

1 **Swelling of a lava plug associated with a**
2 **Vulcanian eruption at Sakurajima volcano,**
3 **Japan, as revealed by infrasound record:**
4 **Case study of the eruption on January 2, 2007**

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12

13 Abstract

14 In order to clarify the time relation of the expansion of a gas pocket and failure of it's the
15 overlying plug of lava during Vulcanian eruptions, infrasound records and video images of the
16 Vulcanian eruption that occurred at Sakurajima volcano on January 2, 2007, were analyzed with
17 respect to their origin times. Weak (≤ 3 Pa) and slowly increasing air pressure preceded the

18 impulsive compression phase by 0.25–0.32 s, and a longer-period rarefaction phase of infrasound
19 waves was recognized at all microphone stations. The velocity of the compression phase was
20 assumed to be supersonic (ca. 400 m/s) up to 850 m above the crater bottom from other recent
21 explosions. On the other hand, the propagation velocity of the preceding weak signal was regarded
22 to be similar to the air sound velocity because the lack of impulsiveness is unlikely to be related to
23 the main compression phase. Therefore, the estimated origin time of the main compression phase
24 was delayed by 0.5–0.7 s from the preceding phase. The origin time of the preceding phase
25 coincided with the onset of the isotropic expansion process of the pressurized gas pocket, which
26 was obtained by the waveform inversion of the explosion earthquake. In contrast, the origin time
27 of the main impulsive phase coincided with the time when the expansion rate reached its peak.
28 This observation suggests that the volumetric increase of the gas pocket caused swelling of the
29 surface of the crater bottom and its subsequent failure. When the expansion velocity exceeded a
30 threshold level, the main impulsive compression phase radiated with a high velocity by the sudden
31 releases of the pressurized gases. The volumetric change at the source was estimated to be 280–
32 560 m³ from the preceding phase of the infrasound. This volume change indicates that the vertical
33 displacement of the swelling ground was on the order of 1.0 m, assuming the radius of the lava
34 plug was ca. 10 m.

35 *Keywords: Sakurajima Volcano, Vulcanian Eruption, Infrasound Wave*

36

37 **Introduction**

38 From the last decade, low-frequency microphones have been used world-wide for
39 acoustic observation of volcanic eruptions. Network or array observations using
40 these microphones have enabled the correct determination of vent locations of the
41 source (Ripepe and Marchetti 2002; Johnson 2005), even if the eruptions are
42 obscured by bad weather conditions or topography. This makes acoustic
43 observations, in particular when coupled with seismometers and/or video cameras,
44 a powerful tool to provide an integrated geophysical analysis for understanding
45 eruption mechanisms and to infer the depth in the conduit. For eruptions at open-
46 vent systems (Garcés and Hansen 1998; Ripepe et al. 2001; Gresta et al. 2004),
47 mechanisms for infrasound generation, as determined from these observations,
48 have been proposed as oscillations of a large elongated bubble at the air-magma
49 interface (Vergnolle and Brandeis 1996; Vergnolle et al. 1996, 2004), bursting of

50 pressurized bubbles (Rowe et al. 2000), and the explosive fragmentation of
51 foaming magma (Ripepe et al. 2001).
52 Despite the common use of infrasound at open-vent explosive systems, their
53 application on Vulcanian systems is still poor. With the aim of understanding the
54 source mechanism of infrasound generation during Vulcanian activity, where a
55 lava plug has been observed at the crater bottom (Stix et al. 1997; Ohminato et al.
56 2006) is destroyed by the explosion (Ishihara 1985), we can not tacitly assume the
57 same mechanism inferred for Strombolian eruptions, in which an infrasound wave
58 generated at the magma free surface that located at a depth of a few tens m within
59 the vent and propagated from that source depth to the air, without interaction with
60 choking materials (Ripepe et al. 2001, 2002). In other words, deformation of the
61 materials would occur at the onset of the eruption.

Fig. 1

62 At Sakurajima volcano, located in southwestern Japan (Fig. 1), explosive
63 Vulcanian eruptions have repeatedly occurred at the summit crater since 1955,
64 and the number of events attained 7888 at the end of 2006. Infrasound waves have
65 always accompanied these eruptions and they have been observed with the low-
66 frequency microphones (Iguchi and Ishihara 1990) and evidenced the existence of

67 a precursor phase followed by a major pressure phase (Sakai et al. 2001).

68 Propagations of infrasound waves in the atmosphere above the crater have

69 occasionally been recorded by video cameras as visualized shock waves (Ishihara

70 1985; Yokoo and Ishihara 2007). Although the propagation velocities and the

71 peak over-pressures for the conspicuous compression phase of infrasound waves

72 have been examined, the weak pressure increase ahead of the strong compression

73 phase (Sakai et al. 2001) has not been taken into account in the considerations of

74 the eruption mechanism.

75 The mechanisms and source dynamics of Vulcanian eruptions of Sakurajima have

76 been mainly studied from a seismological perspective by many researchers

77 (Iguchi 1994; Uhira and Takeo 1994), comparing the seismic signals with the

78 acoustic phenomena (Ishihara 1985). From the analysis of explosion earthquakes

79 and infrasound waves, Tameguri et al. (2002) summarized the sequence of

80 explosive eruption processes as follows. A pressure wave originating from an

81 isotropic expansion at a depth of 2 km propagated upward in a magma conduit

82 with a speed of 1.4–1.9 km/s, and reached a highly-pressurized gas pocket, which

83 was pre-existing at a depth of 300–500 m beneath the crater bottom, within 1 s.

84 The pressure wave then induced expansion of the gas pocket. Strong infrasound
85 wave radiated within 0.3 s after the start of this expansion. Strain steps were also
86 observed at the onset of these explosive eruptions using extensometers deployed
87 in an underground tunnel. The strain steps were caused by an instantaneous
88 pressure decrease that reflected the outburst of the preformed gas pocket (Ishihara
89 1990).

90 Thereby, as proposed from the perspective of macroscopic eruption dynamics by
91 Kanamori et al. (1984), we could assume that the surface phenomena of
92 Vulcanian eruptions are initiated by the “instantaneous failure” of the cap that
93 seals a pressurized gas and magma at the top of the conduit. However, it is known
94 that instant failure with zero in time would not be realistic (Iguchi et al. 2007). A
95 finite time is required for the cap failure, and some kinds of signals associated
96 with this process would be observable.

97 The Green’s function of the air, through which the infrasound waves pass from
98 the source to the microphone, is much simpler than that for the propagation of
99 seismic waves in the ground (Garcés 1997; Johnson 2005). Therefore, it is thought
100 that infrasound records are good indicators for understanding eruption

101 mechanisms, because they directly reflect the source information. In this report,
102 we analyze the infrasound records and video images of the Vulcanian eruption
103 that occurred at 17:53 on January 2, 2007 to determine the exact origin time of the
104 infrasound wave. The time relation between the acoustic and seismic wave
105 generations is then clarified with a higher time resolution at the source with an
106 aim to confirm the process for destruction of the existent lava plug. The eruption
107 analyzed in this investigation was the most vigorous within the last 4 years at
108 Sakurajima volcano, although it was small scaled one compared with the 1970-
109 1990s eruptions.

110 **Observations**

111 **Low-Frequency Microphones and Seismometers**

112 Fig. 1 shows the infrasound observation network at Sakurajima volcano with three
113 low-frequency microphones (Aco, Type 3348/7144). This type of microphone has
114 a flat frequency response in the range of 0.1–100 Hz. Sampling frequencies were
115 200 Hz at stations SVO and ARM, and 100 Hz at KUR. Eruption earthquakes
116 were observed using three broadband seismometers (Akashi, JCP-1 with a flat

117 response of 0.02–120 s, 200 Hz sampling) at stations HAR, ARI and KOM and
118 one long-period seismometer (Akashi, JEP-6B3, 0.025–2.5 s, 200 Hz sampling)
119 installed in a borehole at SBT (Fig. 1). All signals from these sensors were
120 digitized at 24-bit resolution with time data calibrated by GPS and transmitted to
121 SVO via telephone lines.

122 **Video Monitoring Systems**

123 Visual observations with accurate time calibrated by GPS were conducted
124 simultaneously using two image monitoring systems installed at SVO and KUR,
125 on both sides of Sakurajima volcano (Fig. 1). In the SVO system, the shutter
126 timing of the digital camera module was controlled by the 1 PPS signal from a
127 GPS clock module. Images taken by the camera were transmitted to a computer
128 via IEEE1394 cable with a rate of 30 fps, and stored as jpeg formatted files. The
129 other system installed at KUR used a high-sensitive analog TV camera (30
130 fps/NTSC). The time-code was directly inserted on the video images using a time-
131 code generator synchronized with a 1 kHz oscillator, which was controlled by the
132 1 PPS signal from the GPS. These videos were recorded on a HD/DVD video

133 deck. Video images captured by both systems were able to be compared with
134 other records acquired with accurate timing system errors of $\leq \pm 1/60$ s.

