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Mapping of a Melting Zone near Mt. Nikko-Shirane in Northern Kano, Japan, as Inferred from SxP and SxS Reflections

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Abstract: A temporary microearthquake observation with six telemetering stations has been carried out in the earthquake swarm area near Ashio, Tochigi Prefecture, central Japan. Two sharp phases following the direct S wave are frequently observed from the events in this area. Apparent velocity and azimuth of wave approach for these phases suggest that these phases are S to P wave (SxP) and S to S wave (SxS) reflections from an unusual discontinuity. With assuming the discontinuity to be a single flat plane, location of the discontinuity is determined by the use of all available arrival time data of the SxP and the SxS in combination with hypocenter coordinates, which are precisely located by the telemetering network. The estimated location of the discontinuity is in an area southeast of Mt. Nikko-Shirane, which is an active Quaternary volcano. The discontinuity is inclined with a dip angle of 45 degrees and it becomes shallower toward the volcano. An extension of the discontinuity becomes 4 km below the sea level beneath the top of the volcano, suggesting that the SxP and SxS phases are reflected at an upper surface of a magma body related with Mt. Nikko-Shirane, whose recent eruptions occurred in 1872, 1873, 1889, and 1952.

1. Introduction

Seismic activity in Ashio area, located at the western part of Tochigi Prefecture in the northern Kanto District, is very high as has been found by temporary seismic observations carried out in this area (Kaminuma *et al.*, 1970; Suzuki and Kameyama, 1972; Ogino, 1974; Kameyama *et al.*, 1976, 1979; Mizoue *et al.*, 1980; Ito, 1985; Ito *et al.*, 1981). In the vicinity of this high seismic area the volcanic front is running in the NE-SW direction, and active volocano (Mt. Nikko-Shirane) and Quaternary volcanoes (Mt. Nantai, Mt, Sukai and Mt. Nyoho-Akanagi) are distributed around the area.

Ogino (1974), based on microearthquake observation with a local tripartite network in this area, found that two sharp arrivals, followed the S wave by 2.5 to 3.0 sec and 4.5 to 5.0 sec respectively, were frequently observed from the nearby earthquakes with S minus P times less than 1.5 sec. Mizoue (1980) pointed out that these later phases were near vertical S to P wave (SxP) and S to S wave (SxS) reflections from a zone of very low rigidity, such as a magma body, at a depth of about 14 to 17 km. Similar reflection phases were observed in the aftershock observation of the 1984 Western Nagano

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Prefecture Earthquake (Mizoue *et al.*, 1985) and in the reflection surveys of the VI-BROSEIS profiling in the Rio Grande rift near Soccorro (Oliver and Kaufman, 1976 ; Schilt *et al.*, 1979 ; Brown *et al.*, 1980). Recently Mizoue *et al.* (1982) set up a temporary observation network with four telemetering statios and they have mapped depths to the reflector by using travel times of the SxS wave. Assuming the reflector to be horizontal in the calculation of ray paths, they concluded that the reflector lies beneath an area of about 10×10 km^2 where many earthquakes have been occurring in swarms. Their calculated result showed that the discontinuity was dipping with a large angle of 25 to 30 degrees, though the discontinuity was assumed to be horizontal.

In this paper, an extensive study about the location of the zone with very low rigidity is made by analyzing data obtained from a temporary seismic observation.

2. Temporary Microearthquake Observation

A temporary microearthquake observation was carried out in the Ashio area for the period from August 12 to 31 in 1984. As shown in Fig. 1, six telemetering stations have been set up in an area of about 10 km in the NE-SW direction and 7 km in the NW-SE direction. Vertical seismometers with natural frequency of 1 Hz were installed at all stations except at BAR station, where 2.2 Hz seismometer was used. In addition to 1 Hz

