BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 57 (1982), pp. 303-315

15. *Implosion Earthquakes Associated with the 1973 Eruptive Activity of Asama Volcano.*

By Hiroshi IMAI,
Earthquake Research Institute.

(Received April 14, 1982)

Abstract

Several successive small and gentle eruptions were observed during Feb. 16-18 in the course of the 1973 eruptive activity of Asama Volcano, central Honshu, Japan. Many earthquakes associated with the eruptions were recorded. The initial motions of some of these earthquakes were found to be downward and/or pull at all the seismic stations. These earthquakes are termed "implosion earthquakes". Their epicenters clustered within a small area close to the southern part of the summit crater. The depths of their origins are estimated by using some mechanical models possible for interpretation of their downward initial motions and using their onset time differences between two of the stations. Conclusively, the depths of their origins range from 0.5 to 1.5 km measured from the top of the volcano whose height is taken to 2.5 km above sea level. Judging from these results, it seems sure that the implosion earthquakes at a shallow depth in a limited area just below the summit crater of the volcano.

1. Introduction

On February 1 in 1973, after 11 years of dormancy, an eruptive activity commenced on Asama Volcano, which is one of the most active volcanoes in Japan. The activity continued until April 26 of the same year. During the course of this activity, successions of small and gentle eruptions without any detonating sound occurred from Feb. 16 to Feb. 18 (see Plates 1 and 2). Such a succession of eruptions was termed "successive eruptions" (SHIMOZURU, 1979; IMAI, 1982). The number of eruptions totalled more than 3,900 (SHIMOZURU *et al.*, 1975). Many earthquakes associated with the eruptions were recorded at the seismic stations of the Asama Volcano Observatory (A.V.O.) of Earthquake Research Institute installed on the flank and skirt of the volcano. After a careful investigation of the seismic data, the initial motions of some of these earthquakes were shown to be downward or pull at all the stations, such as the ex-

Plate 1. A photo of a successive eruption at Asama Volcano, taken by D. SHIMOZURU on the northern skirt of the volcano in 1973. Two eruption clouds are seen.

Plate 2. A photo of a successive eruption, taken just after the photo shown in Plate 1. It is easy to see that each eruption cloud was formed regularly.

ample shown in Fig. 1. These events are named "implosion earthquakes" (IMAI, 1982) distinguished from "explosion earthquakes" whose initial motions are upward or push for all directions irrespective of their size (MINAKAMI *et al.*, 1970a).

As for such observational findings, TANAKA (1971) seems to be the first to have found the downward or pull initial motions of some earthquakes among the vast number associated with the explosive eruptions which totalled about 32,000 during the 1970–1971 eruptive activities at Akita-komaga-take, northern Honshu, Japan. He thought that the earthquakes occurred at depths of 0 to 300 m or more below the crater, introducing the models by TAKAGI (1953).

