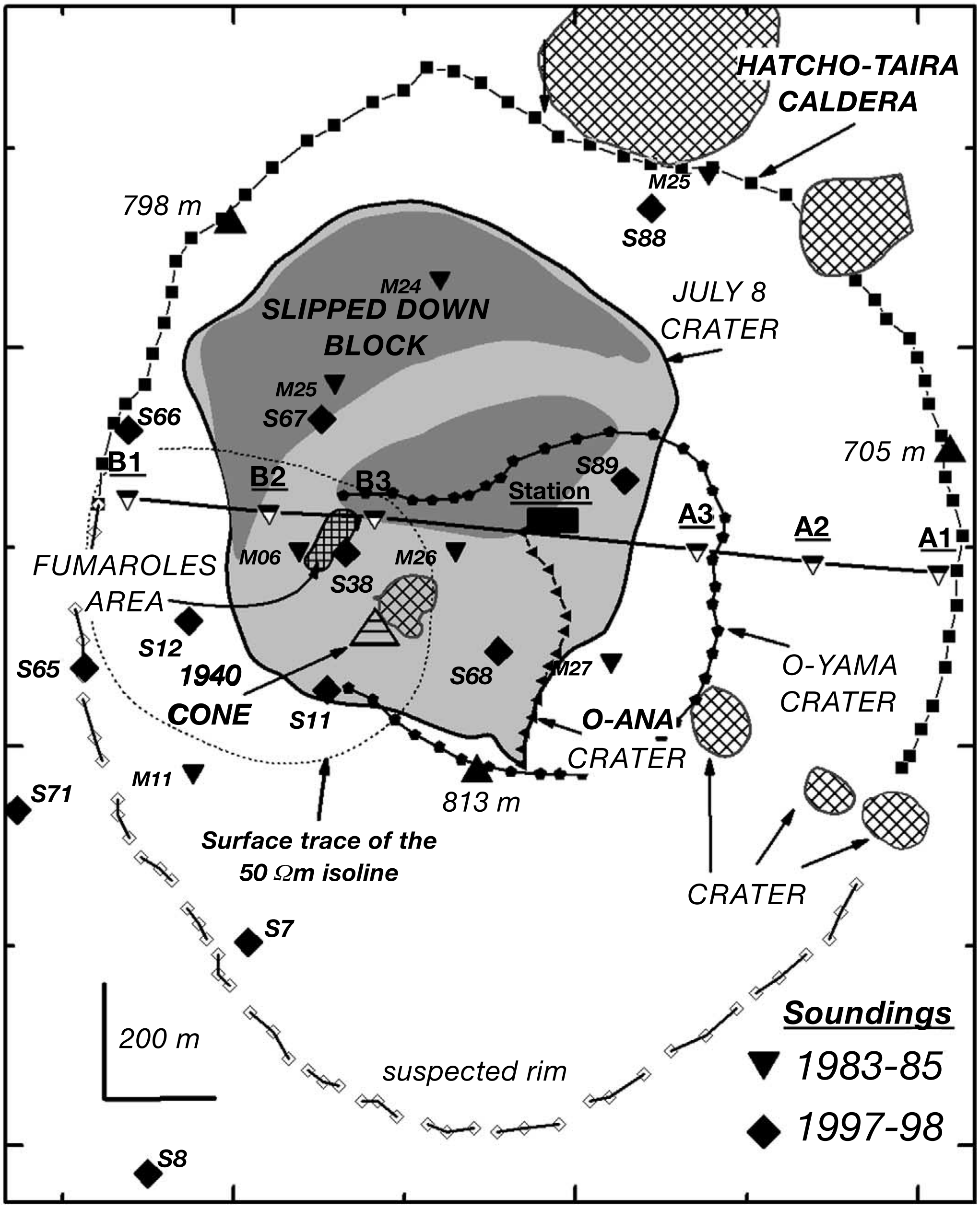


Fig. 2. Sketch of the Miyake-jima summit as delineated in Fig. 1. M*ij* and S*ij* represent the location of 1983 and 1997–98 VLF–ELF and AMT soundings, respectively. Location of the permanent lines of the DC resistivity meter (heavy black line; A1–B1, A2–B2, A3–B3 are injection lines). Short dashed line represents the surface trace of the 50 Ω m contour line of the low resistive medium at depth. The heavy line filled in two grey-level colours represent the area concerned by the July 8, 2000 summit collapse; the dark grey areas are slipped blocks.

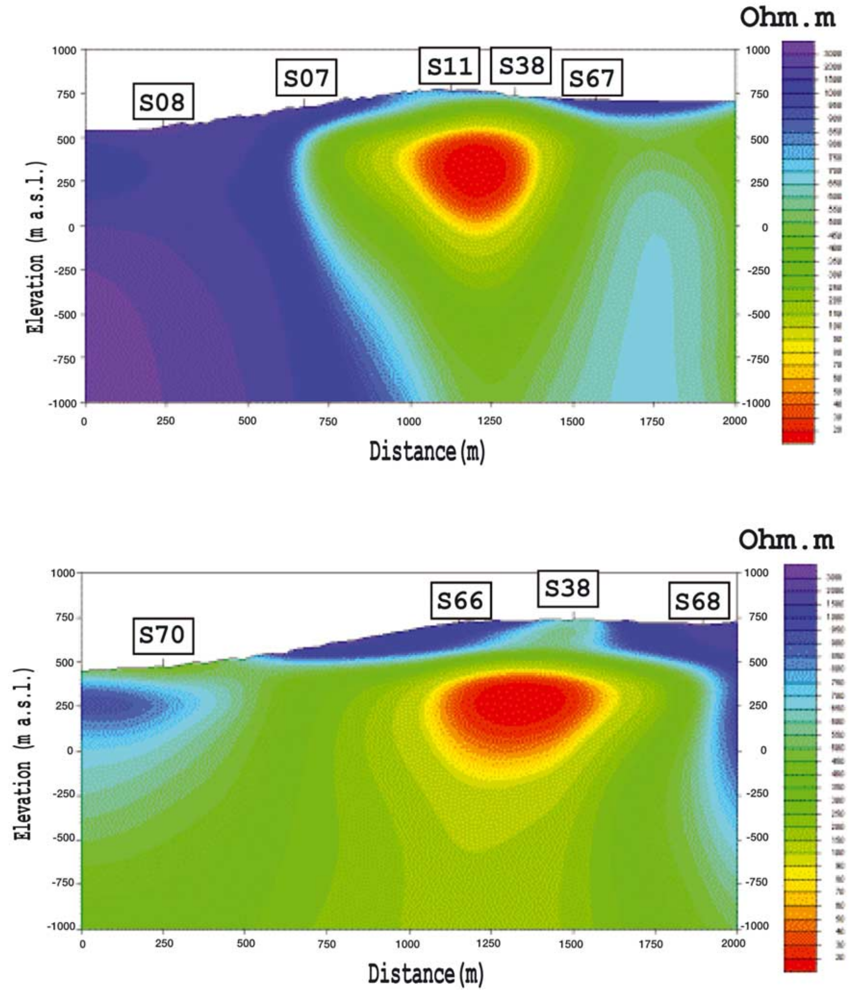


Fig. 3. 1D invariant inversions of 1997–98 AMT soundings. Top: Approximate S–N cross-section. Bottom: NW–SE cross-section.