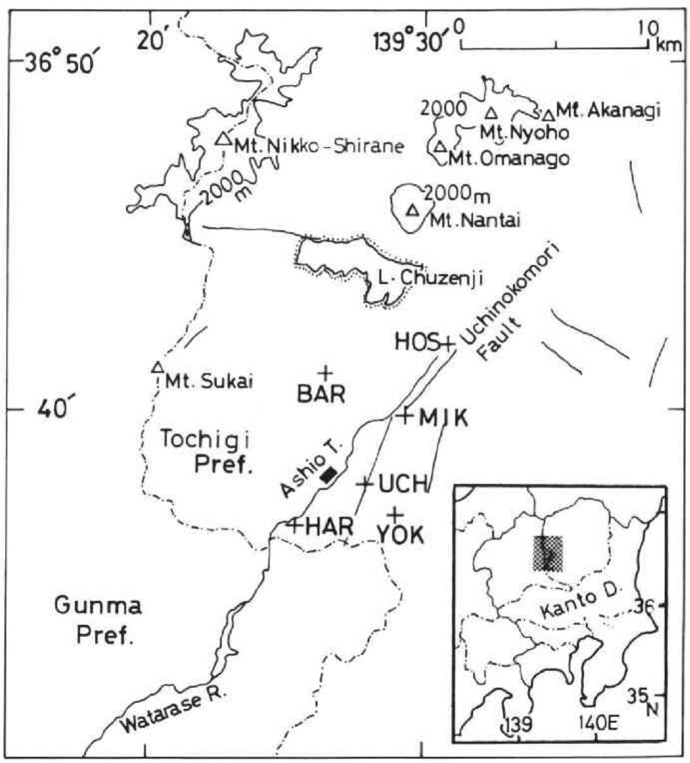

Fig. 1. Location of a temporary seismic network with 6 telemetering stations (crosses) in the area near Ashio, the northern Kanto District.

vertical seismometer, three component seismometers with natural frequency of 4.5 Hz were set up at Uchinokomori station (UCH). A personal computer (IF-800 model 20) with A/D converters was also used at UCH station to record seismograms from the 4.5 Hz seismometers. Seismic signals from the 6 telemetering stations were recorded by the use of a 13-channel magnetic tape recorder. A thermal writing rectigraph with chart speed of 1 mm/s was also used to monitor seismic events.

The reproduction of the seismic records stored in magnetic tape was made as follows. First, approximate times of P arrivals for events occurring in the Ashio area were measured with an accuracy of a few seconds by using the monitor records. Next, the arrival time data thus obtained were fed to a personal computer, which automatically played back the magnetic tape recorder and record the reproduced signals on a 16-channel thermal writing rectigraph in accordance with this arrival time table. Twenty seconds of seismograms were reproduced with a high chart speed of 50 mm/s in order to measure precise arrival times of the P and S phases. Seismograms were also reproduced with a chart speed of 10 mm/s for the measurement and identification of the reflection phases.

Hypocenters of 308 events occurring in the Ashio area have been located by the present observation in the period of only 20 days. Epicenter distribution is shown in Fig.

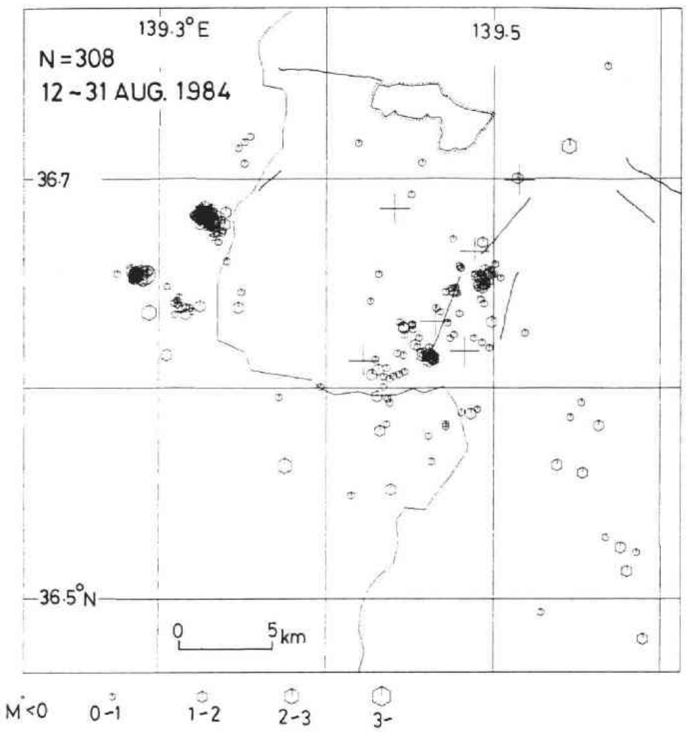

Fig. 2. Epicenter distribution of microearthquakes near Ashio located by the temporary observation network. Active faults are indicated by solid lines. Locations of temporary stations are shown by crosses.

2. Three clusters of epicenters are found in an area near the border of Tochigi and Gunma Prefectures.

3. Characteristic features of SxP and SxS phases

An example of vertical component of seismograms for a event occurring in the Ashio area is shown in Fig. 3. Two phases following the direct S waves by about 3.0 sec and 5.0 sec are clearly recorded at all the six stations. Mizoue *et al.* (1982) pointed out that these later arrivals are near vertical S to P wave (SxP) and S to S wave (SxS) reflections from an unusual velocity discontinuity in the crust. Considering thc amplitude ratio of the SxP and SxS phases, they suggested that the discontinuity is underlain by a material of very low rigidity, which may be an extensive magma body.