135 **Characteristics of Observed Data of the Vulcanian** 136 **Eruption on January 2, 2007**

137 **Infrasound Waveforms**

Fig. 2

138 Fig. 2 shows the observed infrasound waves associated with the explosive
139 eruption on January 2, 2007. The infrasound waves were mainly composed of a
140 first impulsive compression and subsequent longer-period rarefaction phases,
141 similar to an N-shaped shock wave. After the two main phases, some oscillations
142 indicating a return to the ambient pressure lasted approximately 10 s. The
143 waveforms observed at different stations resembled each other. Cross correlation
144 coefficients for the 5 s window from the onset were 0.72 (SVO-KUR), 0.73
145 (SVO-ARM) and 0.92 (KUR-ARM). Spectrograms computed by Fast Fourier
146 Transfer in the 5.12 s time windows, and shifted 0.1 s steps, are also displayed
147 with their waveforms in Fig. 2(a). The intensity of the waveforms was mainly

148 concentrated in the frequencies lower than 3 Hz. The maximum amplitude of the
149 first compression phase was 78 Pa at SVO.

150 Another important feature, that is small and gradually increasing pressure (≤ 3
151 Pa), was recognized 0.25–0.32 s before the onset of the main phase at all stations
152 (Fig. 2(b)). This is referred to as the “preceding phase” after Sakai et al. (2001).

153 The increasing rate of the air pressure in the preceding phase was not constant, but
154 was slightly accelerated with time. This preceding phase was not due to the
155 response of the microphones, but was a part of the infrasound wave itself. The
156 same type of microphones as used here was successful for the capture of shock
157 waves at field explosion experiments using dynamite. The captured shock waves
158 started with an instantaneous pressure increase without a preceding phase (Kato et
159 al. 1999).

160 Characteristics of the infrasound wave of the eruption examined in the present
161 study were commonly found in the records of all 10 eruptions during the period
162 from June 2006 to August 2007 at Sakurajima.

Fig. 3

163 **Video Images**

164 Images taken by the KUR system during the eruption are shown in Fig. 3. The
165 passage of the strong compression phase of the infrasound wave is clearly
166 visualized. Before the eruption, fumarolic steam drifted above the crater rim, as
167 seen in the upper part of the images at 17:53:51-17:53:53. Some of this steam
168 disappeared instantaneously in the image at 17:53:54, and then condensed steam
169 appeared over the crater rim (the following images). After this sequence of
170 phenomena, numerous incandescent ballistics and a dense volcanic cloud were
171 ejected from the inside of the crater (the images after 17:53:57).

172 **Analysis and Results**

173 **Source Location and Origin Time of the Preceding Phase of the**

174 **Infrasound Wave**

175 Source location (x_0, y_0) and origin time $t_{0\text{prec}}$ of the preceding phase were
176 estimated from the arrival times at the three microphone stations (Fig. 1). A grid
177 search method was applied for determination of the location (x_0, y_0) . Grid point

Fig. 4

178 (x, y) was set on the ground surface within the area of the summit crater (Fig. 4;
179 800×700 m, 10-m increment for each).

180 Firstly, the path length L_i from the source points (x, y) to the station i was
181 calculated based on Minakami et al. (1970), using DEM (digital elevation model)
182 data (surveyed on December, 2001). However, we modified the elevation data at
183 the southeastern part of the summit crater (B-crater) as being filled with talus
184 deposits until 700 m altitude, because it was found that on September 2004 the B-
185 crater was buried and no significant topographical changes have been observed

Fig. 5

186 since then (Fig. 5). The method of Minakami et al. (1970) was not so special that
187 it has been already accepted for researchers studying volcanic infrasound waves
188 (e.g., Ruiz et al. 2007); namely, the path-length was assumed to be summative
189 lengths of divided sub-paths above a topographic profile. The simplest one was a
190 summation of two paths, those from the source to the crater margin and from the
191 crater margin to the station.

192 The tentative origin time t_{ten} at each point (x, y) was then calculated as

193
$$t_{\text{ten}} = \frac{1}{N} \sum_i \left| t_{\text{arri}} - \frac{L_i}{c_{\text{effi}}(z)} \right|, \quad (1)$$

194 where N is the number of microphone stations ($N = 3$) and t_{arri} is the arrival
 195 times of the preceding phase at the station i . The preceding phase was regarded
 196 as propagating with an effective speed of sound $c_{\text{effi}}(z)$ at an altitude z along
 197 its path-line from the source to the station (Garcés et al. 1998). The reason for this
 198 was that the preceding phase had no impulsive nature (Fig. 2). $c_{\text{effi}}(z)$ is
 199 described as;

$$\begin{aligned} c_{\text{effi}}(z) &= c_{\text{air}}(z) + w_i(z) \\ &= \sqrt{\gamma R T(z) / \overline{M}} + w_i(z), \end{aligned} \quad (2)$$

201 where $c_{\text{air}}(z)$ is the speed of sound in the air, γ is the specific heat ratio (=1.4),
 202 R is the universal gas constant ($8.3144 \text{ J K}^{-1} \text{ mol}^{-1}$), $T(z)$ is the air temperature
 203 (K), $\overline{M}$ is the mean molar mass of the air ($28.966 \times 10^{-3} \text{ kg mol}^{-1}$) and $w_i(z)$ is
 204 the component of the wind velocity (m/s) along the infrasound path. $T(z)$ and
 205 $w_i(z)$ were calculated from the aerological weather data for every 100 m altitude.
 206 A grid search was conducted so as to minimize the standard deviation;

$$\Delta \varepsilon = \frac{1}{N} \sum_i \left| \left(t_{\text{arri}} - \frac{L_i}{c_{\text{effi}}(z)} \right) - t_{\text{ten}} \right|. \quad (3)$$

208 The minimum deviation provides the source location (x_0, y_0) and the
 209 corresponding t_{ten} is regarded as the origin time $t_{0\text{prec}}$.
 210 The resultant source location (x_0, y_0) of the preceding phase of the infrasound
 211 wave is shown by a double circle with the contour lines of $\Delta\epsilon$ in Fig. 4. The
 212 source of the wave was located in a lateral position from the center of the A-crater
 213 with a spatial resolution of NNE directed area of 85×40 m at $\Delta\epsilon \leq 0.05$ s. This
 214 deviation value was slightly larger than the error of reading of $t_{\text{arr}i}$ (± 0.02 s).
 215 The corresponding origin time $t_{0\text{prec}}$ was simultaneously estimated to be
 216 17:53:51.97 with the minimum $\Delta\epsilon = 0.007$ s. The potential error of $t_{0\text{prec}}$ was in
 217 the range of ± 0.11 s within this considering area of $\Delta\epsilon \leq 0.05$ s.

218 **Origin Time of the Impulsive Compression Phase of the Infrasound**

219 **Wave**

220 Next, the origin time $t_{0\text{comp}}$ of the main impulsive compression phase of the
 221 infrasound wave was estimated from the video record. The passage of the
 222 impulsive compression phase was clearly observed in the video recorded by the
 223 KUR system (Fig. 3). It was recognized by the disappearance of floating

Fig. 6

fumarolic steam at the rim of the summit crater and the increase in luminance of the parts on the images. The increase in luminance was caused by the disappearance of dark-colored steam clouds on the bright sunset light background. Temporary changes of luminance at five regions in and around the steam clouds (small squares labeled a–e in Fig. 3) are shown in Fig. 6. A sudden increase in luminance at $17:53:53.50 \pm 0.05$ corresponds to the disappearance of the clouds, due to the arrival of the compression phase of the infrasound wave. Time errors in these videos were potentially only $\leq \pm 1/60$ s; however, these phenomena were not sufficiently distinct in the space on the images to determine a rigid time of their appearance within that error range because the steam cloud had no fixed form with time. The resulting time data were, therefore, represented with an error of ± 0.05 s.

The steam cloud which disappeared instantaneously with the passage of the main compression phase was positioned horizontally in an area of 20×50 m at the eastern crater rim at an altitude of 920–950 m (Figs. 3, 4 and 5). Hence, the path-length from the estimated source location (the double circle in Fig. 4) to the steam was estimated to be 410–432 m under the assumption of the same source location

241 for both the preceding and main compression phases. As the disappearance of the
 242 cloud above the crater was not well traced during the eruption, the propagation
 243 velocity of the main impulsive compression phase was assumed to be
 244 approximately 400 m/s on average, with reference to the eruptions on April 19,
 245 2006 and November 4, 2007 (392–411 m/s; see Appendix). As a result, the origin
 246 time $t_{0\text{comp}}$ of the impulsive compression phase was determined to be
 247 17:53:52.47–52.63 (Table 1). Even if we consider the variation of the propagation
 248 speed as 392–411 m/s, possible differences of $t_{0\text{comp}}$ was estimated to be only
 249 ± 0.03 s.

Table 1

250 The origin time $t_{0\text{comp}}$ of the impulsive compression phase was 0.5–0.7 s after the
 251 origin time $t_{0\text{prec}}$ of the preceding phase (Fig. 7). Moreover, the time difference
 252 between the two phases at the source ($t_{0\text{comp}} - t_{0\text{prec}}$) was 0.2–0.4 s longer than the
 253 observed arrival time difference at the microphone stations (observed duration of
 254 the preceding phase; $\Delta t_i = 0.25\text{--}0.32$ s). This discrepancy was caused by the
 255 differences in the propagation velocities from the source to the stations. Namely,
 256 the main phase of the infrasound wave ran after the preceding phase with a
 257 supersonic propagation speed (ca. 400 m/s) as an air shock wave. This speed

Fig. 7

258 obviously did not decrease until a distance of ca. 850 m away from the source (see
259 Appendix).