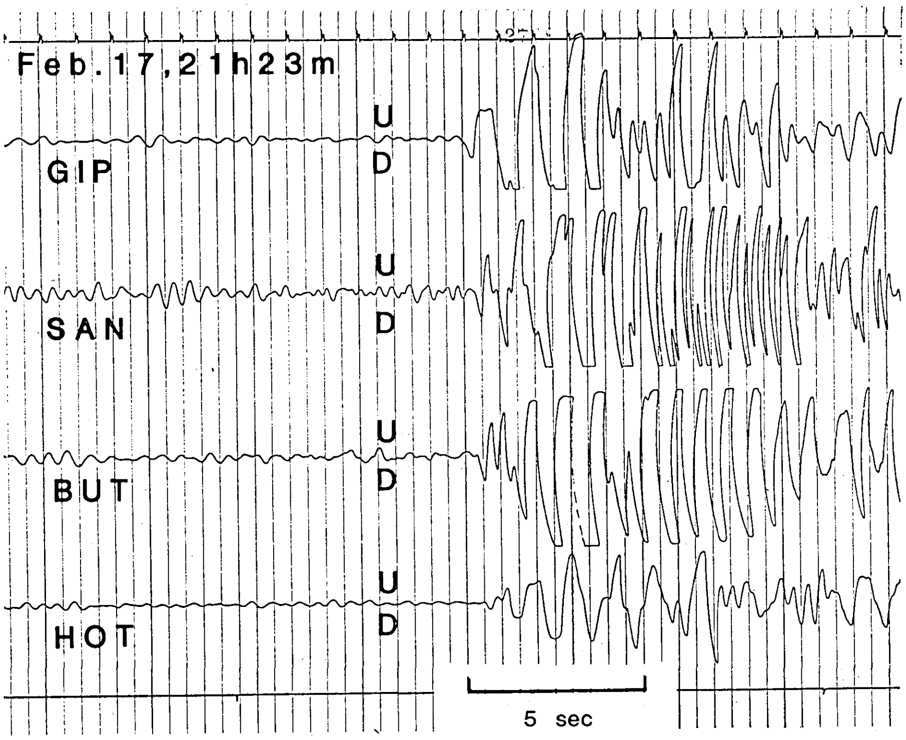


Fig. 1. An example of implosion earthquake seismograms recorded at the seismic stations GIP, SAN, BUT and HOT. Initial motions are downward at all the stations.

IMAI (1982) presented a mechanism of the successive eruptions, introducing a two-phase flow system. He also suggested that the earthquakes associated with the successive eruptions occurred at a shallow depth. However, it is still not precisely known where the implosion earthquakes occurred. The purpose of this paper, according to the method pressented by TANAKA (1971), is to find the possible depth range at which the implosion earthquakes occurred. The corresponding travel time data is taken into account.

2. Seismic Data

During the course of succesive eruptions in 1973, pen-recorder seismograms with a paper speed of 10 mm/sec are available for the four seismic stations which are named SAN, HOT, GIP and BUT (Fig. 2). SAN, HOT and GIP were permanent stations of A.V.O., whereas BUT was temporarily installed on the Butai lava flow on the northeastern flank of the volcano. The locations of these seismic stations are shown in Table 1. The seismographs of HOT, GIP and BUT were of short-period verti-