([8,9]). It exhibits the active hydrothermal system beneath the summit caldera. The top of the low-resistivity structure was at about 300 m depth and the bottom is below the sea level (750 m depth for a 50 Ω m isoline). The low-resistivity medium was vertically elongated, and its source was beneath the western part of the O-Ana crater in the vicinity of the 1940 cone (Fig. 2).

4. 1999–2000 continuous resistivity measurements

In May 1999 a continuous recording of DC apparent resistivity was installed through the Hatcho-Taira caldera in the east–west direction (Fig. 2). The equipment was set in a Schlumberger array (cf. [10]). It was composed of three injection lines of 600, 1000 and 1400 m length and two receiving lines of 100 and 150 m length. Every 6 h the system automatically made measurements. Data were stored in a PC. For each injection line two cycles of 10 current injections were done, one for each receiving line. The current injected into the ground was maintained constant during the data acquisition. Generally, characteristic values were 800 V and 400 mA for the potential and

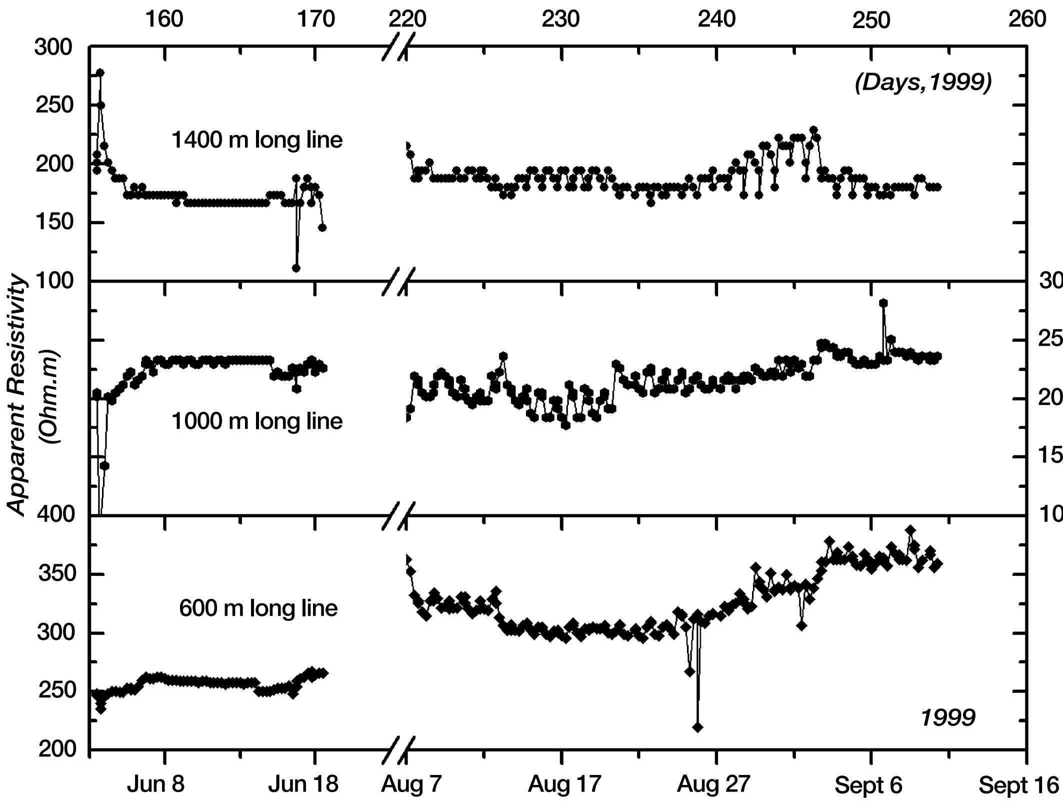


Fig. 4. 6-h sampling recordings of the apparent resistivity computed from the 1400, 1000 and 600 m long injection lines.

the injection current, respectively. Apparent resistivity values obtained on both reception lines were almost identical, so we stacked the 20 corresponding data for each line injection. For each apparent computed resistivity the standard deviation remained less than 5% in relative value. Unfortunately, the resistivity meter broke after October 1999. After calibration and tests, it was re-installed 1 week before the July 8, 2000 eruption. However, the equipment was destroyed in the July 8 collapse and data were lost. Only values obtained during tests made on July 3 are available.

When the resistivity meter was operating in 1999, data showed gradual variations with time (Fig. 4). In June 1999 (days 160–170) mean apparent resistivities remained almost constant around values of 260, 230 and 170 Ω m. Progressive variations appeared in August. Within 1 month apparent resistivities reached values up to 360, 230 and 180 Ω m. Finally, on July 3, 2000 apparent resistivities had drastically changed on the shortest and longest lines; mean values were about 70 and 550 Ω m, respectively (Fig. 5). These results point out that between October 1999 and July 2000, the resistivity pattern, inside and outside the O-Yama crater, had strongly changed. The resistivity had decreased to 20% of the initial value on July 3, 2000 on the 600 m line while the resistivity had reached more than three times its original value on the 1400 m line.

5. July 4, 2000 SP mapping of the Hatcho-Taira caldera

On July 4, 2000 SP surveys were performed in one day of work inside the caldera (Fig. 6). During this time a few earthquakes were recorded beneath the summit, accompanied by some collapses of O-Yama crater rims. Pb–$PbCl_2$ elec-