260 **Interpretation and Discussion**

261 **Origin Time of the Gas Pocket Expansion Revealed by Seismological**

262 **Analysis**

263 As already described by Ishihara (1985, 1990), the main phase of the infrasound
264 wave radiated at the outbreak of a highly pressurized gas pocket beneath the crater
265 bottom and propagated as an air shock wave. Tameguri et al. (2002) demonstrated
266 that isotropic expansion at a depth of 300–500 m revealed by moment tensor
267 analysis of explosion earthquakes is closely related with the occurrence time and
268 amplitude of this shock wave. It was hypothesized that the preceding phase ahead
269 of the main phase of the infrasound wave would be induced by an upward
270 movement of the lava plug toward its failure, due to expansion of the gas pocket.
271 To confirm this, the start time of expansion of the gas pocket was estimated by the
272 waveform inversion of the explosion earthquake, based on the method of
273 Tameguri et al. (2002). In the calculation, a triangle source time function was

assumed for the moment velocity ($\dot{M}_0(t)$). In the observed waveforms associated with the eruption on January 2, 2007 (Fig. 8), the compressional P phase, the subsequent dilatation wave (D phase) and long-period larger motion (LP phase) were clearly recognized as usual explosion earthquakes (Tameguri et al., 2002).

The results of the calculation are summarized in Table 2 and Fig. 9. Moment tensor analysis of explosion earthquakes shows that an isotropic expansion generating the P phase occurred first at a depth of 0.9 km below the sea level at 17:53:51.23 (Fig. 9(a)). Cylindrical contraction then followed at the same depth (Fig. 9(b)), radiating a dilatational elastic wave (the D phase). Approximately 0.8 s after the beginning of the P-phase isotropic expansion, a shallower isotropic expansion occurred at 0.5 km above the sea level (Fig. 9(c); LP1 source), which corresponds to the excitation of the LP phase being closely related to the shock wave at 17:53:52.03. The squared residual for estimation of the origin time of this

source is shown in Fig. 10, which indicates that the resultant origin time is accurate in the order of 0.1 s. The shallower expansion changed to a horizontal contraction 1.1 s later (Fig. 9(d); LP2 source).

290 A noteworthy point of this result is the time of the LP1 source generating the
291 shallower expansion. The origin time of the shallower expansion ($t'_{0LP1}=52.03$ s),
292 evaluated from moment tensor analysis of the explosion earthquake, coincides
293 with the origin time of the preceding phase of the infrasound wave ($t_{0prec}=51.97$ s;
294 Table 1) evaluated from the infrasound source searching. On the contrary the peak
295 time of the moment velocity ($t'_{peak}=52.58$ s) is close to the origin time of the
296 impulsive compression phase ($t_{0comp}=52.47$ – 52.63 s) evaluated from video
297 images. These two correspondences show not only that the main impulsive
298 compression phase of the infrasound wave is certainly related to the shallower
299 expansion source exciting the LP phase, but also that the radiation of the
300 preceding phase is closely related to the expansion process. This seems to support
301 our hypothesis that the preceding phase of the infrasound wave was firstly excited
302 at the upward movement of the lava plug, which acted as a lid of the gas pocket.
303 In addition, the coincidence of the origin time of the main impulsive phase with
304 the peak time of the moment velocity of expansion suggests that the lava plug was
305 destroyed at the time when the expansion velocity attained a peak, 0.5–0.7 s after
306 the start of expansion.

307 Volumetric Change for Excitation of the Preceding Phase of the

308 Infrasound Wave

309 In the locating procedure, the infrasound phase preceding the main shock wave

310 has been assumed to be a pressure wave propagating at sound speed velocity

311 (~ 340 m/s; Fig. 7), as a consequence of the non-impulsive nature of the signal.

312 Accordingly the air pressure change $p_i(t)$ observed at the various infrasound

313 stations i during the preceding phase ($-\Delta t_i \leq t \leq 0$ in Fig. 2(b)) may be

314 described as follows (Lighthill 1978; Vergniolle and Brandeis 1996);

$$315 \quad p_i(t) = \frac{\rho_{\text{air}}(z)}{2\pi L_i} \frac{d^2}{dt^2} V(t - L_i/c_{\text{effi}}(z)), \quad (4)$$

316 where $\rho_{\text{air}}(z)$ and $V(t)$ are the air density (kg m^{-3}) and the volume of the source

317 (m^3), respectively. $\rho_{\text{air}}(z)$ is calculated from the aerological weather data (the

318 atmospheric pressure $p_{\text{air}}(z)$ (Pa), and $T(z)$) by the perfect gas law;

$$319 \quad \rho_{\text{air}}(z) = p_{\text{air}}(z) \overline{M} / RT(z). \quad (5)$$

320 Hence, the source time function of the volume change could be inversely

321 estimated from the observed pressure change of the preceding phase.

322 However, the whole waveform of the preceding phase could not be observed,
 323 because the preceding phase was covered with the subsequent main phase after
 324 the arrival of the main phase at the stations (dashed line in the source time
 325 function in Fig. 7). As the main impulsive compression phase was radiated 0.5–
 326 0.7 s after the origin time of the preceding phase, it is assumed that the preceding
 327 phase continued until the onset of the main phase, but it was overtaken and hidden
 328 by the main shock wave in the pressure records. Assuming that the volumetric
 329 change had the same increasing rate as that estimated from the moment velocity in
 330 the LP1 source (the period from the origin time to the peak time), it was expressed
 331 by a quadratic function of the time ($V \propto \int \dot{M}_0 dt = \alpha t^2$; Fig. 9 and Table 2).
 332 Therefore, we here extrapolated the volume change as if it was not hidden by the
 333 shock wave, by fitting the double-integration of the observed infrasound pressure
 334 data at the station ARM into these quadratic function (Fig. 11), which was the
 335 least distorted of the three stations data during the propagation because ARM has
 336 the shortest path-length from the source (ca. 2.8 km). Consequently, it was 280–
 337 560 m³ considering with the variation of the time of $t_{0\text{comp}} - t_{0\text{prec}}$ as 0.5–0.7 s
 338 (Fig. 11). This estimated volumetric change at the source was equivalent to the

Fig. 11

339 height of the ground bulge, in the order of 1 m (0.9–1.8 m), assuming that the
340 radius of the cylindrical lava plug was the observed value of ca. 10 m (Ishihara
341 1985). However, vertical displacement of considering lava plug were estimated to
342 be 0.3–1.3 m from KUR and SVO data, which was slightly smaller values than
343 those from ARM data, since volume changes were only 210–420 m³ and 90–200
344 m³, respectively. These discrepancies might suggest that some of our assumptions
345 used here were insufficient or incorrect and this point in question would be open
346 to further discussion. The source dynamics for generating preceding phase of
347 infrasound wave associated with Vulcanian eruptions and their physical
348 parameters are necessary to be made a much clearer from combining theoretical
349 and observational approaches.

350

351 **Time Sequence of Infrasound Wave Generation**

352 The results presented and discussed here allow us to infer a complex source
353 mechanism for the infrasound radiated by the Vulcanian eruption of Sakurajima
354 volcano on January 2, 2007, as shown in Fig. 12. A deeper source (0.9 km bsl) is

Fig. 12

355 inferred to radiate a pressure wave within the conduit (stage 0), which once it
356 reaches a shallower gas pocket (ca. 500 m asl), confined below a sealing lava
357 plug, triggers its isotropic expansion (stage 1). This explosion leads to an upraise
358 of the lava plug at the bottom of the crater and the upward process of the lava plug
359 with a 0.5–0.7 s duration would radiate the preceding phase of the infrasound
360 wave. The preceding phase was observed as a weak and gradual increase of the air
361 pressure change at the microphone stations around the crater. The expansion rate
362 of the gas pocket gradually accelerated and when it exceed a threshold level, the
363 lava plug failed and a strong air shock wave, which propagated with a velocity of
364 ca. 400 m/s, started to be radiated (stage 2). This was observed as the main phase
365 of infrasound wave at the stations; a set of compression and rarefaction phases.
366 After breakage of the lava plug (removal of the lid), the gas pocket still expanded
367 isotropically, but its rate changed and began to decrease.

368 **Conclusions**

369 Infrasound of the recent Vulcanian eruption of Sakurajima volcano in 2007 was
370 analyzed with video and seismic records. From the results of the analysis, several
371 conclusions were obtained.

372 (1) In the infrasound waveforms associated with the eruption observed by low-
373 frequency microphones, the preceding phase was clearly recognized. It was
374 characterized by weak and slowly increasing air pressure and it preceded the
375 onset of the main impulsive compression phase by 0.25–0.32 s.