Epicenters for events which have at least one clear observation of the reflection phases are plotted in Fig. 4. Almost all events occurring in an area enclosed by the dotted line have observations of the SxP and/or SxS, although they are not always clear. Many earthquakes occurred in an area near the border of Tochigi and Gunma Prefectures as shown in Fig. 2. However only a few events have the observations of the reflection phases. The SxS phase is observed only at Yokoneyama station (YOK) for

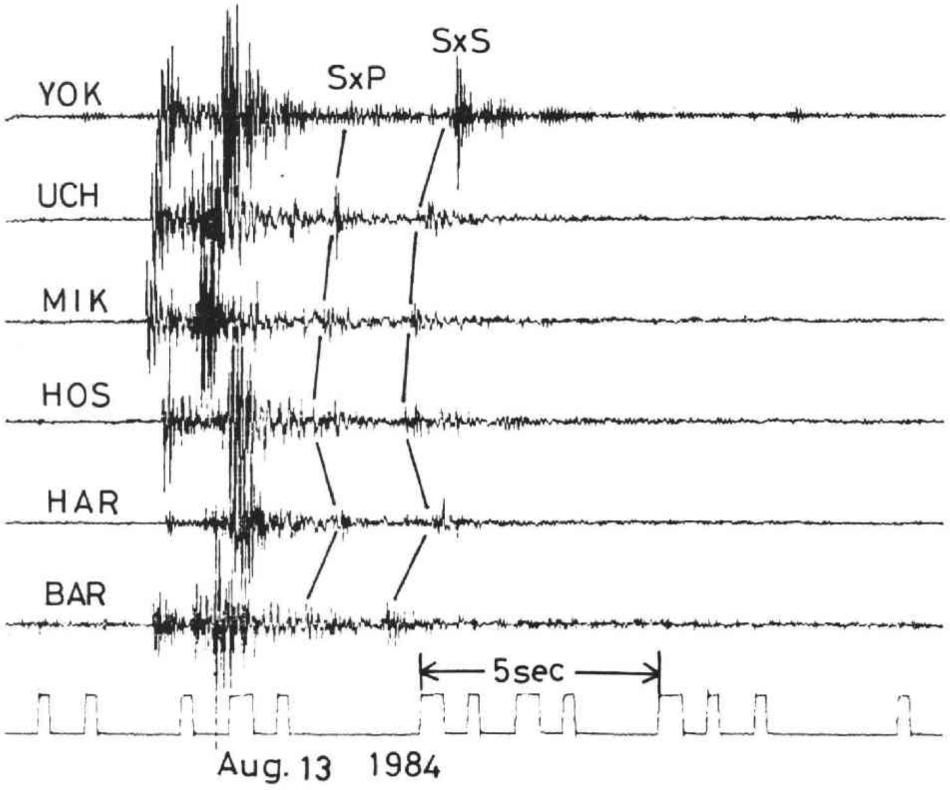

Fig. 3. An example of seismograms for an event occurring near Ashio. The reflection phases are indicated with designations of SxP and SxS.

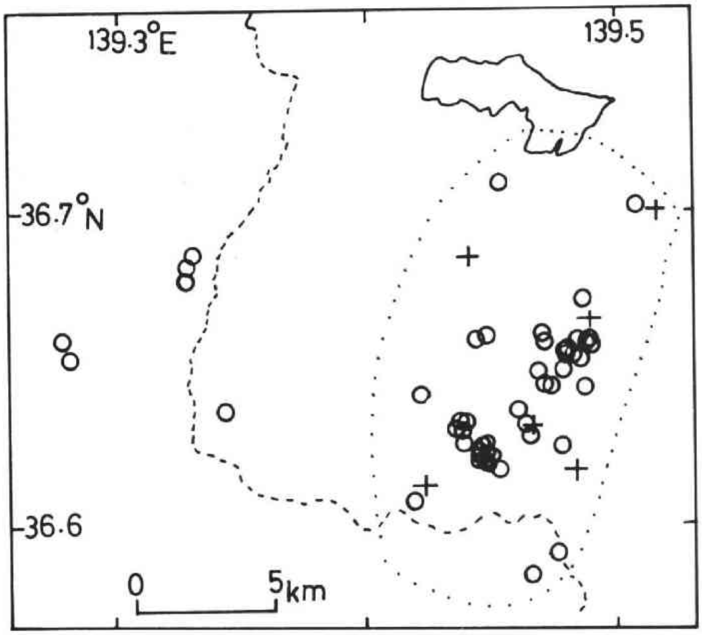

Fig. 4. Plots of epicenter locations for events whose reflection phases are observed. Arrival time data from events enclosed by the dot line are used in the location of the unusual discontinuity.

events occurring near the border.

