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10. *Numerical Estimation of Confidence Region of Fault-Plane Solutions.*

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A numerical method for determining fault-plane solutions and estimating confidence regions from P-wave first motion data was studied. Coverage of first motion data on the focal sphere influences fault-plane solution in the conventional methods, especially in graphical methods. There are sometimes inconsistent directions of first motion which are opposite to adjacent ones though located within common areas of most directions. In the new numerical method such inconsistent first motion data are discarded in an automatic and objective way, and the confidence regions of alternative solutions of the maximum pressure (P) and (T) with scores of 95% or greater are estimated.

The new method was applied to 358 earthquakes which occurred in and around the Kanto region, Central Japan. Fault-plane solutions and their confidence regions with the scores of 95% or greater could be obtained for 294 earthquakes (84%) in the first run. For the remaining earthquakes, the preliminary discarding of inconsistent first motion data made it possible to determine the fault-plane solutions.

Significant differences of the fault-plane solutions were observed between the best fit solutions in previous methods and those by the new method. Equally probable fault-plane solutions for the same earthquake are sometimes separated into several groups and are also observed in a wide range on the focal sphere.

1. Introduction

Fault-plane solutions for the P-wave first motion have been obtained graphically by the trial-and-error method. Such a graphical method is apt to have a lack of objectivity and to be influenced by coverage of first motion data on the focal sphere. Multiple solutions, or equally probable fault-plane solutions for the same earthquake obtained by different investigators or studies, show some disagreemet (Stauder, 1964; Fara and Scheidegger, 1964; Stevens and Hodgson, 1968). Such multiple solutions are produced due to different sets of first motion data in use and are regarded as alternative solutions of equal possibility. In the graphical method it is impossible to estimate the errors of solutions or possible regions of solutions.

Computer determination of fault-plane solutions was begun by KASAHARA (1963) by applying the analytical function of the probability of consistent first motion data to expected radiation patterns, as proposed by KNOPOFF (1961a, b). WICKENS and HODGSON (1967) developed a computer method and applied it to 618 earthquakes which occurred in the world during the period from 1922 to 1962. KEILIS-BOROK *et al.* (1972) used a different weighting method based on the expected radiation of amplitude for several types of source models. In computer determinations the errors of fault-plane solutions are estimated from angular variation by allowing two additional stations to become inconsistent (adopted in the IUGG meeting of 1963; RITSEMA, 1964; WICKENS and HODGSON, 1967; HORIUCHI *et al.*, 1972). ICHIKAWA (1971) also applied a computer method of fault-plane determination to Japanese earthquakes. Recently, focal mechanisms of large earthquakes in and near the Japanese Islands have been routinely determined (ICHIKAWA, 1979). In these studies the score of consistent first motion data was as low as 80% (STEVENS and HODGSON, 1968).

Recently a new method of 95% confidence region has been proposed for the fault-plane solutions by DILLINGER *et al.* (1971, 1972). Such confidence regions have a statistical meaning for error estimation of fault-plane solution, and make it possible to estimate also possible regions of alternative fault-plane solutions. DILLINGER (1972) applied this method to the San Fernando Earthquake of February 9, 1971. DEWEY (1972, 1976) also applied it to the studies of focal mechanisms in Western Venezuela and Northern Anatolia. GUINN and LONG (1977) showed the possible domains of the axes of maximum pressure and tension (P and T). BRILLINGER *et al.* (1980) showed the regional focal mechanism solutions by the joint first motion data.

First motion data collected from seismological bulletins, such as those of the Japan Meteorological Agency (JMA) and the International Seismological Centre (ISC), seem to include inconsistent data as much as 15 to 29% (HODGSON and ADAMS, 1958; STEVENS and HODGSON, 1968; ISACKS and MOLNAR, 1971; DAS and FILSON, 1975). On the other hand, the first motion data read directly from the WWSSN seismograms have only a small number of inconsistent data as much as 1% (SYKES, 1968).

For such low-quality data fault-plane solutions with high confidence levels can not be expected. Many seismologists have experienced with the cases where some first motion data are obviously in error of opposite directions from adjacent ones. Such erratic data might lead to misdetermination of fault-plane solutions and these should be discarded by some objective method.