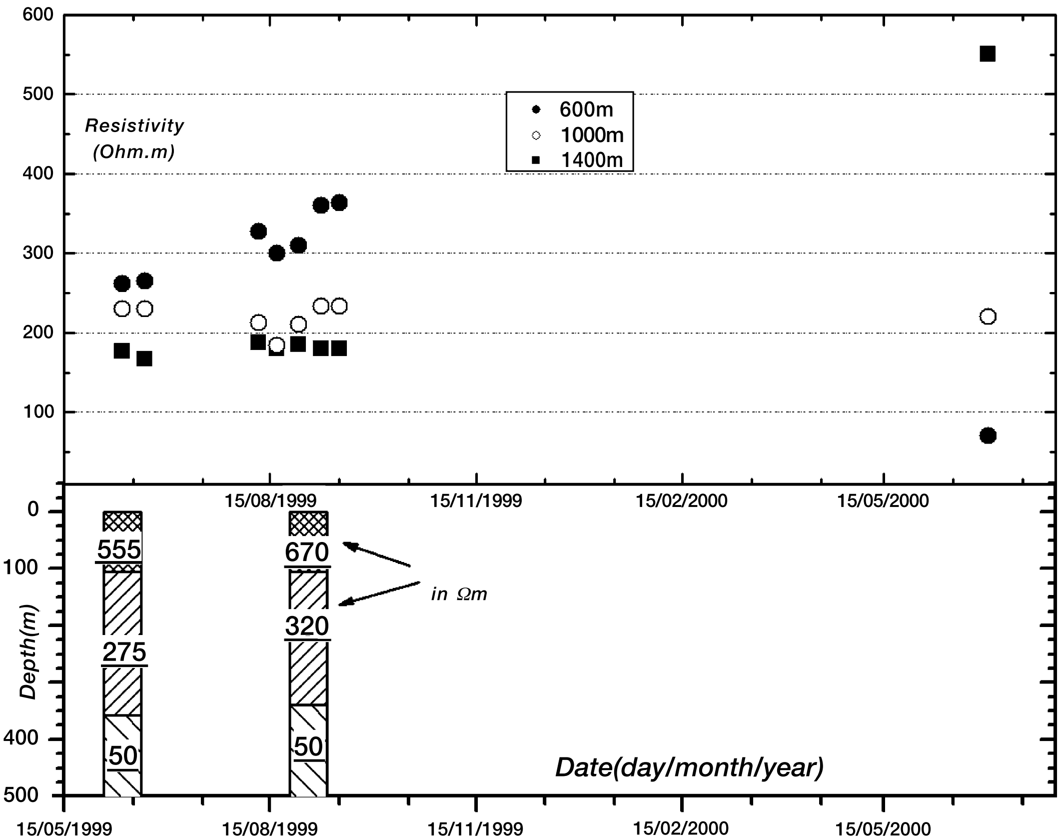


Fig. 5. Top: Mean resistivity changes on the 1400, 1000 and 600 m long injection lines between May 1999 and July 3, 2000. Bottom: corresponding 1D models.

trodes were used [11]. The reference electrode was the same for all surveys. Relative potential values were measured every 25 m along each survey line while the location was determined by a GPS (Global Positioning System) receiver with a precision on the order of 5–10 m. To avoid integrative errors with a frog-leap method we unrolled the same cable attached to the reference electrode along each profile [12]. During surveys the homogeneity of the measurement was regularly checked; side by side measurements did not exceed tens of mV. Values obtained before and after surveys with the mobile electrode indicated a drift of the potential with time of less than 5 mV.

Previous large-scale SP surveys made in 1995 and 1996 had shown that the central part of the volcano was the seat of a noticeable hydrothermal system while the volcano flanks were progressively affected by a topographic effect [5,7]. This well-known topographic effect, due to ground-water circulation above the vadose zone, expresses a decrease of the potential when the altitude of measurements increases. This linear relationship was on the order of −1.1 mV/m on Miyake-jima. Therefore raw SP data of 2000 surveys were corrected by this coefficient to isolate SP anomalies due to the hydrothermal activity of the summit (Fig. 6).

An inverse distance to a power method, with weighting of 2, was used to compute the spatial distribution of SP anomalies. Positive anomalies up to 150 mV relative to the reference *R* occur along the O-Yama crater rim, especially on the west and south borders; their elongated shapes

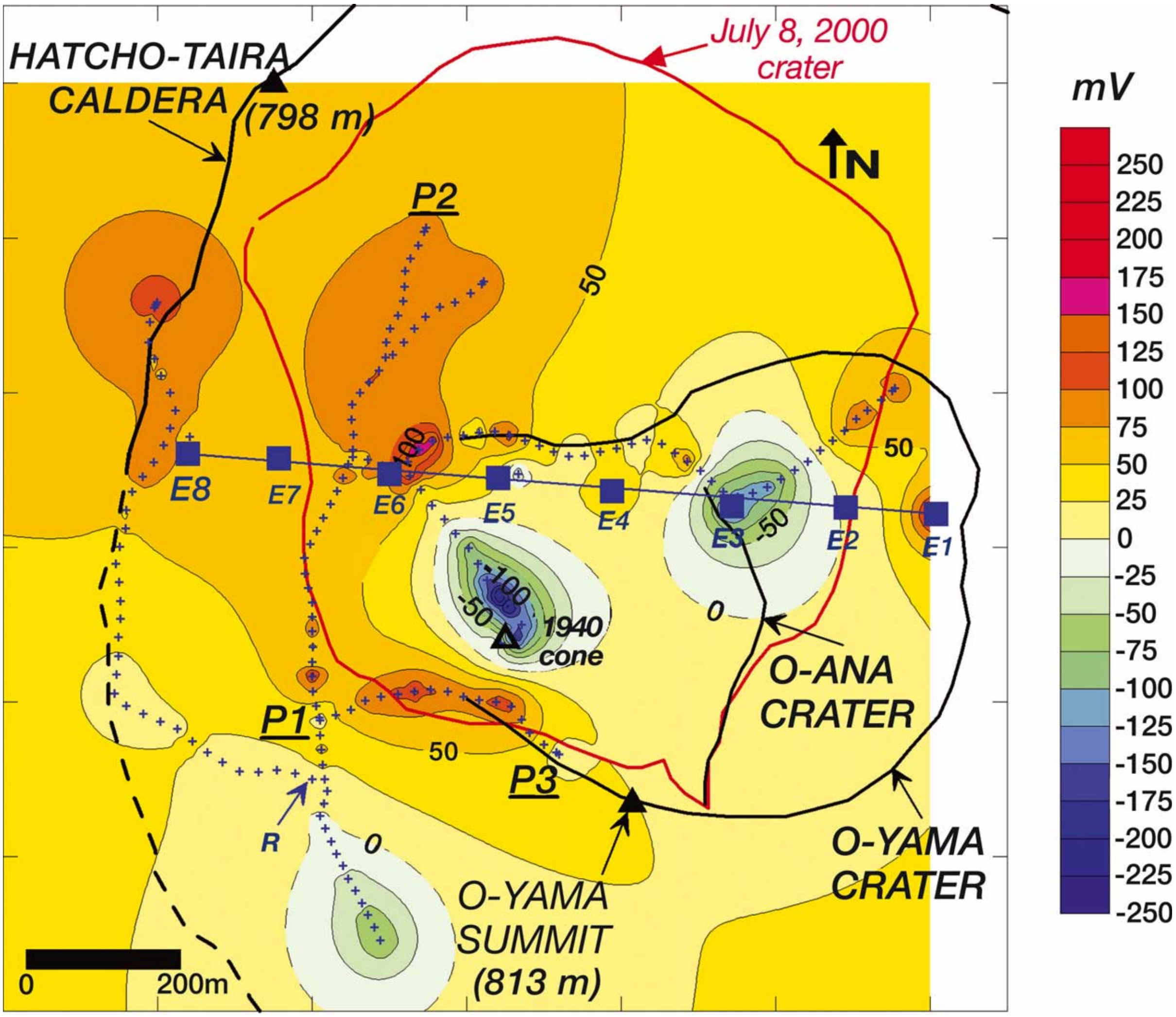


Fig. 6. SP mapping made on July 4, 2000. Contour lines are every 25 mV. Survey stations are figured by blue crosses. R represents the location of the reference electrode. P1–P2 and P1–P3 are SP survey profiles also done in 1995. Remote P4–P5 survey is in Fig. 1. Blue squares connected by a blue line represent the permanent 1 km long SP line with electrode names.

followed the rims (Fig. 6). The western positive anomaly spread above the fumaroles zone in existence since the 1962 eruption. The southern positive anomaly was unknown. Two large negative anomalies were recognised inside the Hatcho-Taira caldera with an amplitude less than −225 mV for the western one. This negative anomaly lies over the 1940 cone which has been the seat of thermal activity during at least the past 30 years. The eastern smooth negative anomaly covers the north–east depression of the O-Yama crater.