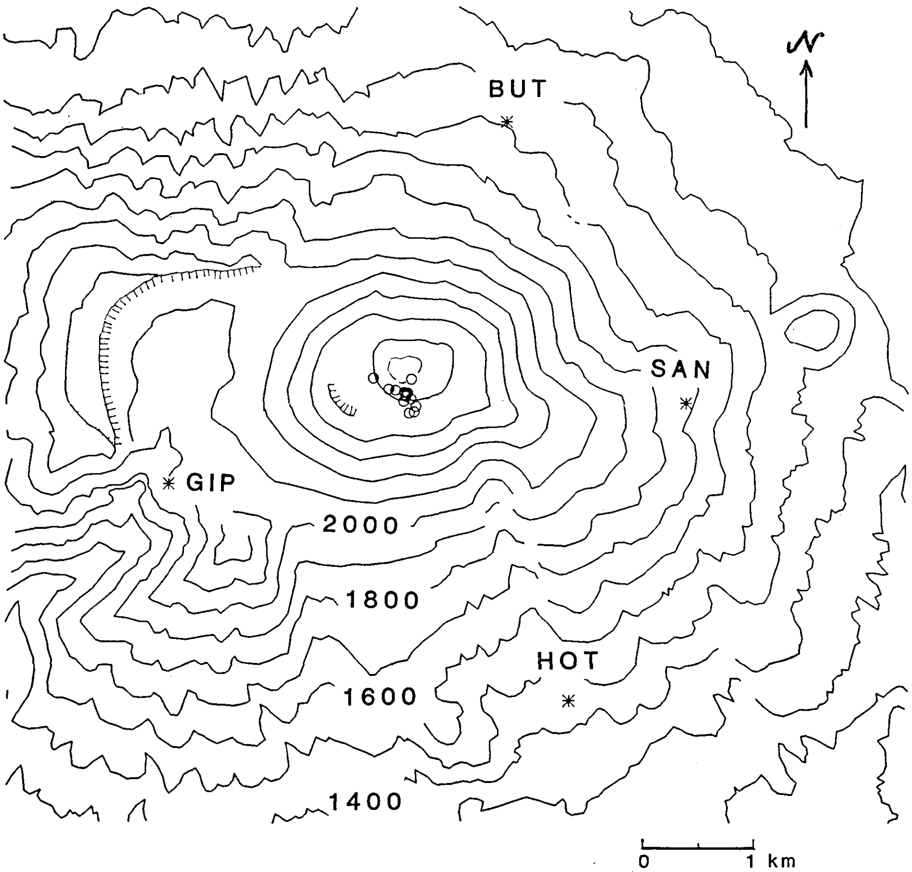


Fig. 2. Locations of seismic stations (*) and epicenters (open circles) of twelve implosion earthquakes. Numerals represent altitudes of contours in meters.

cal component (1 Hz), whereas those of SAN were of three components. There were other permanent stations of A.V.O. Their data, however, is not used in the present study because they were of the drum-recording system with a slow paper speed (1 mm/sec) which was virtually ruined by superposition of tremors and intermittent earthquakes.

Table 1. Location of seismic stations of A.V.O.

Station	Altitude (Height above sea level)	Horizontal distance from the crater
GIPpayama	2033 m	2380 m
SANnotorii	1825	2540
BUTai	1700*	2250*
HOTokeiwa	1462	3350

* Slight inaccuracy possible.

Table 2. P wave arrivals and initial motions of implosion earthquatkes that occurred at Asama Volcano in 1973.

No.	Month	Date			GIP		SAN			BUT		HOT		KUR	
		Day	Hour	Min.	Sec.	V*	Sec.	V*	HR**	Sec.	V*	Sec.	V*	PHR***	RHR***
1	Feb.	17	19	16	38.00	D	38.05	D	W	38.10	D	38.25	D	Pull	Pull
2			19	42	33.40	D	33.55	D	W	33.50	D	33.75	D	Pull	Pull
3			20	45	14.70	D	15.05	D	W	14.85	D	15.25	D	Pull	Pull
4			21	23	32.30	D	32.40	D	W	32.35	D	32.60	D	Pnll	Pull
5			22	46	58.80	D	58.85	D	W	58.75	D	59.15	D	Pull	Pull
6			23	00	10.40	D	10.55	D	W	10.55	D	10.75	D	Pull	Pull
7			23	45	14.60	D	14.85	D	W	14.80	D	15.10	D	Pull	Pull
8			23	50	04.50	D	04.55	D	W	04.65	D	04.75	D	Pull	Pull
9	Feb.	18	00	04	58.50	D	58.60	D	W	58.55	D	58.80	D	Pull	Pull
10			02	45	26.65	D	26.75	D	W	26.80	D	26.90	D	Pull	Pull
11			03	54	58.30	D	58.35	D	W	58.35	D	58.55	D	—	Pull
12			04	44	18.55	D	18.75	D	W	18.65	D	18.95	D	Pull	Pull

V*, HR** and PHR*** represent the direction of P-wave initial motion in vertical, E-W and radial components respectively.
D: downward; W: westward.
KUR is one of the permanent stations of A.V.O.

Even in the seismograms which are studied here, a large number of earthquakes were inevitably overlapped by tremors and the preceding quakes. There were twelve good recordings of implosion earthquakes and their seismic magnitudes range from 1.0 to 1.6 (IMAI, 1982). Table 2 lists their P wave arrival times and directions of their initial motions. Errors in onset time of P wave are considered to be within 0.05 sec. S wave arrivals are difficult to identify at any station and at any time during the course of successive eruptions.

3. Method of Analysis and Its Result

Basically, if we have four data on P wave arrival times for an earthquake and a P wave velocity structure is assumd, the hypocenter can be determined because the number of unknowns is four. As mentioned in the previous section, however, good seismic data is available from only four stations located nearly equally distant from the summit crater. IMAI (1982) suggested that implosion earthquakes occur just under the summit crater, for instance, within the volcanic conduit. Therefore, considering the geometry of the network, it is not thought possible to determine the depth range of the earthquakes. Even if their depths were obtained by using a usual hypocentral determination by a computer program, the solutions would be unstable and vary greatly from a slight erroneous reading of an onset time at a station, and it might be said that the values are unreliable.