Assuming these later phases to be plane waves, the apparent velocity and the azimuth of wave approach are determined for events from which the reflected phases are observed at more than two stations. As shown in Fig. 5, most of the obtained apparent velocities for the SxP are larger than 6 km/s, which is considered to be a standard value

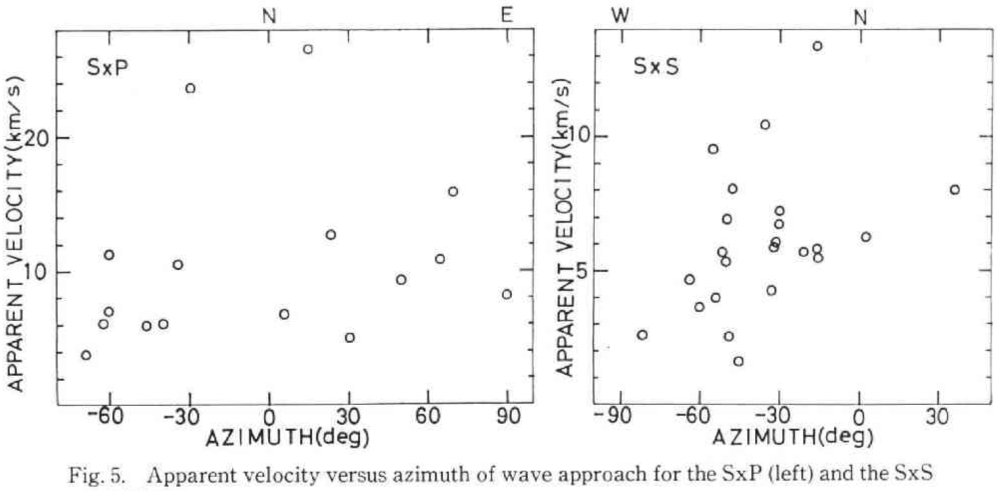

Fig. 5. Apparent velocity versus azimuth of wave approach for the SxP (left) and the SxS (right).

of the P wave velocity in the granitic layer. On the contrary, about 50% of the obtained apparent velocities for the SxS are less than 6 km/s. This feature is consistent with our interpretation that the two later phases are the SxP and SxS reflections, respectively. Mizoue *et al.* (1982) got the same conclusion by plotting the particle motion of the reflection phases.

Most of the obtained apparent velocities of the SxS are in a range from 5 to 7 km/s. The range of incident angles corresponding to this velocity range is from 30 to 45 degrees, if S wave velocity is assigned to be 3.4 km/s. Values of the azimuth of the wave approach for the SxS show that most of the SxS are propagated from northwest. Therefore it is concluded that the discontinuity is distributed beneath an area northwest of the temporary network and the discontinuity is dipping toward southeast with a large dip angle of about 30 to 45 degrees.

4. Location of Reflector

As clear from the ray paths of the SxS schematically shown in Fig. 6, the travel time of the SxS is equal to that of the S wave propagating along a straight line connecting a receiver to an image source, which stands at a symmetry point of the hypocenter location with respect to the reflector. Consequently, locations of image sources can be determined by the calculation of hypocenter location program using only arrival time data of the SxS. The location of the reflector is obtained from a line connecting an image source to its real source. Since the origin time for each event can be determined by arrival times of P and S waves, it is not neccessary to determine the origin time in the location of image sources.

Calculated epicenter locations for image sources together with those for real sources are plotted in Fig. 7. Locations of the image sources are determined for events whose arrival time data of the SxS are three or more. The S wave velocity is assumed to be

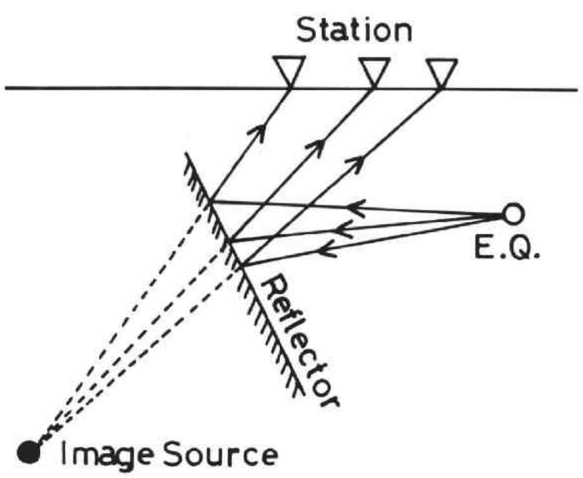

Fig. 6. Geometry of real source (E.Q.), image source and reflector.