376 (2) The origin time of the preceding phase, which was estimated from the arrival
377 times at the stations, corresponds to the start time of the expansion for the
378 pressurized gas pocket determined by waveform inversion of explosion
379 earthquakes. On the other hand, the origin time of the main impulsive
380 compression phase, which is estimated from video images, was close to the
381 time when the expansion velocity of the gas pocket reached a peak value. The
382 time difference between the origin times of the preceding and the main phases
383 was 0.5–0.7 s at the source.

384 (3) The identification of different signals originating at sequential times point to a
385 complex process generating infrasound from Vulcanian eruptions at
386 Sakurajima volcano. At the eruption onset, a gas pocket sealed by a
387 consolidated lava plug began to expand first, which induced swelling-up of the
388 lava plug and this radiated the preceding phase of the infrasound wave. The
389 expansion rate of the gas pocket gradually accelerated within 0.5–0.7 s and
390 when it exceeded a threshold level, the swelling lava plug led to a failure. At
391 this time, the main impulsive compression phase of the infrasound wave was
392 radiated by the sudden release of pressurized gases. After the failure of the
393 lava plug, the expansion rate changed and began to decrease.

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405 **Appendix A. Propagation Velocity of the Impulsive** 406 **Compression Phase of an Infrasound Wave**

407 The propagation velocities of a set of compression and rarefaction phases of the
408 infrasound waves associated with the Sakurajima Vulcanian eruptions on 1980s
409 were higher (440–570 m/s) than the speed of sound in air at a distance near to the
410 source (Ishihara 1985; Yokoo and Ishihara 2007). Two recent cases of video
411 images taken by the SVO monitoring systems were analyzed to estimate the travel
412 speeds of these main phases, by the detection of sudden luminance changes along
413 the propagation path of the wave.

414 At the eruption on April 19, 2006, a temporal condensation cloud caused by
415 passage of the rarefaction phase of the infrasound wave appeared at 09:50:21.1.

416 This cloud formation was recognized as luminance increasing at altitudes ranging
417 1060–1265 m (Fig. A.1(a)). This range corresponds to the weather clouds existing
418 before the eruption. By tracing the onset time of luminance changes in altitude at
419 every 5 m, the apparent propagation velocity of the wave was estimated as 392
420 m/s (± 11 m/s) on average. A propagating wave was also observed as weak
421 changes in brightness at altitudes of 1250–1600 m for the eruption on November
422 4, 2006 (Fig. A.1(b)). The onset time of the increase in brightness at altitudes of
423 1315–1660 m indicated that the velocity of the wave was 411 m/s (± 11 m/s).
424 From these two results, the main phase of the infrasound waves were certainly
425 faster (ca. 400 m/s) than the speed of sound in air at a distance near to the source
426 (until 360–870 m above the crater bottom).

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496

497 Figure Captions

498 Fig. 1. Observation network of low-frequency microphones, seismometers and video cameras at
499 Sakurajima volcano. Solid squares indicate the microphone stations (SVO, KUR and ARM). Three
500 broadband seismometers were installed at ARI, HAR and KOM, and one long-period seismometer
501 was installed at SBT (open circles). Video cameras were installed at SVO and KUR (open
502 triangles).

503 Fig. 2. (a) Observed infrasound waveform with spectrogram for the eruption on January 2, 2007.
504 Inset numbers are the maximum pressure amplitudes. (b) Close-up of the waveforms shifted by the
505 arrival times of the main impulsive compression phase (shown by the arrows in (a)) to be zero in
506 time.

507 Fig. 3. Selected images of the eruption taken by the KUR monitoring systems from 17:53:51 to
508 17:54:00. Disappearance of fumarolic steam caused by the passage of the impulsive compression
509 phase of the infrasound wave is shown by the two circles in the image at 17:53:54. Luminance
510 changes in five small squares shown in the image at 17:53:51 (a–e; 20×20 pix) were analyzed.

511 Fig. 4. Source location of the infrasound wave for the eruption on January 2, 2007 (double circle).
512 The red contour lines represent the resultant $\Delta\mathcal{E}$. Source locations associated with the 10

513 eruptions during 2006–2007 are indicated by circles. The hatched area at the eastern crater rim
 514 indicates the location of the fumarolic steam that was visible from KUR (see Figs. 3 and 5).
 515 Fig. 5. Aerial photograph of the summit crater of Sakurajima volcano (taken from the northeast on
 516 August 6, 2005; courtesy of SVO). The B-crater had been buried by talus deposits since
 517 September 2004. The white squared zone at the crater rim (lower left) denotes the fumarolic steam
 518 indicated by arrows in Fig. 3.
 519 Fig. 6. Luminance changes in the five small squares shown in Fig. 3. Onset times of the impulsive
 520 compression phase of the infrasound wave are recognized as sudden increases in luminance (light-
 521 gray colored time; disappearance of fumarolic steam at the five regions).
 522 Fig. 7. Schematic time-spatial relation for the generation and propagation of the infrasound wave.
 523 Fig. 8. Vertical velocity waveform for the explosion earthquake on January 2, 2007, observed at
 524 HAR (Fig. 1) and the synthetic one (black solid and red broken lines, respectively). P, D and LP
 525 indicate the P-wave first, dilatational and largest long-period motions, respectively (Tameguri et
 526 al., 2002). Onsets of their phases were indicated by arrows.

527 Fig. 9. Resultant source time functions of moment rate for each phase of the explosion earthquake

528 The periods (a) to (d) were the source times of the P , D, LP1 and LP2 phases, respectively.

529 Details are in the text and Table 2.

530 Fig. 10. Reliability of the origin time of the LP1 source (t'_{0LP1}) for the eruption on January 2,

531 2007. Residual is plotted against the time variation.

532 Fig. 11. Estimated volumetric change for an excitation of the preceding phase using pressure data

533 observed at ARM (solid and dotted lines). Zero in time is set by the arrival time of the main phase

534 at ARM. The dashed line at $t > 0$ is assumed from the estimated moment change ($V \propto t^2$).

535 Fig. 12. Schematic sequential image for the surface phenomena at the explosive eruption of

536 Sakurajima volcano on January 2, 2007. Stage 0: pressurized gas pocket is sealed with a

537 consolidated lava plug. Stage 1: swelling up of the crater bottom, which excites a preceding phase

538 of the infrasound wave, due to expansion of the gas pocket beneath the crater. Stage 2: the lava

539 plug (crater bottom) is failed. At this time, the main phase of the infrasound wave is radiated. After

540 the failure of the lava plug, the expansion rate of the gas pocket decreases.

541 Fig. A.1. (a) Snapshots before and during the eruption on April 19, 2006, taken by the SVO

542 monitoring system (left), and luminance changes at several altitudes from 09:50:20 for this

543 eruption (center: upward means brighten changing). Each arrow indicates the onset time of an
544 increase in luminance. Relationship between these onset times and the altitude is displayed in the
545 diagram with a 1.0 s window width (right). (b) Two captured images for the eruption on November
546 4, 2006, and luminance change during the 5 s above the crater of the eruption. After 17:33:40.8,
547 weak increases in luminance were also observed.

548 Table 1. Estimated origin times for the infrasound wave and expansion of the shallower gas
549 pocket.

		time (hh:mm:ss)
origin time of preceding phase	$t_{0\text{prec}}$	17:53:51.97
origin time of main impulsive compression phase	$t_{0\text{comp}}$	17:53:52.47–52.63
origin time of shallow gas pocket's expansion	$t'_{0\text{LP1}}$	17:53:52.04
Peak time of expansion velocity of shallow gas pocket	t'_{peak}	17:53:52.58

550 Table 2. Results of the moment tensor analysis for the explosion earthquake on January 2, 2007.

	P phase	D phase	LP phase	
			LP1	LP2
source time of moment velocity (17:53:ss)				
origin time	51.23	51.43	52.03	53.13
peak time	51.33	51.73	52.58	53.73
end time	51.43	52.03	53.13	54.33
source depth (km bsl)	0.90	0.90	-0.50	-0.50
moment tensor (Nm)				

$\mathbf{M}_{xx}$	3.5×10^{11}	-16.1×10^{11}	5.8×10^{11}	-6.3×10^{11}
$\mathbf{M}_{yy}$	3.6×10^{11}	-17.2×10^{11}	6.1×10^{11}	-6.5×10^{11}
$\mathbf{M}_{zz}$	3.5×10^{11}	-8.1×10^{11}	6.0×10^{11}	-0.8×10^{11}
$\mathbf{M}_{xy}$	-0.2×10^{11}	0.6×10^{11}	-0.3×10^{11}	0.4×10^{11}
$\mathbf{M}_{xz}$	-0.1×10^{11}	0.9×10^{11}	-0.4×10^{11}	0.5×10^{11}
$\mathbf{M}_{yz}$	0.1×10^{11}	-0.5×10^{11}	0.2×10^{11}	-0.3×10^{11}