In this paper, first, the epicenters of the earthquakes are determined by assuming a constant P wave velocity of 2.0 km/sec and using the onset time differences between the stations. As shown in Fig. 2, the epicenters (open circles) cluster within a small area close to the southern

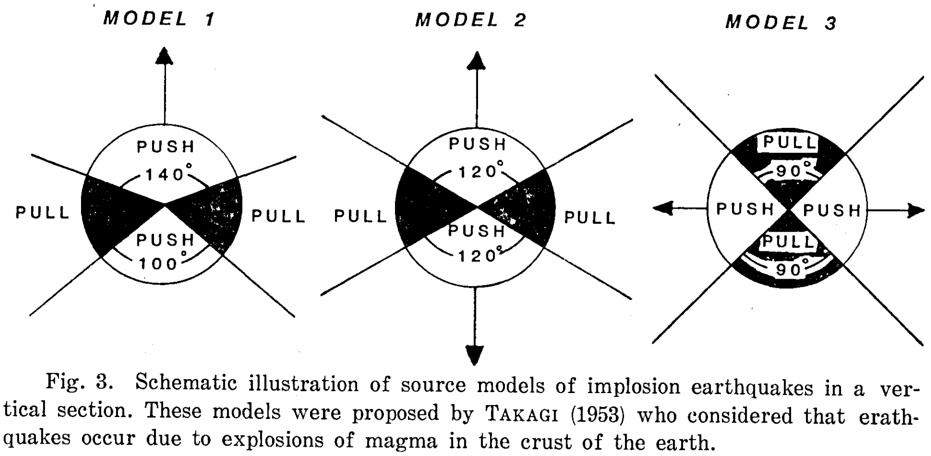


Fig. 3. Schematic illustration of source models of implosion earthquakes in a vertical section. These models were proposed by TAKAGI (1953) who considered that erathquakes occur due to explosions of magma in the crust of the earth.

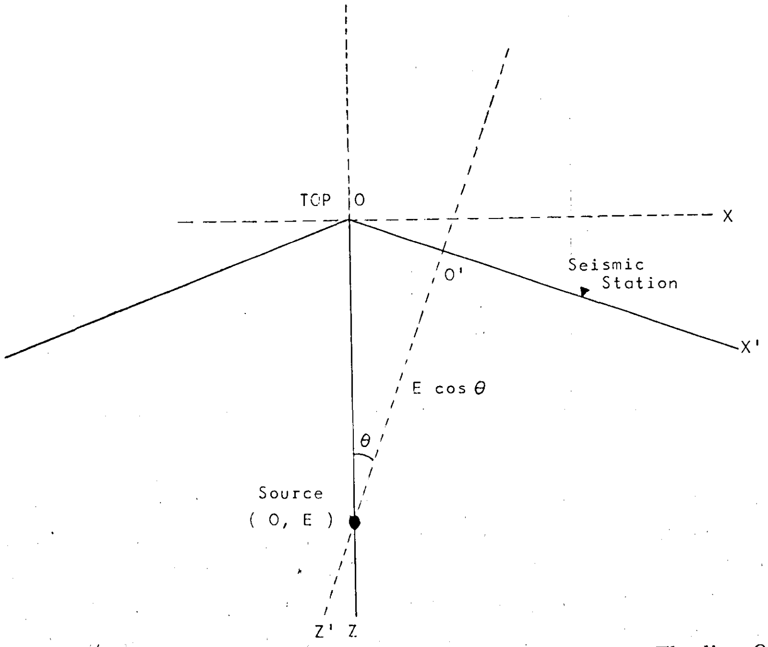


Fig. 4. Explanation of the coordinate system of $X'O'Z'$. The line $OO'X'$ represents a flank line of the volcano where a seismic station is located. When a source is situated at the depth E, the inward distance is taken as $E\cos\theta$.

rim of the summit crater. The small size of the epicentral region is consistent with the fact that waveforms of these earthquakes were similar to each other (IMAI, 1982). The errors in locations are, roughly speaking, about 300 m for each quake.