In the numerical method of the fault-plane determination, the weighting method of stations accompanying to reliability (station bias) has been performed (KASAHARA, 1963; WICKENS and HODGSON, 1967). However, in recent years dozens of new observing stations have begun to report first motion data and, therefore, such a method of station bias is not adequate.

Computer methods or numerical methods of fault-plane determination are classified into the two groups, in which the axes of the maximum stresses (P and T) or the pole axes (X and Y) are used. In KASAHARA'S (1963) and WICKENS and HODGSON'S method (1967) the pole axes of the nodal planes are arranged to search for possible solutions. DILLINGER *et al.* (1971. 1972) adopted a somewhat different way by using the pole axes, or the so-called "complementary circles" in their "graphic-numerical" combined methd. Such methods using the pole axes make it necessary to distinguish the directions of the first motion, or to define the locations of the pressure and tension axes as an additional procedure. On the other hand, GUINN and LONG (1972) and HORIUCHI *et al.* (1972) used directly the sets of the axes of maximum pressure and tension. In the present study tentative fault-plane solutions are represented by the sets of the axes of maximum pressure and tension, and the poles of nodal planes and the null vector are located for only the usable solutions by the numerical method.

Accurate focal depths and take-off angles are especially required for nearby stations in order to determine the nodal plane solutions accurately (SUTTON and BERG, 1958; HERRMAN, 1975). In the present study the hypocentral locations have been determined by correcting observed travel times using the mean Pn residuals at each station (MAKI, 1981). Expected travel times are obtained for a given velocity structure by the seismic ray theory (BULLEN, 1963; JULIAN and ANDERSON, 1968). Take-off angles are also calculated for their focal depths using the same velocity structure. In this study the velocity structure is adopted from ICHIKAWA and MOCHIZUKI'S paper (1971) which was proposed as a standard model for the Japanese Islands. This velocity structure is consistent with the recent studies of the crustal structure by the Research Group for the Explosion Seismology and also with the upper mantle structure used for the Jeffreys and Bullen travel-time table.

Only the P-wave first motion data are used, and the PKP or other later phases are not used because of their lower consistency as mentioned by HODGSON and ADAMS (1958).

In the present study an improvement of representation of the 95% confidence region for low-quality data will be discussed, and later some advantages of the new method will be presented.

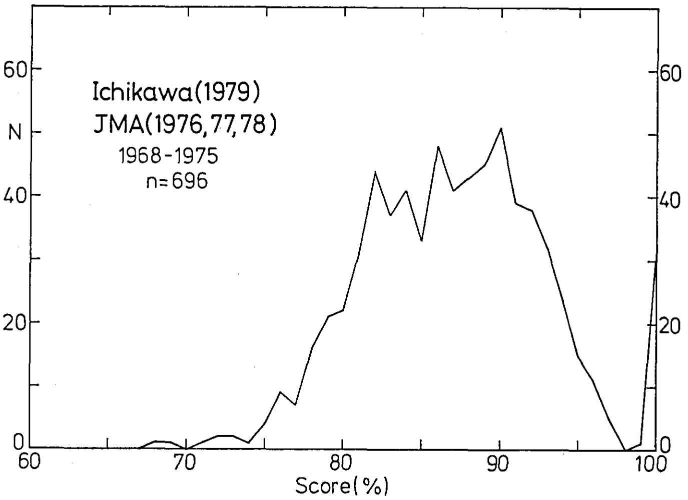

Fig. 1. Frequency distribution of the P-wave scores of 696 earthquakes which occurred in and around Japan during eight years (1968-1975) taken from ICHIKAWA (1979) and JMA (1976, 1977, 1978).

2. Inconsistent data of the P-wave first motion

Best fit solutions have been simply searched in the graphical or computer method, even though only the lower scores of consistent data cannot be obtained. But existence of inconsistent first motion data might affect not only fault-plane solutions but also possible regions of alternative solutions, or confidence regions.