6. SP variations between 1995 and July 4 and 11, 2000

In 1995, in order to define the features of the hydrothermal system on the volcano, SP surveys were performed with a 200 m spatial sampling [7]. Surveys done on July 4 and 11, 2000 with a 25 m spacing allow us to evaluate time and spatial variations generated by the hydrothermal activity during the 5 years preceding the eruption along some of the older profiles. In order to com-

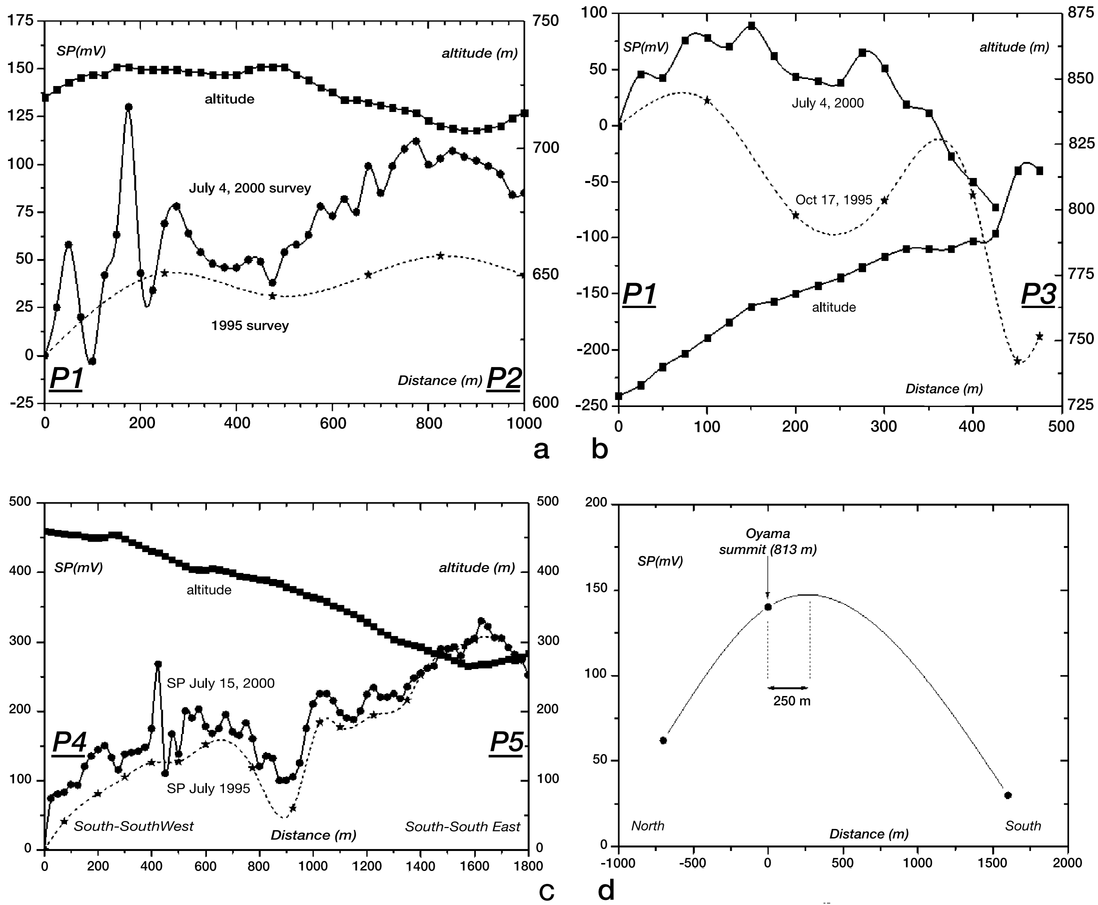


Fig. 7. Comparison of SP 1995 and July 4, 2000 surveys. (a) Across the Hatcho-Taira caldera from south to north. (b) Along the southern rim of the Hatcho-Taira caldera. (c) Along the circular road on the south volcano flank at a mean altitude of 400 m (see Fig. 1). (d) Amplitude of the SP anomaly between July 2000 and 1995 versus a NNW–SSE direction. A spline fit was applied to connect points.

pare the features of the large spatial scale SP anomalies a simple spline fit was applied to SP data (Fig. 7).

One survey (P1–P2) started from the southwestern part of the Hatcho-Taira caldera towards the north (Figs. 6 and 7a). Between 1995 and 2000 a positive anomaly reached a maximum of 50 mV on the northwest part of the O-Yama crater. This anomaly seems to disappear to the north as in 1995. A second survey (P1–P3) bordered the southern rim of the O-Ana crater (Figs. 6 and 7b). A powerful positive anomaly, up to 150 mV, took place there. It corresponds to a section of the south border of the newly formed caldera, the depth of which was maximum there (about 250 m). 2 km to the south of the volcano summit (P4–P5) the changes in the SP anomalies between 1995 and 2000 were smooth but still positive with a mean value of 30 mV; they spread over a distance of 1.5 km (Figs. 1 and 7c).

These observations allow us to draw the mean maximum amplitude of the newly generated SP anomaly between 1995 and 2000 with the distance from the O-Yama summit along a NNW–SSE direction (Fig. 7d). The maximum amplitude could be about 150 mV for a source located 250 m to the south of the O-Yama summit, but still inside the Hatcho-Taira caldera.