After the epicenters were determined, we next try to estimate the source depth range, based on the method by TANAKA (1971). If we can assume a focal mechanism of the earthquakes, then the downward initial motions at the four seismic stations will constrain the source depths. As for mechanical models of implosion earthquakes, the three alternate models proposed by TAKGAI (1953) are first considered as shown in Fig. 3. TAKAGI (1953) thought that magma chambers exist in the crust and that earthquakes occurred as a result of explosion of magma in the chambers. The arrows in Models 1 and 2 in Fig. 3 show the points and the directions of forces acting on the wall of a magma chamber or a dyke intruded from depth when the magma explodes inside of it. In Model 3, forces act circularly on the wall of a cylinder like a volcanic conduit.

The P wave velocity at a depth Z is assumed as follows;

$$V_P = 2.0 + 0.76\,Z'. \qquad (1)$$

The depth Z' is $Z\cos\theta$ which is an inward distance from the flank line

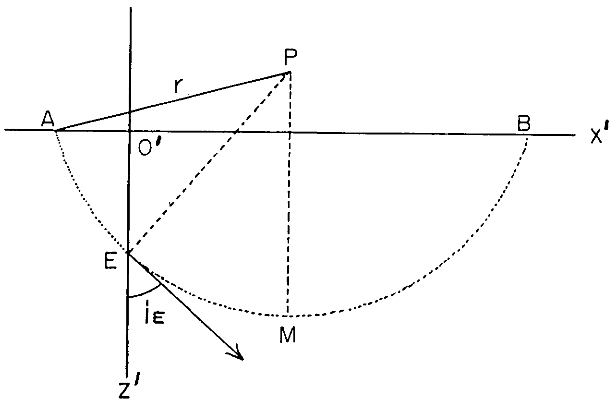


Fig. 5. An example of a ray-path depicted by using the ray-tracing method.

($O'X'$ in Fig. 4 or Fig. 5) at a respective station. Thus, a structure parallel to the flank line of the volcano is assumed, considering the shallow geological structure of a strato-volcano like Asama Volcano. The P wave velocity at the surface is assumed to be 2.0 km/sec, which is nearly consistent with the velocity at the uppermost part of the volcano, 1.9 km/sec, proposed by MINAKAMI *et al.* (1970b).

According to the above assumptions and an emission angle i_E at the depth E of an origin, the geometry of a ray path can be determined as a part of a circle for each set of data as shown in Fig. 5. The method is applied to our sets of data. As shown in Fig. 6, for example, the upper and lower limits of the depth range of a source to explain the downward initial motion can be obtained for the HOT seismic station. The results as to E_s and E_d for Models 1 and 2 are shown in Table 3. As for Model 3, the depth ranges helpful for the interpretation of our seismic data are not obtained.

The above investigations are based on the source models proposed by TAKAGI (1953). However, Model 4, illustrated in Fig. 7, may be preferable for implosion earthquakes. In this model, a force acts only downward just the opposite of Model 1. Such a force system is preliminarily proposed, based on the assumption that implosion earthquakes are caused by the down film flow in a process of a large bubble ascending in magma through a volcanic conduit followed by a gravitational inner collapse (IMAI, 1982). The results concerned with Model 4 are also shown in Table 3. The higher the model number, the more likely the deeper the depth range. Judging from the nodal line of each model, this feature is reasonable. Thus, the results depend on the adopted model. However, the values are constrained by the travel time study.