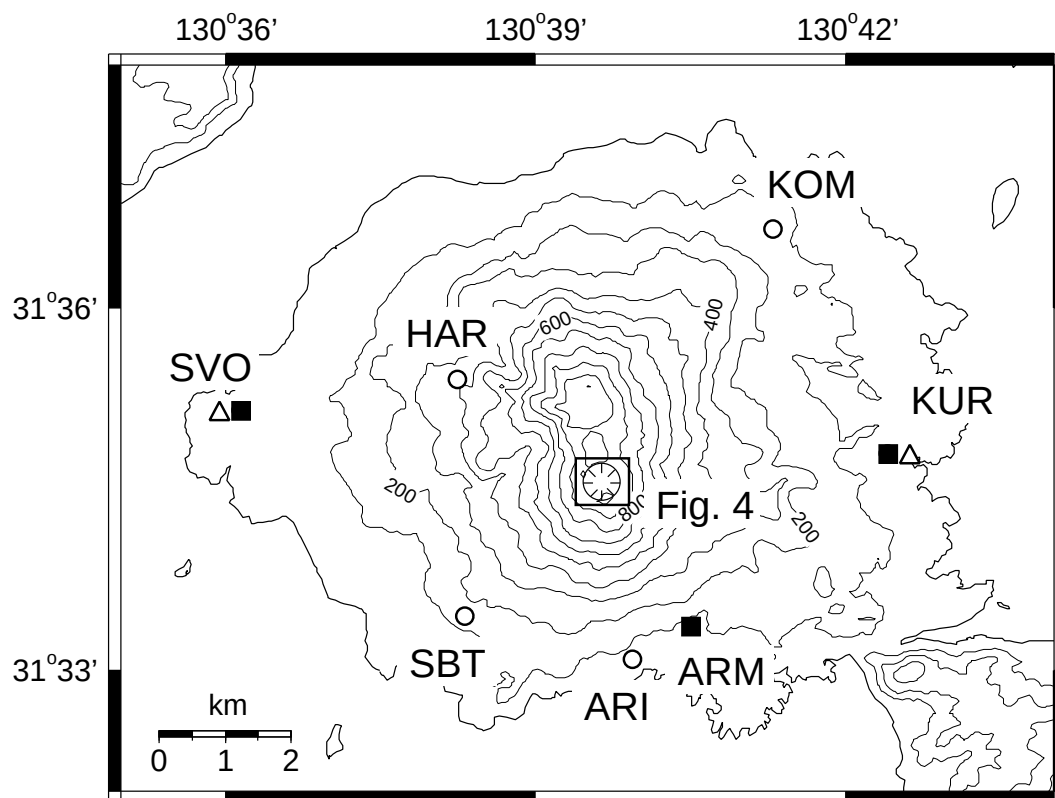


Figure 1: Yokoo et al.

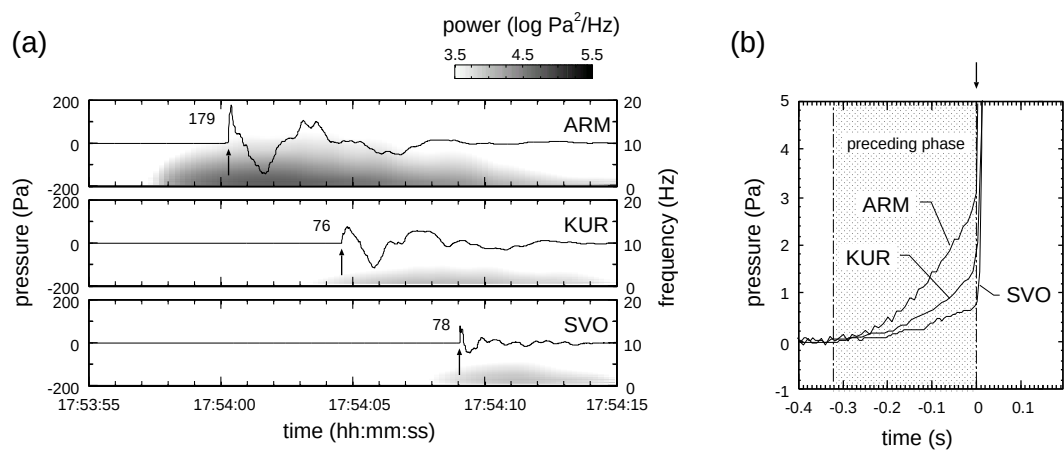


Figure 2: Yokoo et al.

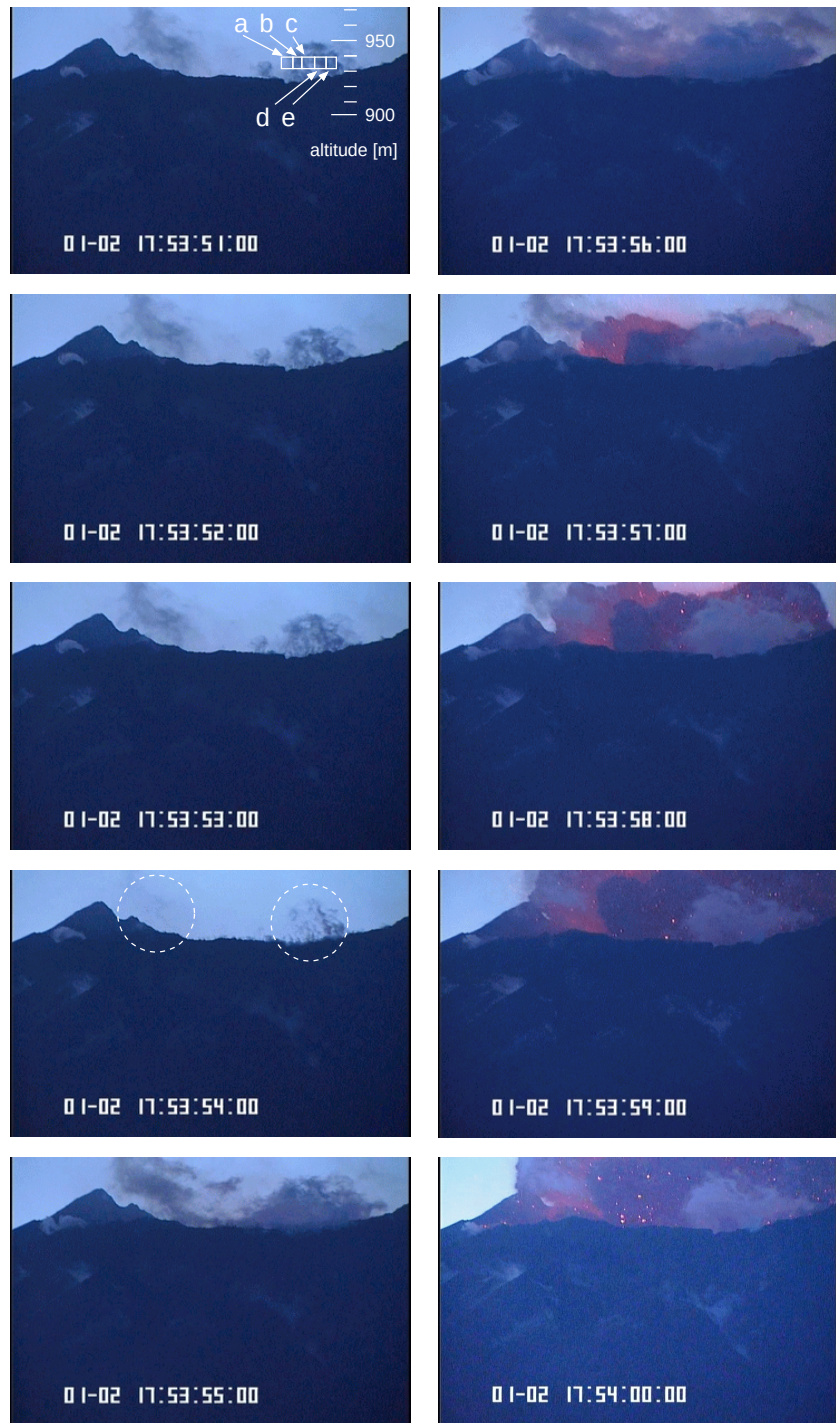


Figure 3: Yokoo et al.