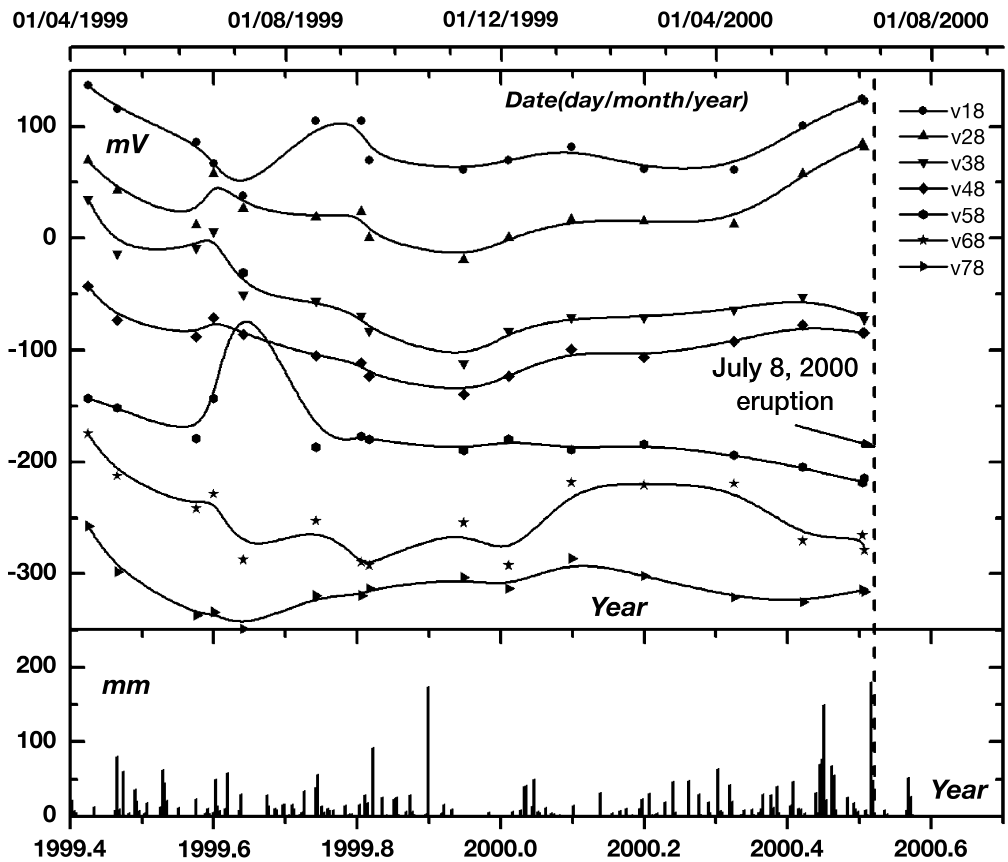


Fig. 8. (Top) Time changes of the SP values along the 1 km long line crossing the Hatcho-Taira caldera when E8 is the electrode reference. (Bottom) Daily rainfall between May 1999 and July 2000. A spline fit was applied to connect points.

7. SP monitoring through the Hatcho-Taira caldera between mid-1999 and July 2000

A 1 km long SP line was set in an east–west direction through the Hatcho-Taira caldera during May 1999 (Fig. 6). This line was composed of eight non-polarisable Pb–$PbCl_2$ electrodes buried at least at 60 cm depth [11]. Potential measurements between electrodes were regularly made and referred to electrode E8 located on the west flat part of the caldera (Figs. 6 and 8). The location of the electrodes in relation to the July 8, 2000 caldera was the following (Fig. 6). Electrodes E8 and E7 were outside the O-Yama crater. They were outside the initial collapse. E6 was outside of the western rim of the O-Yama crater and E5 inside the crater; both of them disappeared with the formation of the new caldera. E4 and E3 were in the centre of the O-Yama crater and were also lost. To the east, E2 and E1, installed inside the O-Yama crater, were temporarily saved from the collapse. In the following we will not discuss short-term variations such as the one in the E5–E8 difference in July 1999; they are only based on one or two data sets. Long-term trends were observed on all stations; a general decay from April 1999 to November–December 1999 followed by a gradual increase of the potential difference at all electrodes, except at E5 (Fig. 8). This common behaviour of the SP remained until February–April 2000 when SPs changed more rapidly. For electrodes E6, E5, and E7 with a smaller amplitude, the potential was then decreasing; the variation reached −55