Here we should check the depth ranges obtained adove by calculating

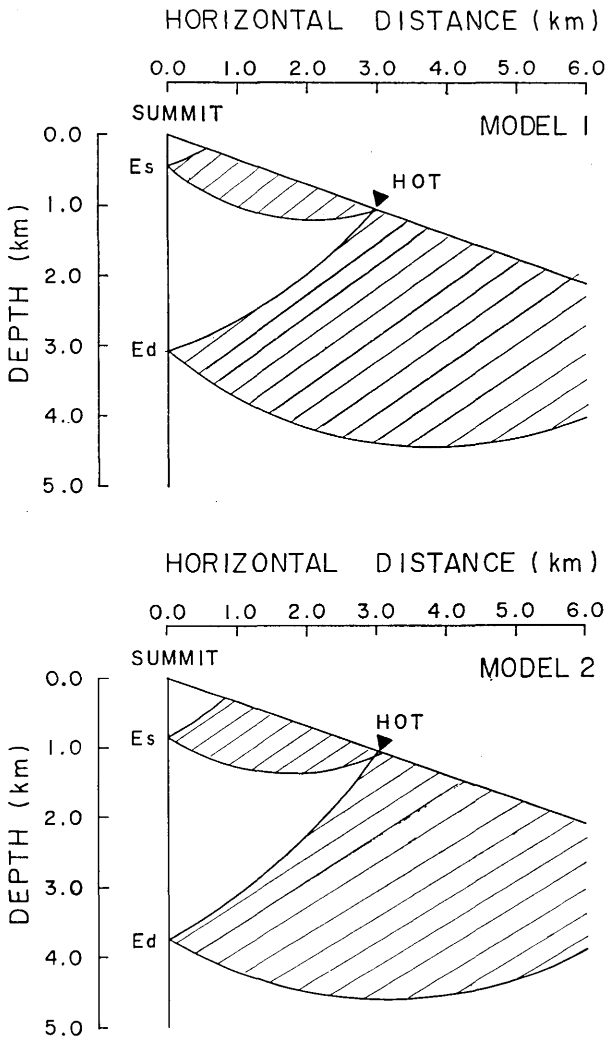


Fig. 6. An example of determining the source depth range of an implosion earthquake for a station. The hatched areas show the areas where the direction of P wave initial motion will be downward. E_s and E_d are the upper and lower limits of the source depth which explains the downward initial motion of P wave at HOT.

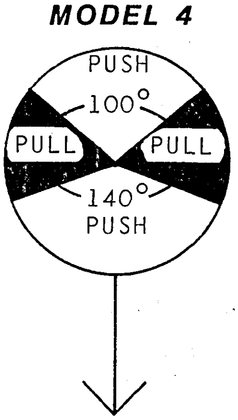
the travel times from origins to seismic stations whether or not the onset time differences between two of the stations can be roughly interpreted by the results. If we know an emission angle i_E at an origin and have a P wave velocity structure as given by Eq. (1), we can calculate the travel time T from the origin to a seismic station as follows;

$$T^{(\pm)}=k^{-1}\left\{\cosh^{-1}\left(\frac{V_M}{V_O}\right)\pm\cosh^{-1}\left(\frac{V_M}{V_E}\right)\right\}, \quad (2)$$

where,

$$V_E=V_O+kE, \quad (3)$$

$$V_M=V_E \operatorname{cosec} i_E. \quad (4)$$



Fig, 7. Schematic illustration of an additional source model of implosion earthquakes. The arrow indicates the force direction.

V_O, V_E and V_M are the P wave velocity at the surface, the source depth E, and the deepest point of the seismic ray for coordinate system $X'O'Z'$ (see Fig. 5), respectively. k is a constant taken as 0.76 in this paper as used in Eq. (1), and the sign $+/-$ corresponds to i_E being less or more than 90°, respectively (see Fig. 5).

Figure 8 shows an example of our method for determining the source depth range of an implosion earthquake. For example, the plotted data of SAN_{O-C} is obtained as follows. First, the travel time is calculated from the origin depth to the seismic station SAN using Eqs. (2)–(4). Let us call the result SAN_C. Next, using the same depth, the travel time corresponding to the seismic station GIP is calculated and the result is called T_{GIP}. Then, SAN_O is defined as T_{GIP} plus the onset time difference between the observational data from GIP and SAN for the corresponding earthquake. SAN_{O-C}, thus, is obtained as SAN_O minus SAN_C. The data from GIP, therefore, is treated as the standard and from the point of view the ordinate is captioned $T-T_{GIP}$. Such a procedure is carried out for various depths just under the epicenter of the earthquake. The line of SAN_{O-C} is drawn by the above method, which is similarly applied to the data of BUT and HOT. Ideally speaking, the depth of the earthquake should be determined by the consideration that $T-T_{GIP}$ should be zero for each set of data at the same time. However, considering the error in reading onset time and the uncertainty of seismic velocity structure under the volcano, the values are determined under the condition that all the O–C data is within ±0.05 sec. The results are listed in Table 3. When we consider the results of the travel time study as the most important, a thought of which seems valid, we can