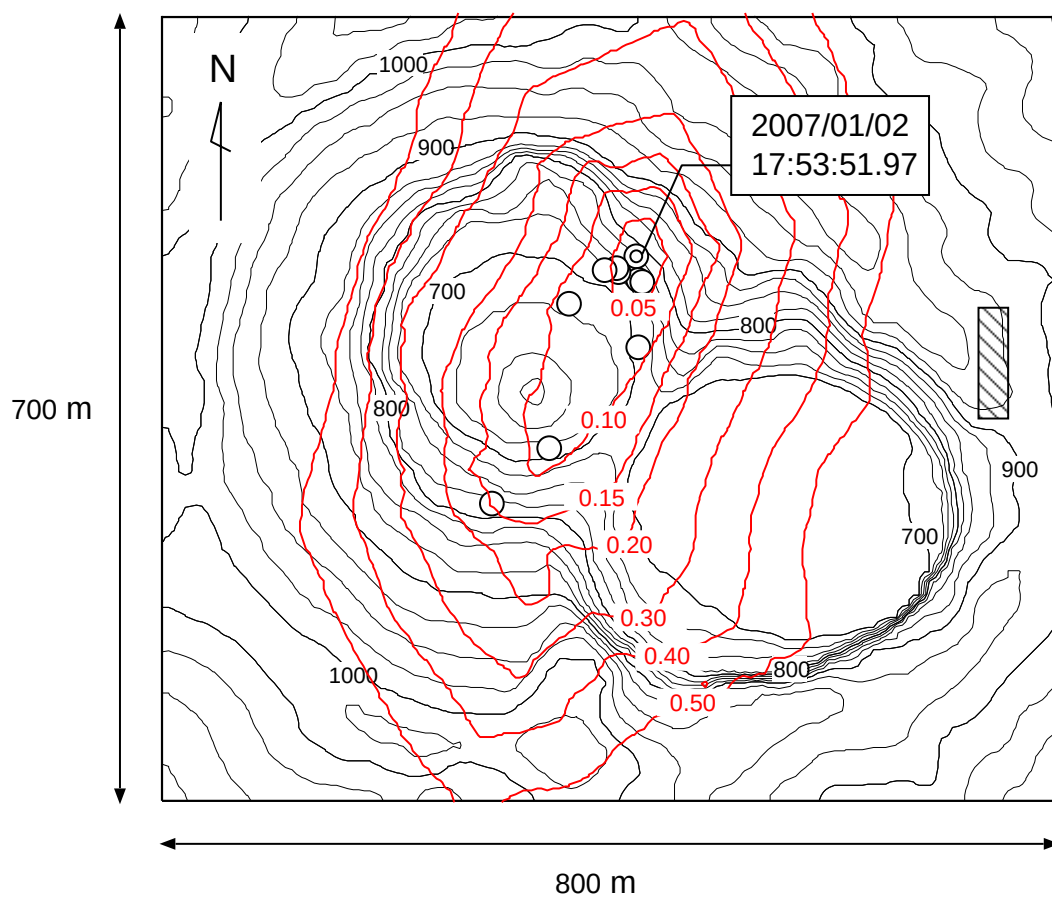


Figure 4: Yokoo et al.

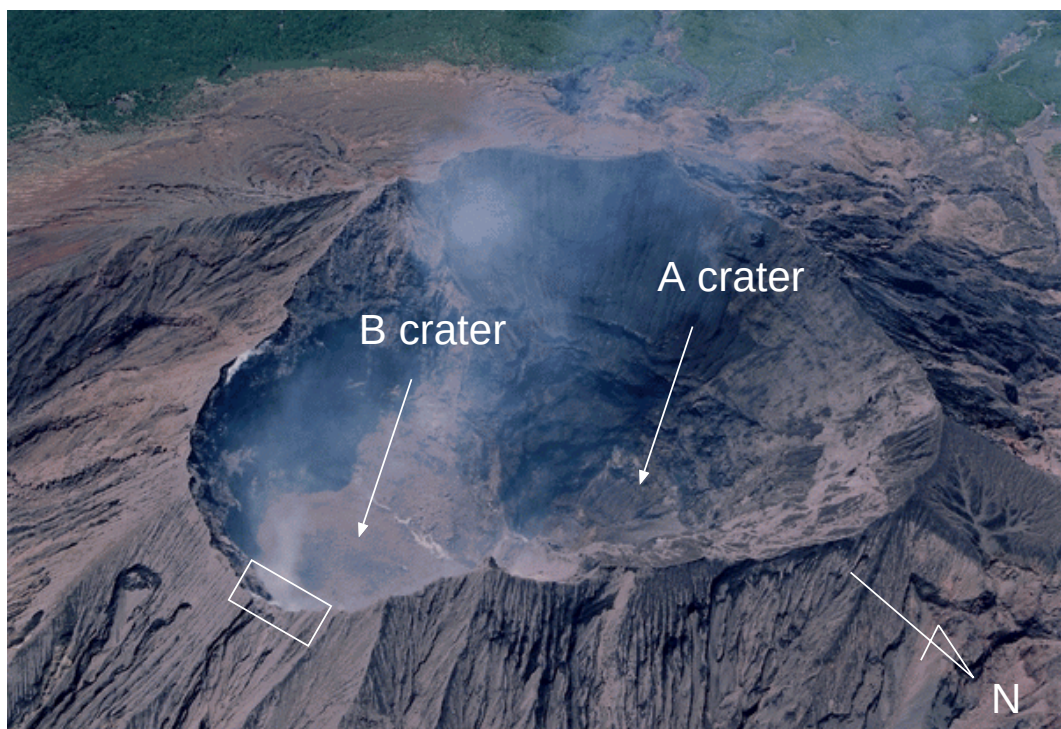


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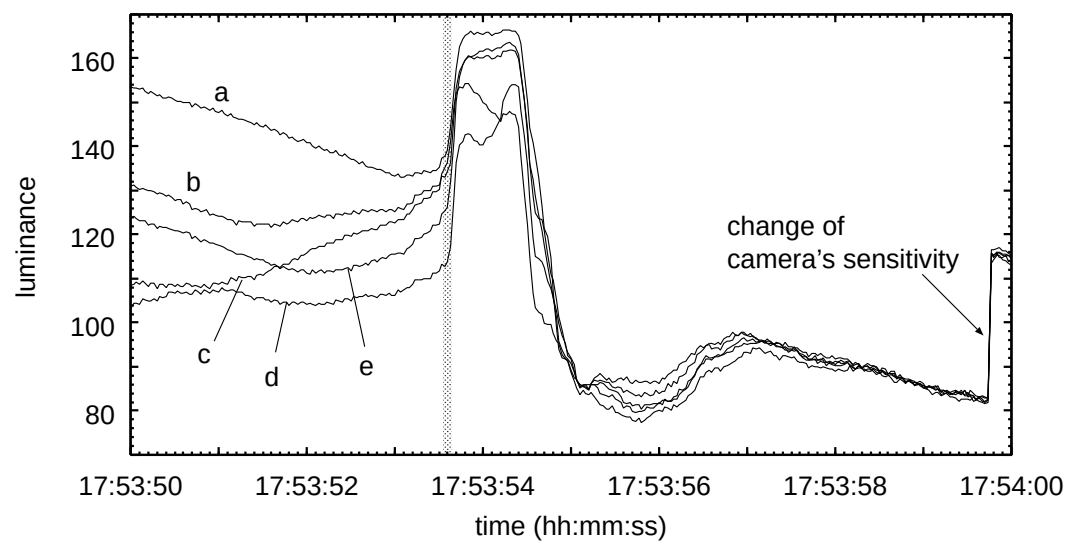


Figure 6: Yokoo et al.

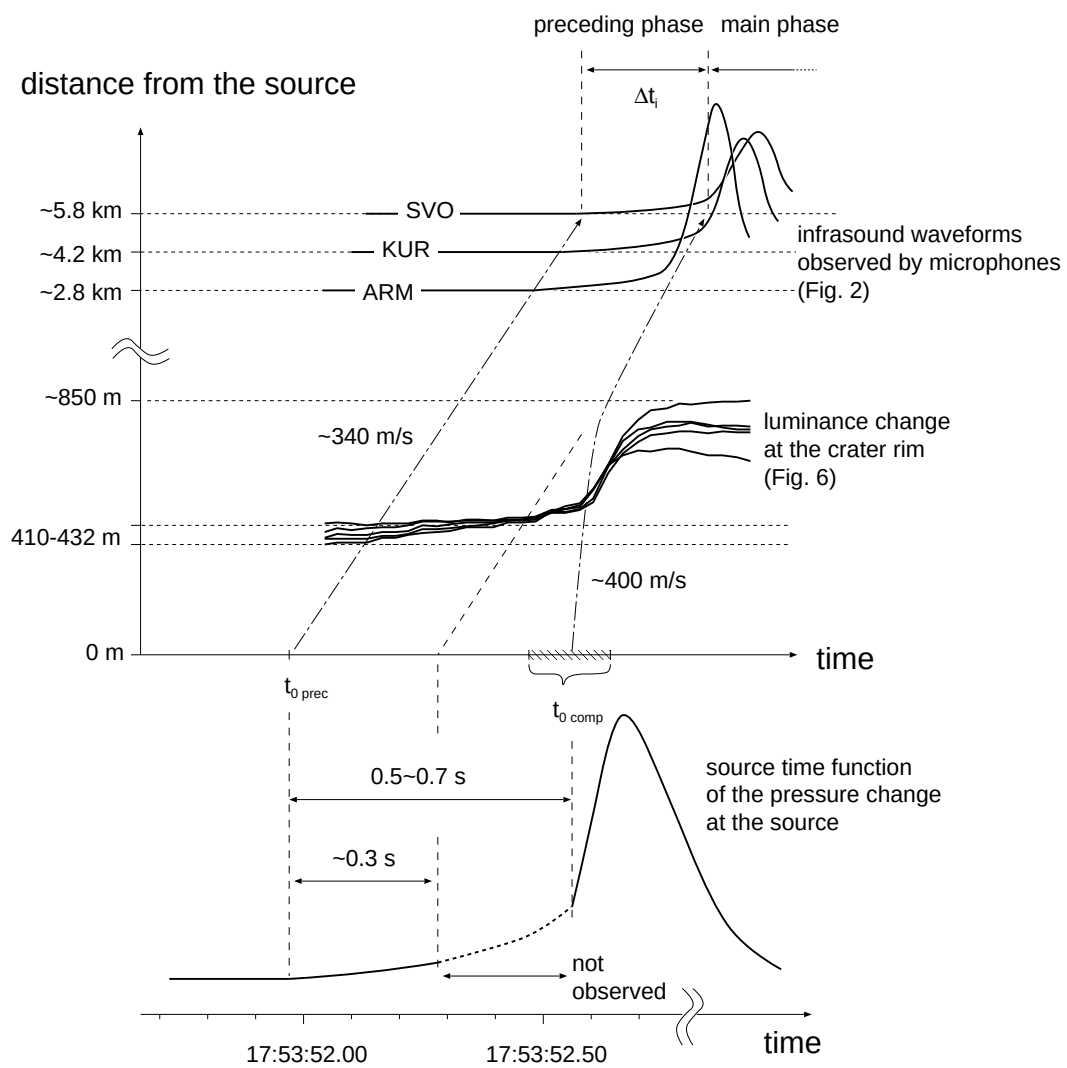


Figure 7: Yokoo et al.