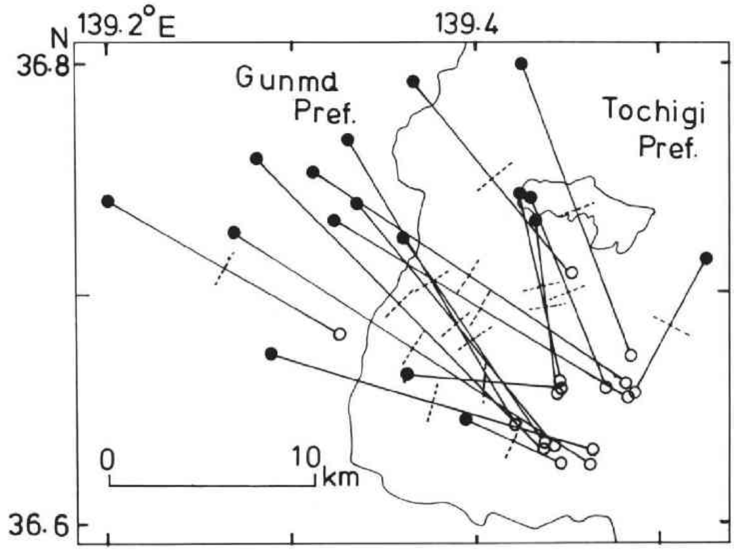

Fig. 7. Locations of real sources (open circle) and image sources (solid circle). Dotted lines perpendicular to solid lines, connecting real sources to their image sources, indicate reflectors.

3.4 km/s. Most of image sources are located on the northwest side of their real sources. Dip directions of the reflector are known from straight lines connecting image sources to their real sources. Locations of image sources and real sources are plotted on the

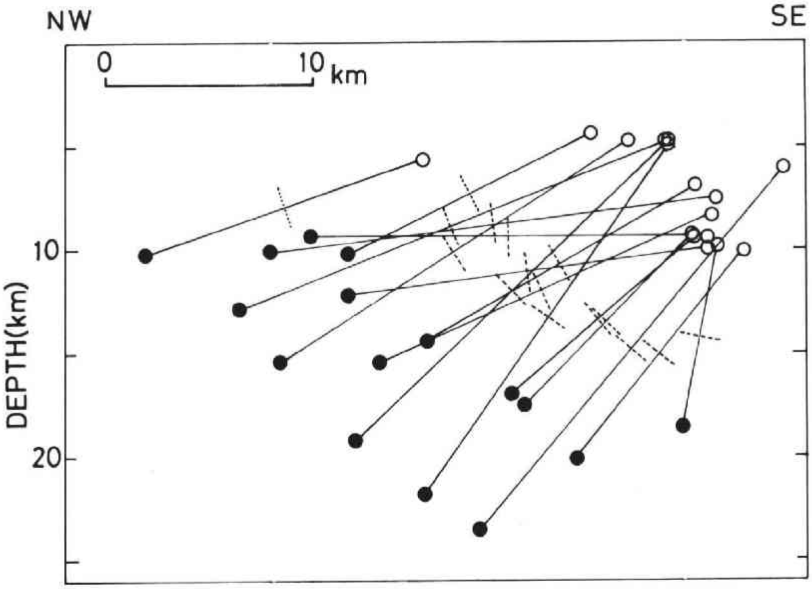

Fig. 8. Plots of real sources (open circle) and image sources (solid circle) on the vertical cross section in the northwest-southeast direction. Dotted lines perpendicular to solid lines indicate reflectors.

vertical cross section in the northwest-southeast direction (Fig. 8). Since most of image sources are located on the northwest side of their real sources, approximate dip angles of the reflector are given by dotted lines perpendicular to solid lines which connect image sources to their real sources. An averege value of the dip angle of the reflector becomes about 45 degrees.

It is noticed that there are considerably large errors in the location of image sources. This is partly due to a lack of stations where clear SxS phases are recorded, and partly to that image sources are in an area outside the temporary seismic network. Considering errors in the location of image sources, it is possible to insist that locations of the reflector, shown by the dotted lines in Fig, 8, coinside with each other.

Next, using all arrival time data of the SxS, location of the reflector is estimated under an assumption that all SxS phases are reflected at a single flat plane. A method of determining location of this flat plane is as follows. At first, initial values of the dip angle and the dip direction of the flat plane are arbitrarily assumed. Then, the depth of the flat plane and the location of a reflection point for each observed SxS phase are calculated so that arrival time minus origin time becomes travel time of the S wave along a path connecting the source, this reflection point and the corresponding station. Travel times of the SxS are calculated exactly by taking into account the dip direction and dip angle of the reflector. Because initial values of the dip angle and dip derection of the reflector are arbitrarily assumed, distribution of reflection points may not agree with initially assumed inclination of the reflector. Next, values of the depth, the dip angle and the dip direction of the flat plane are determined from the distribution of