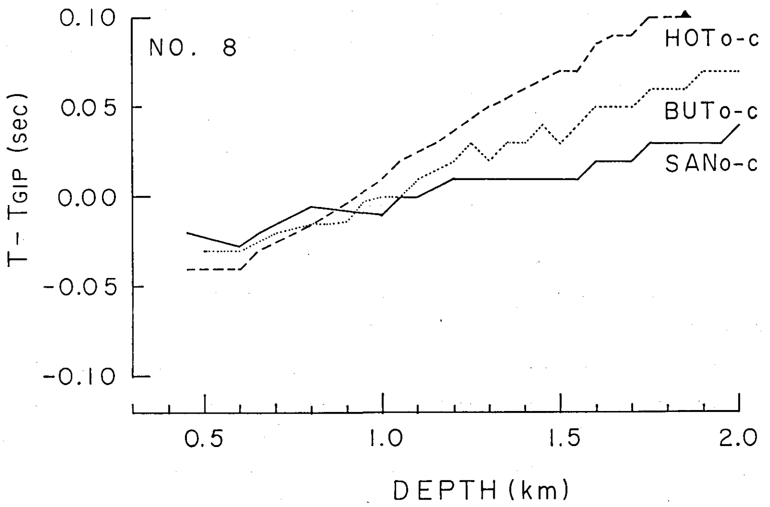


Fig. 8. An example of determining the source depth range of an implosion earthquake due to a comparison of the calulated onset times at HOT and SAN relative to those at GIP. In this case, the depth range is determined to be 0.5 to 1.3 km from the top of the volcano if the O-C data for three stations is within ± 0.05 sec.

determine the source depth ranging roughly from 0.5 to 1.5 km in Model 1, 0.9 to 1.5 km in Model 2 and 1.3 to 1.5 km in Model 4, respectively.

Such depth ranges appear to be similar to those of the explosion earthquakes associated with the 1973 eruptions of the volcano, determin-

Table 3. Source depth range of implosion earthquakes obtained by the model studies and the travel time studies

No.	Model 1 E_s E_d	Model 2 E_s E_d	Model 4 E_s E_d	Travel Time Study
1	0.45—2.10 km	0.85—2.65 km	1.25—3.40 km	0.65—1.30 km
2	0.45—2.05	0.90—2.60	1.35—3.30	0.50—1.00
3	0.50—1.85	0.95—2.35	1.40—2.95	[0.80]*
4	0.45—2.05	0.90—2.60	1.30—3.30	1.10—1.50
5	0.50—2.15	0.90—2.75	1.35—3.45	[1.00]
6	0.45—2.00	0.85—2.55	1.30—3.25	0.55—1.40
7	0.50—1.90	0.90—2.45	1.35—3.10	0.65—0.70
8	0.45—2.05	0.85—2.60	1.25—3.35	0.50—1.30
9	0.45—2.05	0.90—2.60	1.30—3.35	0.90—1.45
10	0.45—2.05	0.85—2.55	1.25—3.25	0.65—1.45
11	0.45—2.10	0.85—2.65	1.25—3.35	1.05—1.55
12	0.50—1.95	0.90—2.50	1.35—3.15	0.75—1.10

*[ ]: The value includes much uncertainty.

ed by IMAI (1980). Therefore, the earthquakes associated with the volcanic eruptions, including both explosion and implosion earthquakes, might have occurred at a similar depth range limited to the area below the summit crater of the volcano.