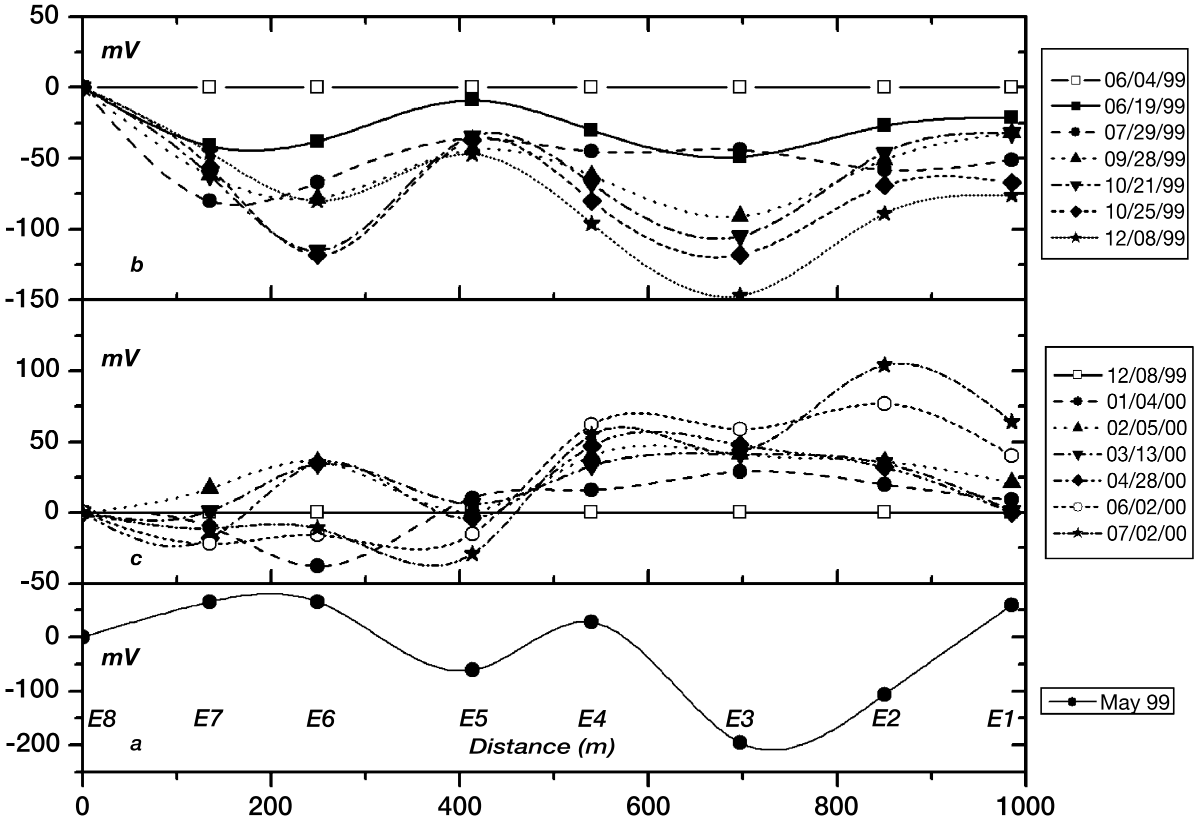


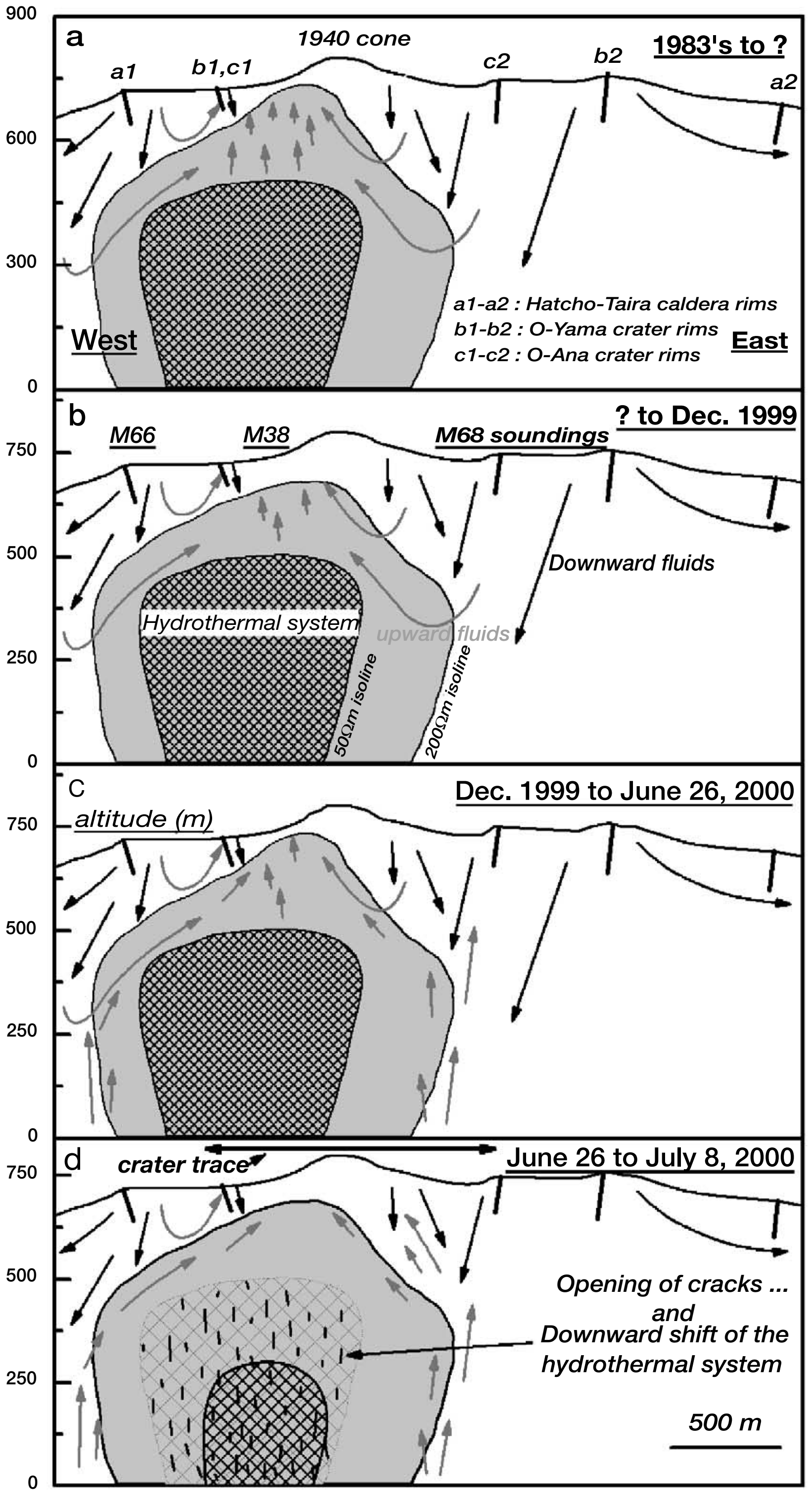
Fig. 9. (a) Time variation of SP changes between June 1999 and December 1999. (b) Time variation of SP changes between December 1999 and July 2000. A spline fit was applied to connect points. (c) SP values obtained in May 1999 along the 1 km long SP line.

mV in E6–E8 difference. For electrodes E4 and E3, located in the centre of the O-Yama crater, the increase of the potential subsisted until early June; then a gradual decrease started. Finally, for electrodes located on both ends of the SP line (E1, E2 (and E7)), the potential increased after March: 75 mV in E2–E8 difference.

Continuous SP recordings made at several stations located on the volcano can exhibit an annual variation of a few tens of mV/km due to seasonal rainfalls (i.e. [13]). Between 1996 and 2000 the minima and maxima of these SP annual variations took place in April and October–November, respectively. Therefore the changes observed on the permanent, 1 km long SP line were not due to seasonal climatic changes (Fig. 8).

The SP values measured in May 1999 give information on the ground-water pattern related to the local summit structure (Fig. 9c). Values point out two negative anomalies relative to their external borders. This pattern imaged the meteoric water to accumulate inside or along crater or caldera rims [14]. Thermal transfers and hydrothermal circulations preferentially take place along these interfaces. On the Miyake-jima volcano these negative SP anomalies were well associated with O-Ana and O-Yama crater rims; its western border corresponded to the western limit of the fumarole area for electrodes E6 and E5 (Figs. 2 and 9a). To the east, E2 and E1 marked the eastern border of the O-Yama crater.

The time variations of the potential differences can be considered in two periods, May–December 1999 and December 1999 to July 2000, corresponding to two different phases of activity of the hydrothermal system. To emphasise these var-



900
600
300
0
a
1940 cone
1983's to ?
a1
b1,c1
c2
b2
a2
a1-a2 : Hatcho-Taira caldera rims
b1-b2 : O-Yama crater rims
c1-c2 : O-Ana crater rims
West
East
b
? to Dec. 1999
M66
M38
M68 soundings
750
500
250
Downward fluids
Hydrothermal system
upward fluids
50Ωm isoline
200Ωm isoline
C
Dec. 1999 to June 26, 2000
altitude (m)
d
June 26 to July 8, 2000
crater trace
Opening of cracks ...
and
Downward shift of the
hydrothermal system
500 m

iations, SP data can be compared for several periods of time, taking May–June 1999 as reference time for the first period (Fig. 9a) and December 1999 for the second one (Fig. 9b). This procedure suppresses the static part of the potential along the SP line related to the volcano structure and the steady-state activity of the hydrothermal system at that epoch.

During the first period the SP pattern corresponds to an increase of negative potential values at electrodes close to the inner part of the future collapse (Fig. 9a). Electrodes E6 and E3, which always had lower values, were the closest to the future caldera rims. This period corresponds to an increase of downward water transport along the pre-existing caldera rims (see Section 8). This general pattern is drastically reversed after December 1999 (Fig. 9b). Till April 2000 a gradual increase of the potential, up to 50 mV, was recorded at all stations except at E5. It corresponded to a renewal of the hydrothermal activity inside the O-Yama crater. Beyond April 2000 sharp variations appeared. Negative variations were again recorded in the vicinity of the probable focus of the future collapse (electrodes E6–E5) while positive variations accelerated to the east of the SP line. This pattern of negative, positive and then negative SP variations indicates periods in which the infiltration of water at the spot of the future caldera is sometimes counterbalanced by pulses of hydrothermal activity.