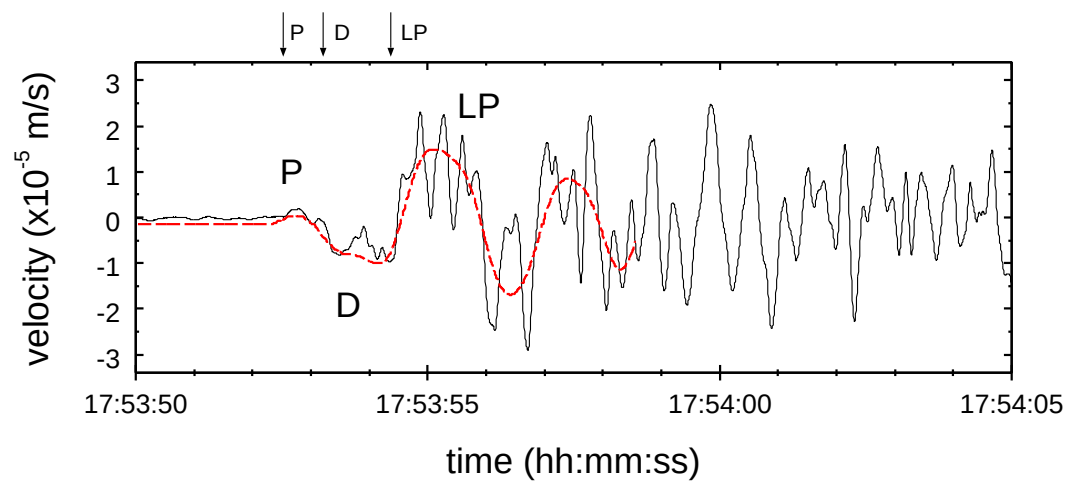


Figure 8: Yokoo et al.

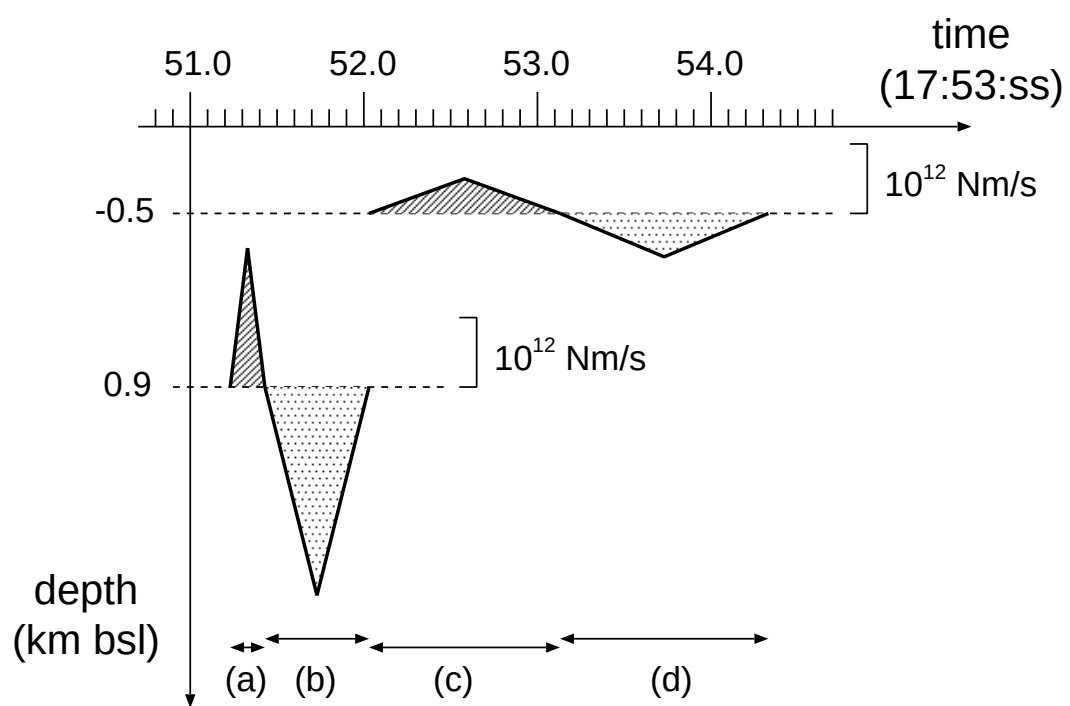


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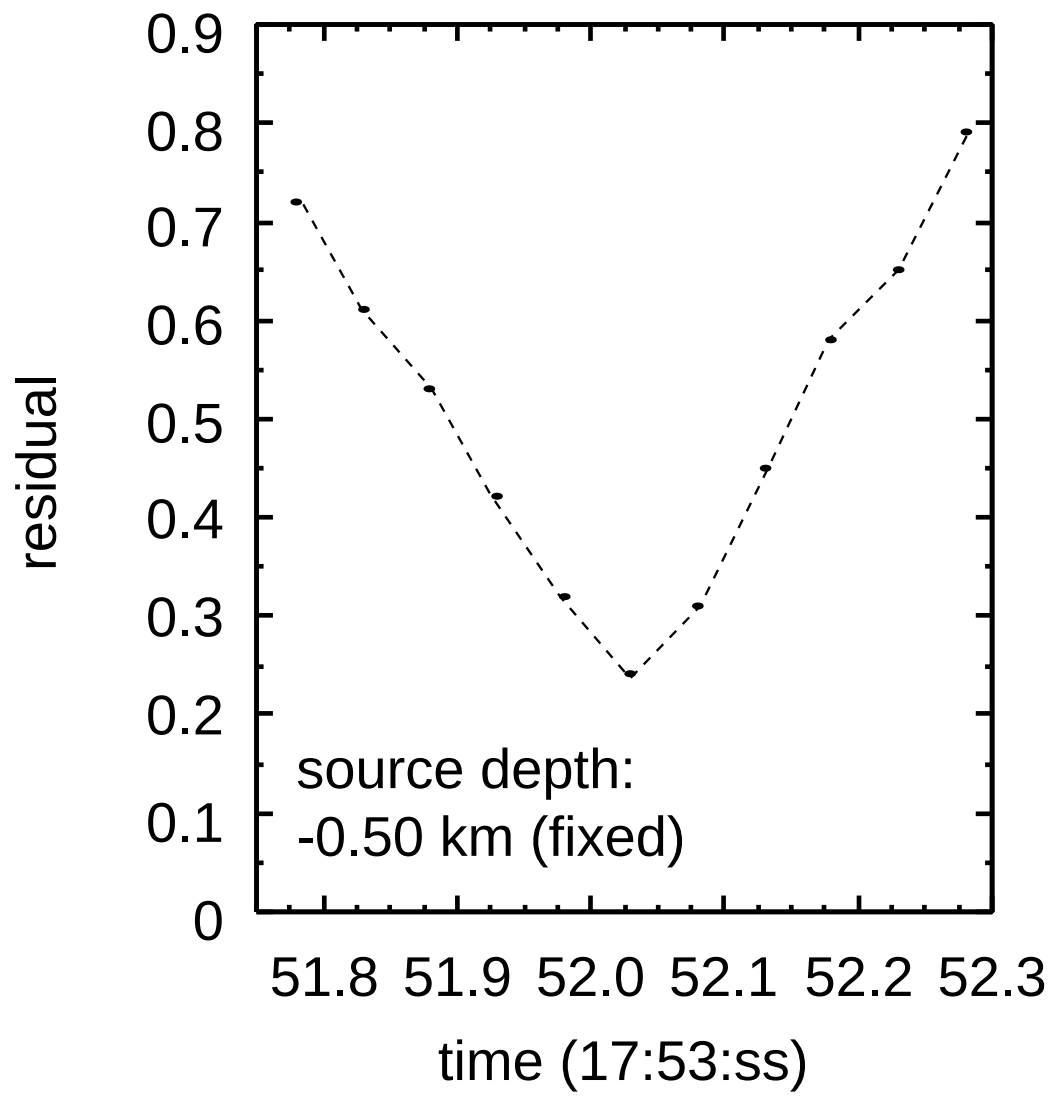