4. Conclusion

The source depth ranges of implosion earthquakes associated with successive eruptions have been estimated. Taking into account some of the uncertainties included in our procedures and also judging from the results relative to waveform similarity proposed by IMAI (1982), we can conclude that implosion earthquakes occurred roughly in the range of 0.5 to 1.5 km just below the summit crater of the volcano, although the values strongly depend on the mechanism used for interpretation of initial motions. The results should be important in understanding the manner and cause of successive eruptions. Although many models could be considered for successive eruptions and the corresponding implosion earthquakes, just which model is best suited for them will be a matter of controversy in the future.

Acknowledgement

The author would like to express his sincere thanks to Prof. D. SHIMOZURU for his critical review of this manuscript and for his uncountable suggestions made available for this study.

References

IMAI, H., 1980, Explosion earthquakes associated with the 1973 eruptions of Asama Volcano. (part II) The summary of studies on explosion earthquakes and a model of explosive eruptions inferred from seismic data, *Bull. Earthq. Res. Inst.*, **55**, 537-576.

IMAI, H., 1982, A mechanism of successive eruption as inferred from seismic data associated with the 1973 eruptive stage of Asama Volcano, *Arc Volcnism —Physics and Tectonics—, Advances in Earth and Planetary Sciences* (Ed. D. SHIMOZURU and I. YOKOYAMA), in press.

MINAKAMI, T., S. UTIBORI, S. HIRAGA, T. MIYAZAKI, N. GYODA, and T. UTSUNOMIYA, 1970a, Seismometrical studies of Volcano Asama (Part 1). Seismic and volconic activities of Asama during 1934-1969, *Bull. Earthq. Res. Inst.*, **48**, 235-301.

MINAKAMI, T., S. UTIBORI, T. MIYAZAKI, S. HIRAGA, H. TERAO and K. HIRAI, 1970b, Seismometrical studies of Volcano Asama (Part 2). Anomalous distribution of the P arrival times and some information of the velocity of the P wave propagating through the Volcano, *Bull. Earthq. Res. Inst.*, **48**, 431-489.

SHIMOZURU, D., S. UTIBORI, N. GYODA, E. KOYAMA, T. MIYAZAKI, T. MATSUMOTO, N. OSADA and H. TERAO, 1975, The 1973 eruptive activity of Asama Volcano. General description of volcanic and seismic events, *Bull. Earthq. Res. Inst.*, **50**, 115-151.

SHIMOZURU, D., 1979, An eruptive mechanism inferred from volcanic earthquakes of Asama Volcano (abstr.), in *abstracts and timetable of IUGG*, Canberra, Australia.

TANAKA, Y., 1971, The mechanism of the explosion earthquakes, *Bull. Volcanol. Soc. Japan*, **16**, 153-161.

TAKAGI, S., 1953, On the origin of earthquake (the fourth paper)—On the case of a periodic force—, *Quarterly J. Seismol.* (*JMA*), **17**, 1-30.

---

15. 1973年浅間火山断続的微噴火に伴う"内裂"地震

地震研究所　今　井　　博

1973年浅間火山噴火活動に際し，比較的小規模な断続的噴火が同年2月16日から同月18日にかけて多発した．個々の微噴火に対応して地震が発生し記録された．殆どの地震はその初動が微動あるいはその地震の前に発生した地震の尾部と重なり判別が困難であった．しかし，火口を取り巻く4観測点での早送り記録において，初動方向が判別可能であり，しかも，上下成分の初動が全て引方向を示す記象が12個認められた．この12個の地震は水平動のデータにおいても引き波で始まると認られる地震で，爆発地震 (Explosion earthquake) に対して"内裂地震 (Implosion earthquake)"とも言うべき地震である．4観測点は火口を中心にほぼ円形に配置されており従来の方法では震源の深さを決定するには不都合であると思われる．本報文では，まず等走時残差曲線により震央を求め，いくつかの地震発生のメカニズムを用いて震源がいかなる深さの範囲にあれば初動方向や走時残差の観測事実が説明できるかを検討した．その結果，震央は火口付近に集中し，山頂を海抜 2500 m と仮定して，震源が山頂から 0.5～1.5 km の範囲にあれば観測データがおおむね説明できる事が判った．この結果は，噴火地震 (噴火に伴う地震) が火道内部で発生しているという考えを強く指示するものである．