Fig. 1 shows the frequency distribution of the scores (in per cent) of the consistent data for fault-plane solutions of 696 earthquakes in and near the Japanese Islands, which are determined routinely by ICHIKAWA (1979) and by JMA (1976, 1977, 1978). Most of these earthquakes have scores ranging from 75 to 95%. Scores near 100% were observed only for 64 earthquakes with a small number of the first motion data around 10. For earthquakes of well-observed first motion data, scores of 95% or greater were found for only a few of the earthquakes.

Figs. 2a and 2b show the frequency distributions of the scores for the 29 aftershocks of the 1964 Alaska Earthquake (STAUDER aud BOLLINGER, 1966) and 618 earthquakes which occurred around the world during the 41 years from 1922 to 1962 (WICKENS and HODGSON, 1967), respectively. For the Alaska Earthquake, the first motion data read directly on the WWSSN seismograms were used, while for the others the first motion data were collected from the seismological bulletins or from question-

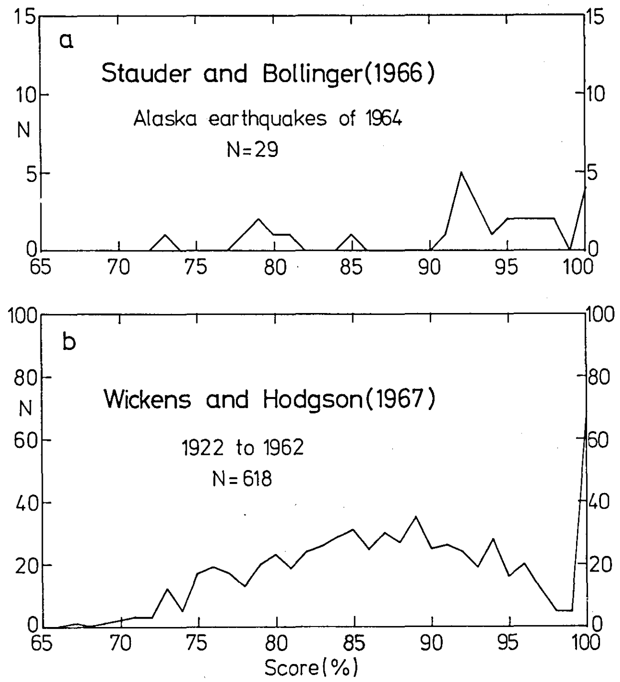

Fig. 2. Frequency distribution of the P-wave scores of (a) 29 aftershocks of the 1964 Alaska Earthquake by STAUDER and BOLLINGER (1966), where the first motions were read directly on the WWSSN seismograms, and (b) 618 earthquakes in the world during 41 years from 1922 to 1962, computer-determined by WICKENS and HODGSON (1967).

naires. Like in Fig. 1. scores over 95% were observed only for a small number of earthquakes, even using the WWSSN data.

HODGSON and ADAMS (1958) showed that the inconsistent portions of first motion data for published fault-plane solutions reach 18.3%. Some parts of these inconsistent first motion data are observed at the same stations. Methods of the station bias were then adopted by KASAHARA (1963) and WICKENS and HODGSON (1967). STEVENS and HODGSON (1968) adopted scores of 80% as one of the criteria for the well-determined fault-plane solutions.

Statistical confidence regions should be discussed on the basis of a significant level as high as 95% (DILLINGER *et al.*, 1971, 1972; POPE, 1972). Low scores of the consistent data as seen in the previous may not be used in the construction of the confidence regions.

Particular data of first motion have occasionally a definite role in the determination of fault-plane solutions. It is dangerous to determine fault-plane solutions or possible regions of alternative solutions without discarding such inconsistent data. Thus, the probable errors of fault-plane solution obtained by the method of allowing some additional data to be wrong (WICKENS and HODGSON, 1967; HORIUCHI *et al.*, 1972) might be affected by inconsistent data.

KNOPOFF (1961a, b) represented the P-wave score or agreeing number of first motion data for N observations as follows,

$$R_p=\sum_{i=1}^{N}\left\{\frac{1}{2}+\frac{1}{2}\chi_i^o\cdot\chi_i^c(\beta)\right\}, \tag{1}$$

where χ_i^o denotes the observed first motion, or "+1" for compression and "−1" for dilatation, and $\chi_i^c(\beta)$ denotes the theoretical first motion, "+1" or "−1", at an observational station for fault-plane solution with the vector β. Then R_p represents the number of stations at which the observed first motion data agree with the theoretical ones.