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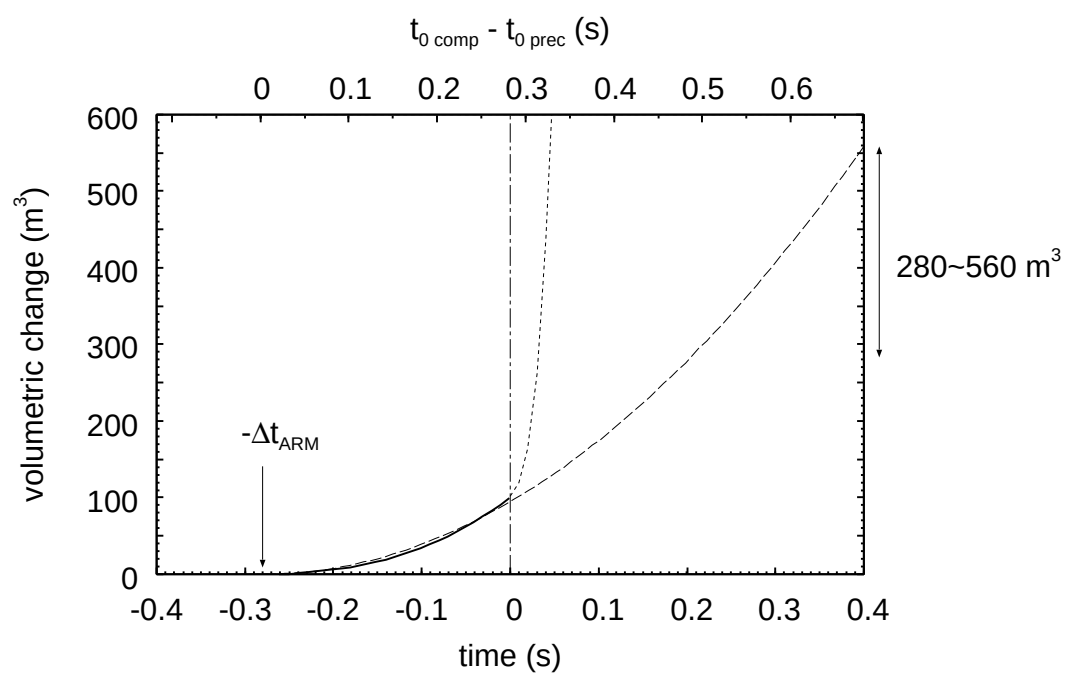


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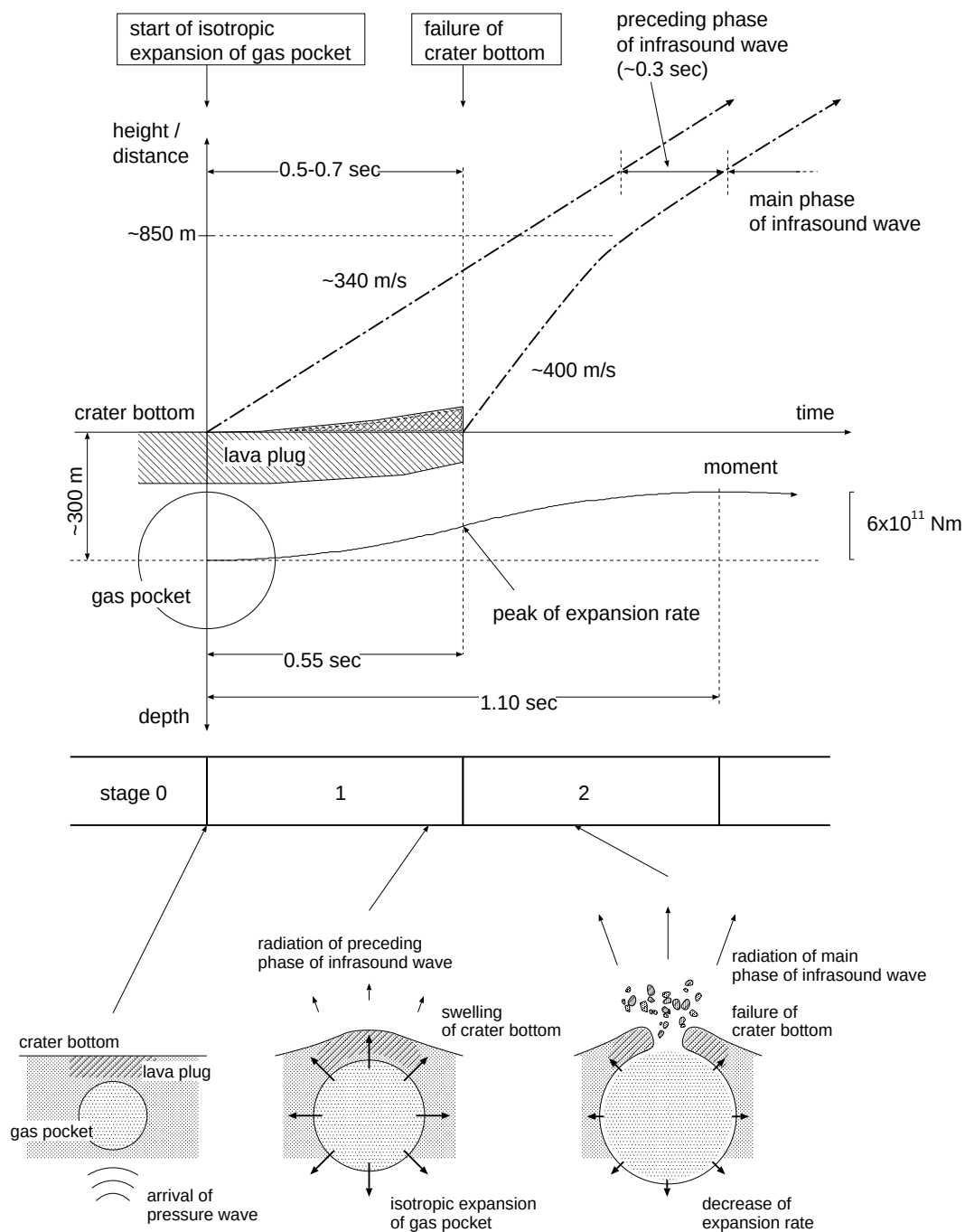


Figure 12: Yokoo et al.

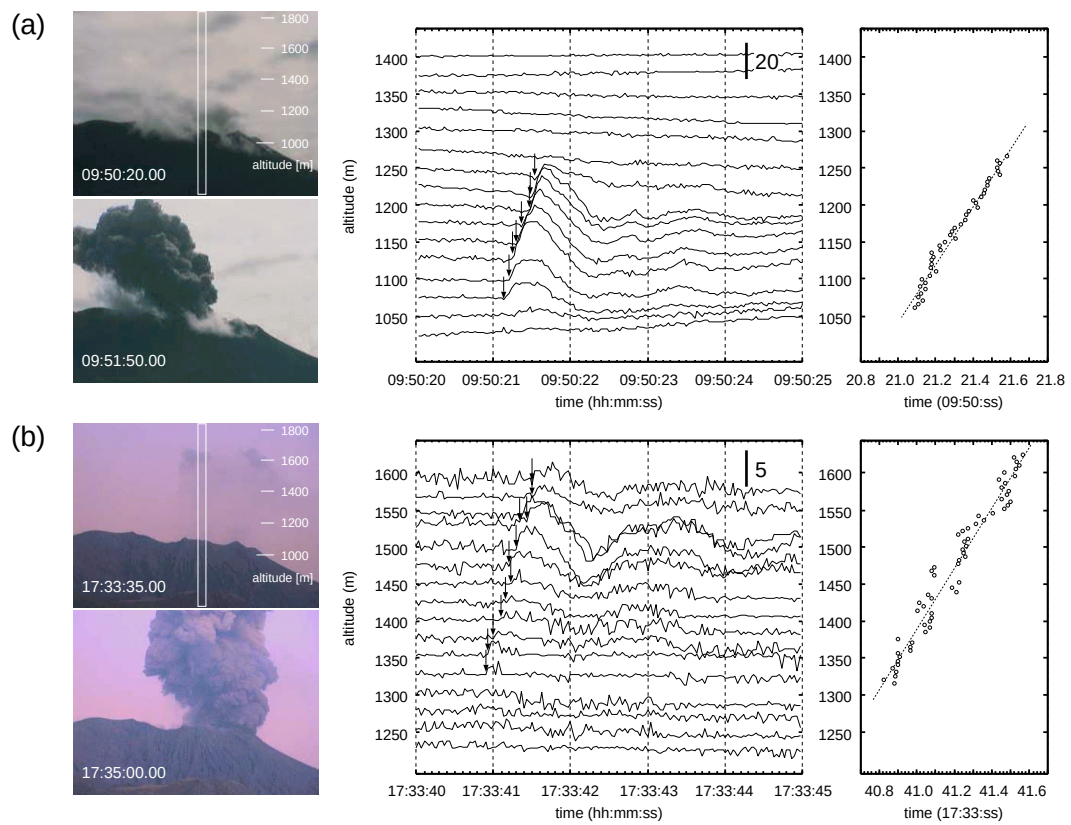


Figure 1: Yokoo et al.