8. Discussion

We base the interpretation of SP variations on the well-accepted hypothesis that a downward water flux produces a negative SP anomaly at the ground surface of a volcano while an upward fluid flow generates a positive one (i.e. [15–24]).

In 1995 a large-scale SP mapping of Miyake-jima has revealed a powerful hydrothermal system centred on the Hatcho-Tairo caldera [5,7]. The associated 2.7 km maximum width, positive anomaly, up to 600 mV in amplitude (maxima–minima), suggests a thermal source located beneath the volcano summit. In 1996 a south–north profile made across the island and going through the Hatcho-Taira caldera was resurveyed. No noticeable SP change was detected. Therefore Miyake-jima was the seat of a stable hydrothermal activity until – at least – 1996. This existing hydrothermal system on Miyake-jima pointed out a possible coming eruption controlled firstly by a phreatic activity.

The 1997–98 AMT campaigns clearly identified the existence of the low-resistivity medium beneath the 1940 cone (Figs. 2 and 3). It most probably corresponds to the emplacement of the superficial active hydrothermal system evidenced by the SP surveys and mapping. It took its origin at several hundreds of metres deep, below the sea level, where hot gas coming from a deep magma chamber could be mixed with fresh ground water through porous rocks, faults, craters or caldera rims. The top of this low-resistivity medium was only at a very few hundred metres beneath the ground surface. The extension was getting narrower towards the ground surface in the vicinity of S38 sounding. The lowest resistivity values are located beneath the 1940 cone, which seems to correspond to the centre of the July 8, 2000 collapse. The thickness and the horizontal extensions did not reach 500 m (for the 50 Ω m isoline). The surface projection of this low-resistivity zone approximately encompasses the western O-Ana crater rim (Fig. 2).

Let us consider the resistivity structure from the AMT soundings in the vicinity of the DC resistivity meter. Different techniques were used to per-

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Fig. 10. Schematic interpretation of the hydrothermal system evolution prior to July 8, 2000 caldera formation. a1–a2: Limit of the Hatcho-Taira caldera; b1–b2: Limit of the O-Yama crater; c1–c2: Limit of the O-Ana crater. Cross-hatched lines figure the hydrothermal system as evidenced by 1D-inversions (50 Ω m isoline). Grey area corresponds to the 200 Ω m isoline. Heavy black and grey arrows represent downward and upward fluid flows, respectively. Panels a–d represent periods during which the hydrothermal activity changes. (a) Steady state. (b) Gradual decay. (c) Rise of the activity. (d) Disappearance of the hydrothermal system at depth and subsistence of a small system near the ground surface.

form 1980–85 and 1997–98 AMT soundings and only reasonable assumptions can be developed. Resistivity values at the end of 1985 (M6, M26) were of the same order of magnitude as the 1997–98 ones (S12, S38). In the east part of the O-Ana crater the 1997–98 S68 sounding still indicated high resistivity values in the first hundred metres depth, which indicates the end of the extension of the hydrothermal system to the east. These results suggest that no drastic resistivity changes have occurred in the area of the future 2000 caldera between 1984 and 1997–98. Only a possible enlargement of the conductive zone to the south was recognised by the 1997–98 AMT soundings.

This hypothesis can also be assumed for the period 1997–98 to May 1999 when the DC resistivity meter started to operate. Values measured by the DC method were compatible with those of the 1997–98 S38 sounding, an apparent resistivity of about 300–350 Ω m near the ground surface which decreased as the depth increased (Figs. 4 and 5). Continuous magnetic measurements made on the volcano summit also suggested that the hydrothermal system was more or less in a steady state between 1998 and May 1999 [24].

Detailed changes can be estimated after June 1999. Four days before the July 8, 2000 eruption, SP surveys made along some of the 1995 ones clearly show that a new hydrothermal source, superimposed to the stable and global one observed in 1995, has taken place to the south of the O-Ana crater (Fig. 6). This new, localised and independent thermal source could be the one detected by continuous magnetic measurements [6].

The 1 km long SP line exhibits (i) negative anomalies which coincide with the east and west rims of the newly formed caldera (Fig. 9c) and (ii) changes in the hydrothermal activity in the year preceding the eruption (Fig. 8). These observations suggest that the permanent hydrothermal activity beneath the Hatcho-Taira caldera has favoured the mechanical weakness of some existing structures inside the Hatcho-Taira caldera, essentially the rims of the O-Yama and O-Ana craters. The large-scale positive SP anomaly revealed by the comparison between the 1995 and 2000 surveys has become – at most – slightly weaker between 1999 and 2000 (Figs. 7 and 8). Therefore the source of the global anomaly, located inside the southern part of the Hatcho-Taira caldera, appeared between 1996 and May 1999.

For the 600, 1000 and 1400 m long lines a small increase of the apparent resistivity was observed between May and September 1999, followed by drastic changes between September and July 3, 2000. Before December 1999, a noticeable change in the volcano activity had not yet appeared and 1D models, computed for May and August 1999, suggest that a low-resistivity structure is still at some hundreds of metres depth. It can most probably be associated with the existing hydrothermal system centred in the vicinity of the 1940 cone (Figs. 3 and 5). No 1D computation can be effective for July 3, 2000; the low-resistivity structure near the ground surface has to be lying on a too high-resistivity substratum. Therefore it seems that changes in the lateral resistivity contrasts have become prevalent (cf. [25]). O-Ana, O-Yama and the newly formed crater rims have probably disturbed the resistivity pattern of the resistivity distribution of the ground. The resistivity variation, from 360 to 70 Ω m, observed on the 600 m long line between September 1999 and July 2000, shows that about the first 150 m depth of the O-Yama crater has become a low-resistivity layer. For the same period of time the 1400 m long line, set outside the O-Yama crater, shows a large increase of the resistivity from 180 to 550 Ω m. If we consider the time when the SP measurements along the DC resistivity meter lines show a smooth and temporary increase of the hydrothermal activity, the changes in the high–low resistivity near the ground surface could have started in December 1999.

If we consider the SP and resistivity observations, the magnetic changes [24], the absence of distinct changes in the ground temperature and the flow rate of the fumaroles (T. Kagiyama, personal communication), and the formation of void evidenced by gravimetric surveys in the days preceding the July 8, 2000 eruption [3], we can propose an interpretation of the changes in the hydrothermal system as follows (Fig. 10). A possible gradual hydrothermal activity has taken place in the southern part of the volcano between 1995 and 1999. However, water infiltration through the Hatcho-Taira caldera and in particular through the O-Yama crater became the dominant water flux during the last years, in contrast to the smooth thermal steady-state activity occurring during decades over the 1940 cone (Fig. 10a). The hydrothermal exchanges have favoured the argillation of existing crater rims such as those of the O-Ana crater which have mainly controlled the shape of the newly formed caldera. Till December 1999 the increase of water infiltration, compared to upwarmed rewarmed fluids, along O-Ana crater rims may have been reflected in SP measurements and could have generated a gradual resistivity increase in the first hundreds of metres (Fig. 10b). After December 1999 a weak renewal of the hydrothermal activity took place along the crater rims, generating some upward flow in their vicinity (Fig. 10c). It accelerated after April 2000. This flow pattern could have generated the low-resistivity layer of 150 m depth inside the O-Yama crater evidenced on July 3 on the 600 m long resistivity meter line. The 550 Ω m resistivity measured on the 1400 m long line can be interpreted by the opening of cracks and fissures in the volcano, and the formation of a void above the sea level, between June 26 and July 3, when strong tectonic earthquakes of magnitude up to 6.4 occurred (Fig. 10d) ([3,24]). The ground water trapped in the hydrothermal system was progressively flowing downwards through the fissures and the cracks till a few kilometres depth where earthquakes were located. After the July 8 collapse of the Miyake-jima summit this ground water was again confined within unwelded blocks and was strongly reheated by a close and deeper magmatic source. The pore pressure again increased to some threshold, which gave rise later to strong phreatic explosions such as the July 14 and August 18, 2000 ones.