DILLINGER *et al.* (1971, 1972) and POPE (1972) gave the likelihood of the P-wave score by the following binomial distribution,

$$L(\beta, \chi)=p^{R_p}\cdot(1-p)^{N-R_p}, \tag{2}$$

where p denotes the trial probability, and N and R_p represent the total number of observations and the number of consistent data. In the present study the ratio of the number of consistent first motion data to the total number of observations will be used as the P-wave score, or R_p/N instead of R_p in (1) (POPE, 1972).

In the present study an objective and automatic method of discarding inconsitent first motion data will be discussed.

3. A numerical method of fault-plane determination by winnowing first motion data

For a double-couple source system (x, y, z) where the force couples act at the origin in the x and y directions, the far-field P-wave amplitude is given as follows (STAUDER, 1960; HERRMAN, 1975),

$$U_p=\frac{2xy}{4\pi\rho\alpha^3R^3}K'(t-R/\alpha), \tag{3}$$

where ρ, α and R denote the density, P-wave velocity and hypocentral distance, respectively. $K'(t)$ denotes the time derivative of the force couple acting at the source. For the geographical coordinates $(\bar{x}, \bar{y}, \bar{z})$ of the station,

$$\begin{aligned} x &= a_{11}\bar{x} + a_{12}\bar{y} + a_{13}\bar{z}, \\ y &= a_{21}\bar{x} + a_{22}\bar{y} + a_{23}\bar{z}, \\ z &= a_{31}\bar{x} + a_{32}\bar{y} + a_{33}\bar{z}, \end{aligned} \tag{4}$$

where a_{ij} $(i, j=1, 2, 3)$ denotes the direction cosine of the geographical coordinates $(\bar{x}, \bar{y}, \bar{z})$ to the coordinates of the force system (x, y, z). The $\bar{x}$, $\bar{y}$ and $\bar{z}$ axes are assumed to be directed northward, eastward and downward, respectively.

On the other hand the geographical coordinates of the station $(\bar{x}, \bar{y}, \bar{z})$ are represented by the azimuth Φ and take-off angle i_h, as follows

$$\begin{aligned} x &= R \cdot \sin i_h \cos \Phi, \\ y &= R \cdot \sin i_h \cos \Phi, \\ z &= R \cdot \cos i_h, \end{aligned} \tag{5}$$

where Φ is measured clockwise from the north and i_h is measured from the vertical downward.

The direction cosines, a_{ij}, are given in terms of the azimuth and dip angle for the axes of maximum pressure (τ_P, π_P) and tension (τ_T, π_T),

$$\begin{aligned} a_{11} &= 1/\sqrt{2}\,(\cos \tau_T \cos \pi_T + \cos \tau_P \cos \pi_P), \\ a_{12} &= 1/\sqrt{2}\,(\sin \tau_T \cos \pi_T + \sin \tau_P \cos \pi_P), \\ a_{13} &= 1/\sqrt{2}\,(\sin \pi_T + \sin \pi_P), \\ a_{21} &= 1/\sqrt{2}\,(\cos \tau_T \cos \pi_T - \cos \tau_P \cos \pi_P), \\ a_{22} &= 1/\sqrt{2}\,(\sin \tau_T \cos \tau_T - \sin \tau_P \cos \pi_P), \\ a_{23} &= 1/\sqrt{2}\,(\sin \pi_T - \sin \pi_P), \end{aligned} \tag{6}$$

where τ denotes the strike, measured clockwise from the north, and π denotes the plunge, measured downward from the horizontal.

For given sets of the axes of maximum pressure and tension, theoretical polarities at a station (Φ, i_h) can be obtained by using the above equations. In the present study tentative axes of maximum pressure and tension are given homogeneously in a grid of 10° on the focal sphere.