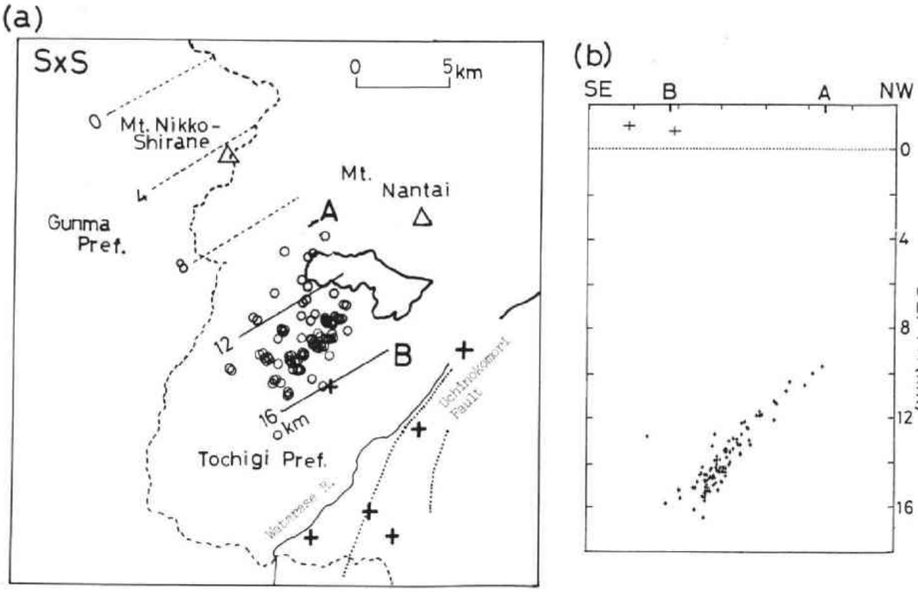

Fig. 9. Depth distribution of the reflector (left) and plots of reflection points on a vertical cross section perpendicular to the reflector (right). Circles in the left figure show locations of reflection points. Arrival times of the SxS only are used.

reflection points so that the following equation becomes minimum.

$$\rho^2 = \sum_i d_i^2 \tag{1}$$

where d_i is a distance from the flat plane to i-th reflection point. By using values of the dip angle and the dip direction in this solution, the location of a reflection point corresponding to each observed SxS is calculated again in a similar way. This procedure is repeated till a convergent solution is obtained. An initial value of the dip angle is set to be zero. A convergent solution is obtained after five times of iterations.

Calculated locations of the reflection points and the reflector are shown in Figs. 9(a) and (b). Arrival time data of the SxS from events enclosed by the dotted lines in Fig. 4 are used for this calculation. Total number of arrival time data is 111. Obtained values of the dip direction and the dip angle are S45E and 40 degrees, respectively. It is clear from a distribution of reflection points projected on a vertical cross section perpendicular to the reflector (Fig. 9(b)) that reflection points lie almost in a single flat plane. The location of the reflector thus determined is consistent with that obtained by the use of arrival times of reflected waves from individual events, as shown in Figs. 5, 7, and 8, but is different from that by Mizoue *et al.* (1982) who have mapped the depth of

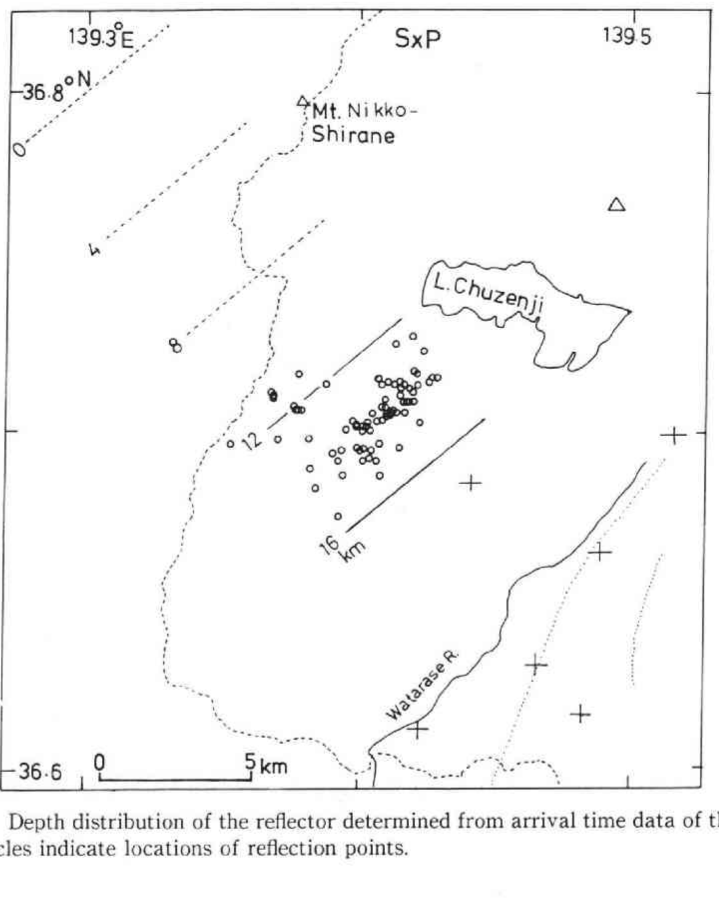

Fig. 10 Depth distribution of the reflector determined from arrival time data of the SxP. Circles indicate locations of reflection points.

the discontinuity under an assumption that the reflector is horizontal in the calculation of theoretical travel times.