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References

[1] M. Tsukui, Y. Suzuki, Eruptive history of Miyakejima volcano during the last 7000 years (in Japanese with English abstract), Bull. Volcanol. Soc. Japan 43 (1998) 149–166.

[2] Japan Meteorological Agency, Recent seismicity in the Miyakejima and Niijima-Kozushima region, Japan - the largest earthquake swarm ever recorded, Earth Planets Space 52 (2000) 1–8.

[3] M. Kaidzu, T. Nishimura, M. Murakami, S. Ozawa, T. Sagiya, H. Yarai, T. Imakiire, Crustal deformation associated with crustal activities in the northern Izu-islands area during summer, Earth Planets Space 52 (2000) 9–17.

[4] M. Furaya, S. Okubo, Y. Tanaka, W. Sun, H. Watanabe, J. Oikawa, T. Maekawa, Caldera formation process during the Miyakejima 2000 volcanic activity detected by spatio-temporal gravity changes, J. Geogr. 110 (2001) 217–225.

[5] Y. Sasai, J. Zlotnicki, Y. Nishida, P. Yvetot, P. Morat, H. Murakami, Y. Tanaka, Y. Ishikawa, S. Koyama, W. Sekiguchi, Electromagnetic monitoring of Miyake-jima volcano, Izu-Bonin Arc, Japan: A preliminary report, J. Geomag. Geoelectr. 49 (1997) 1293–1316.

[6] Y. Sasai, J. Zlotnicki, Y. Nishida, M. Uyeshima, P. Yvetot, Y. Tanaka, H. Watanabe, Y. Takahashi, Evaluation of electric and magnetic field monitoring of Miyake-jima Volcano (Central Japan): 1995-1999, Ann. Geofis. 44 (2001) 239–260.

[7] Y. Nishida, N. Matsushima, A. Goto, Y. Nakayama, A. Oyamada, M. Utsugi, H. Oshima, Self-potential studies in volcanic areas (3) Miyake-jima, Esan and Usu, J. Fac. Sci. Hokkaido Univ. 10 (1996) 63–77.

[8] H. Utada, Y. Sasai, I. Nakagawa, S. Koyama, Y. Ishikawa, Y. Hamano, Changes in the electrical resistivity associated with the 1983 eruption of Miyake-jima volcano (in Japanese with English abstract), Bull. Volcanol. Soc. Jpn. 29 (1984) 113–124.

[9] H. Utada, Y. Sasai, T. Shimomura, T. Yukutake, T. Yamamoto, Changes in the resistivity for the two years after the 1983 eruption of Miyake-jima volcano (in Japanese), Report on the second Joint Geophysical and Geochemical Observations of Miyake-jima Volcano, 1986, pp. 35–46.

[10] D.S. Parasnis, Principles of Applied Geophysics, 4th edn., Chapman and Hall, London, 1986, pp. 115–125.

[11] G. Petiau, A. Dupis, Noise, temperature coefficient, and

long time stability of electrodes for telluric observations, Geophys. Prospect. 28 (1980) 792–804.
[12] S. Michel, J. Zlotnicki, Self-potential and magnetic surveying of La Fournaise volcano (Reunion Island): Correlations with faulting, fluid circulation and eruption, J. Geophys. Res. 103 (1998) 17845–17857.
[13] J. Zlotnicki, J.L. LeMouël, Y. Sasai, P. Yvetot, M.H. Ardisson, Self-potential changes associated with the volcanic activity. Short-term signals associated with March, 9, 1998 eruption, Ann. Geofis. 44 (2001) 335–354.
[14] J. Zlotnicki, G. Boudon, J.P. Viodé, J.F. Delarue, A. Mille, F. Bruère, Hydrothermal circulations beneath Mount Pelée inferred by self potential surveying. Structural and tectonic implications, J. Volcanol. Geotherm. Res. 84 (1998) 73–91.
[15] R.F. Corwin, D.B. Hoover, The self-potential method in geothermal exploration, Geophysics 44 (1979) 226–245.
[16] T. Ishido, H. Mizutani, Experimental and theoretical basis of electrokinetic phenomena in rock-water systems and its applications to geophysics, J. Geophys. Res. 86 (1981) 1763–1775.
[17] F. Massenet, V.N. Pham, Experimental and theoretical basis of self-potential phenomena in volcanic areas with reference to results obtained on Mount Etna (Sicily), Earth Planet. Sci. Lett. 73 (1985) 415–429.
[18] F.D. Morgan, E.R. Williams, T.R.. Madden, Streaming potential of westerly granite with applications, J. Geophys. Res. 94 (1989) 12449–12461.
[19] P. Antraygues, M. Aubert, Self potential generated by two-phase flow in a porous medium: Experimental study and volcanological applications, J. Geophys. Res. 98 (1993) 22273–22281.
[20] T. Ishido, J.W. Pritchett, Numerical simulation of electrokinetic potentials associated with subsurface fluid flow, J. Geophys. Res. 104 (1996) 15247–15259.
[21] A. Revil, P.A. Pezard, Streaming electrical potential along faults in geothermal areas, Geophys. Res. Lett. 25 (1998) 3197–3200.
[22] P. Adler, J.L. LeMouël, J. Zlotnicki, Electrokinetic and magnetic fields generated by flow through a fracture zone: a sensitivity study for La Fournaise volcano, Geophys. Res. Lett. 26 (1999) 795–798.
[23] L. Journiaux, M.L. Bernard, J.P. Pozzi, Streaming potential in volcanic rocks from Mount Pelée, J. Geophys. Res. 105 (2000) 8319–8401.
[24] Y. Sasai, M. Uyeshima, J. Zlotnicki, H. Utada, T. Kagiyama, T. Hashimoto, Y. Takahashi, Magnetic and electric observations during the 2000 activity of Miyake-jima volcano, Central Japan, Earth Planet. Sci. Lett. 203 (2002) 769–777.
[25] W.M. Telford, L.P. Geldart, R.E. Sheriff, D.A. Keys, Applied Geophysics, Cambridge University Press, London, 1983, pp. 633–701.