An extension of the estimated reflector intersects to the earth's surface at northwest of Mt. Nikko- Shirane, which is an active Quaternary volcano. Depth of the reflector beneath the top of Mt. Nikko- Shirane is 4 km below the sea level. Mizoue *et al.* (1982) have pointed out that the reflector might be an upper surface of a zone of very low rigidity such as a magma body. The present result suggests that this low rigidity zone is a magma body related to Mt. Nikko- Shirane.

The Location of the reflector is calculated again by using SxP arrival times only in order to confirm uniqueness of the solution. A simillar method mentioned above is used to determine the location of the reflector. Reflection points and the calculated depth of the reflector are shown in Fig. 10. Total number of arrival time data used is 81. Calculated values of the dip direction and the dip angle are S45E and 40 degrees, respectively. This result agrees well with that obtained from the SxS.

Final location of the reflector is determined by using arrival times of both the SxS and the SxP. Calculated result is shown in Fig. 11. Depth to the reflector beneath the

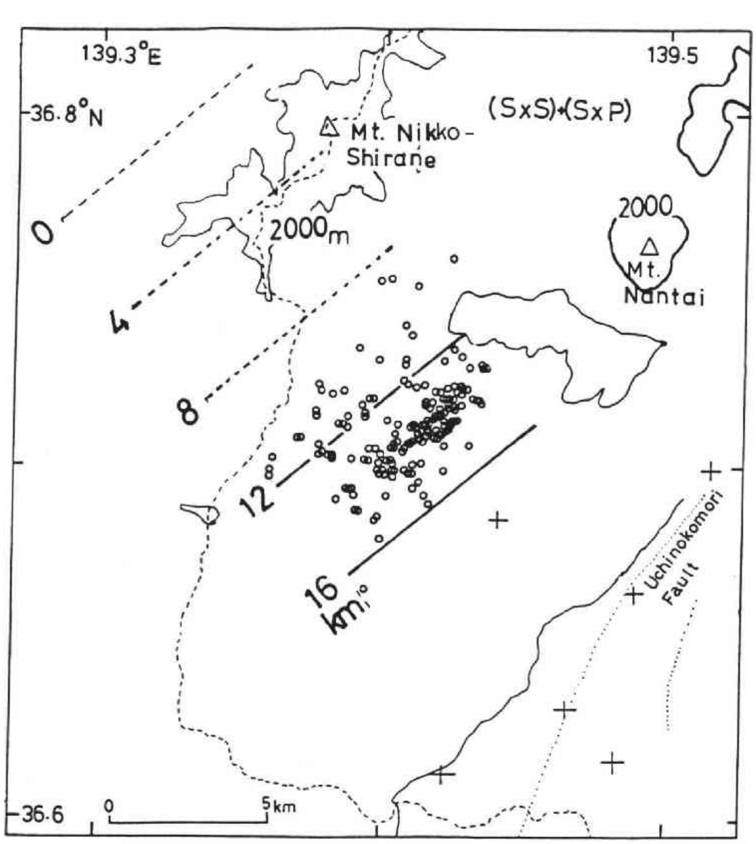

Fig. 11. Depth distribution of the reflector determined by using both the SxS and the SxP. Circles indicate locations of reflection points.

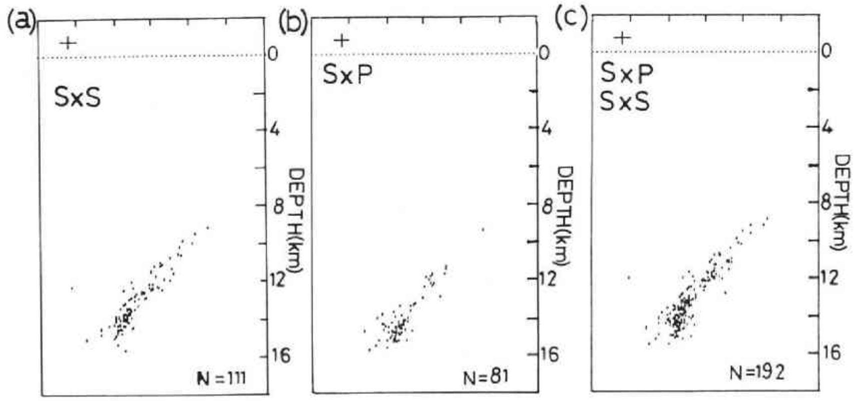

Fig. 12. Vertical cross sections of the reflection points determined by arrival time data of the SxS(a), the SxP(b), and both the SxP and the SxS(c).

top of Mt. Nikko- Shirane is about 4 km. Reflection points are distributed in an area of 6×10 km² southwest of Lake Chuzenji.

As mentioned above, three cases of the location of the reflector have been obtained. Reflection points for each case are projected on a vertical cross section perpendicular to the reflector (Fig. 12). These results agree well with each other.

5. Discussion and Conclusions

A temporary seismic network with six telemetering stations was set up in an area near Ashio in the northwestern part of Tochigi Prefecture, Kanto district. Two sharp phases following the direct S waves by 2.5-3.0 and 4.5-5.0 sec are frequently recorded at all stations from events occurring in the Ashio area. Mizoue *et al.* (1982) have demonstrated that these phases are S to P wave (SxP) and S to S wave (SxS) reflections from a reflector over a zone of very low rigidity such as a magma body. In this paper, an extensive study about the characteristic feature of the reflected waves and the location of the discontinuity were made by the use of arrival time data of the SxP and the SxS observed at the six telemetering stations in the Ashio area. The results are summarized as follows.

(1) Assuming the reflected wave to be plane wave, the apparent velocity and the azimuth of wave approach for the SxP and the SxS are obtained. Most of the estimated apparent velocities for the SxP are larger than the P wave velocity in the granitic layer of the crust. On the contrary, about 50% of the obtained apparent velocities for the SxS are less than the P wave velocity. This agrees with the interpretation that these two later phases are SxP and SxS reflections. Values of the azimuth of wave approach for the reflected phases show that they are propagated from the northwest.

(2) The location of the reflector is determined by using arrival times of the SxP and the SxS in combination with hypocenter coordinates, which are precisely located by the telemetering network. Reflection points are distributed in an area of 6×10 km² southwest of Lake Chuzenji with depths ranging from 9 km to 16 km. The discontinuity is

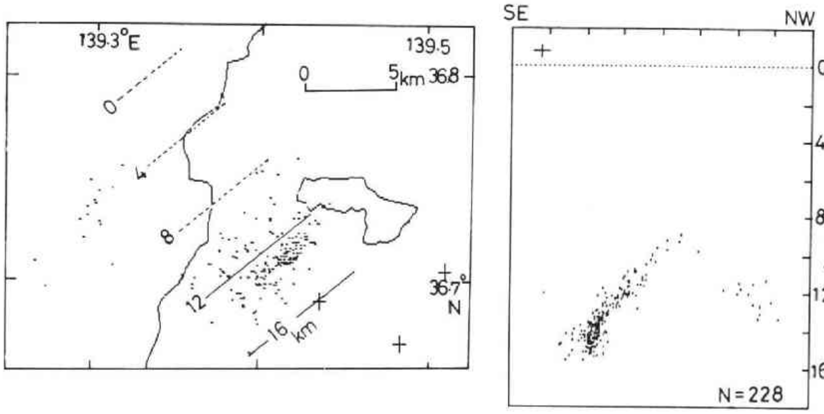

Fig. 13. Location map (left) and vertical cross section of reflection points (right) for the SxP and the SxS from events occurred near Ashio and near the border of Tochigi and Gunma Prefectures. The depth distribution of the reflector is the same as that in Fig. 11.

dipping with a large angle of about 45 degrees. The depth of the discontinuity becomes shallower toward northwest, where an active Quaternary volcano of Mt. Nikko-Shirane is located. An extension of the discontinuity becomes 4 km below the sea level beneath the top of Mt. Nikko-Shirane.

The location of the reflector obtained in the present study strongly suggests that the unusual discontinuity is the upper surface of a magma body related to volcanic activity of Mt. Nikko-Shirane, whose recent eruptions occurred in 1872, 1873, 1889 and 1952.

For locating the reflector only events occurred beneath an area near Ashio are used, as shown in Fig. 4. Although many events occurred in an area near the border of Tochigi and Gunma Prefectures, the number of events with the reflected phases is quite few. By using the values of the dip angle and the dip direction determined above, reflection points of the SxS from events occurring near the border are determined. As shown in Fig. 13, depths of reflection points of the SxS from these events are much deeper than those estimated from the extension of the reflector located above. This result shows that it is impossible to extend the flat reflector model to these data. Arrival time data of reflected phases from these events are not enough to determine the location and the inclination of the reflector. Further seismic observation in this area is necessary to determine the extent and the shape of this unusual discontinuity.

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