Fig. 3a shows the distribution of 324 $(=36\times 9)$ axes of tentative maximum pressure (P) on the focal hemisphere. Fig. 3b represents 19 axes of the maximum tension (T) for one of the axes of maximum pressure given in Fig. 3a. For a pair of the axes of maximum pressure and tension, a null vector (N) is numerically located. Solid circles show a pair of these axes, denoted by P, T and N. According to the orthogonal condition the angular distance between them should be 90°. Fig. 3c denotes a set of nodal planes for the above set of the axes of maximum pressure and tension, and null vector. Poles of the nodal planes are de-

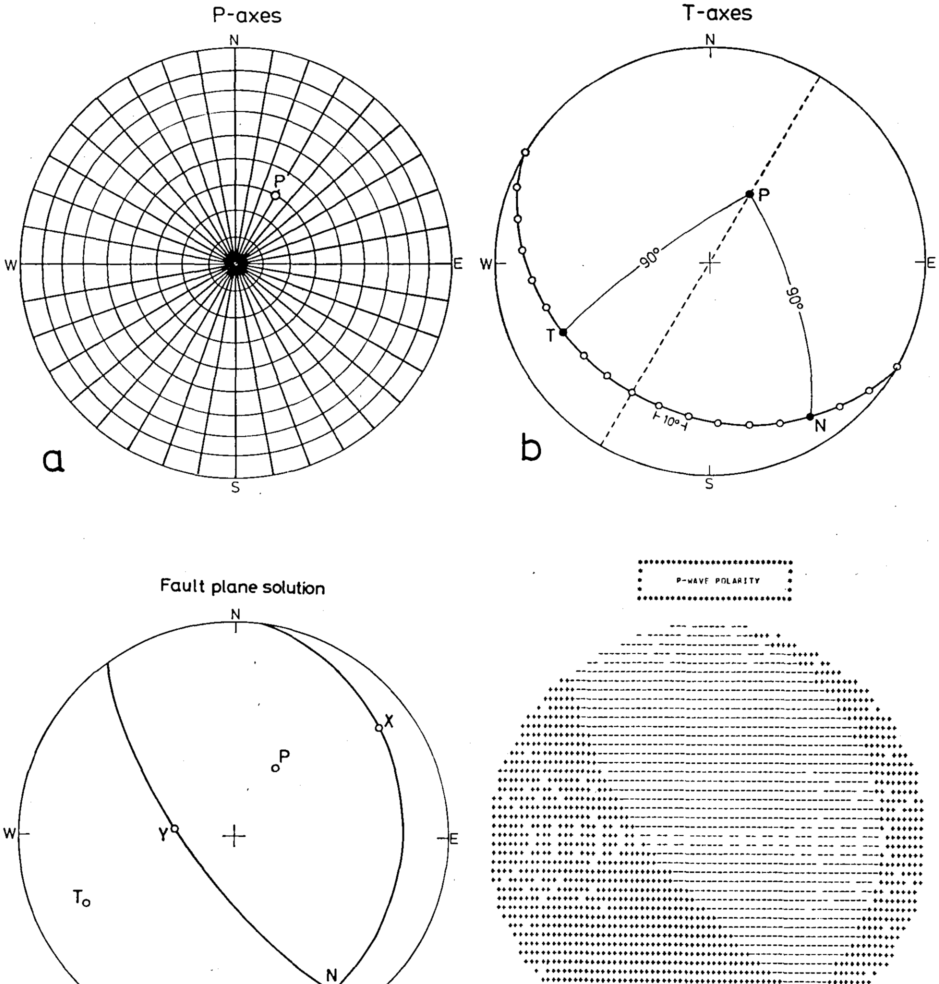

Fig. 3. Equal-area projection of the axes of maximum pressure and tension and null vector, and expected polarities in the new method, (a) 324 (=36×9) tentative axes of maximum pressure (P) assigned in an equal interval of 10° of azimuth and take-off angle, (b) 19 tentative axes of maximum tension (T) and null vector (N) for a given axis of maximum pressure, (c) a set of fault-plane solution, where thick lines denote the nodal lines, and X and Y mean the pole axes of the nodal planes, (d) theoretical radiation pattern of P wave first motion where "+" denotes the compression, and "−" dilatation, respectively.

noted by X and Y. Fig. 3d represents a theoretical radiation pattern of the P-wave first motion for a set of stress axes shown in Fig. 3c, where

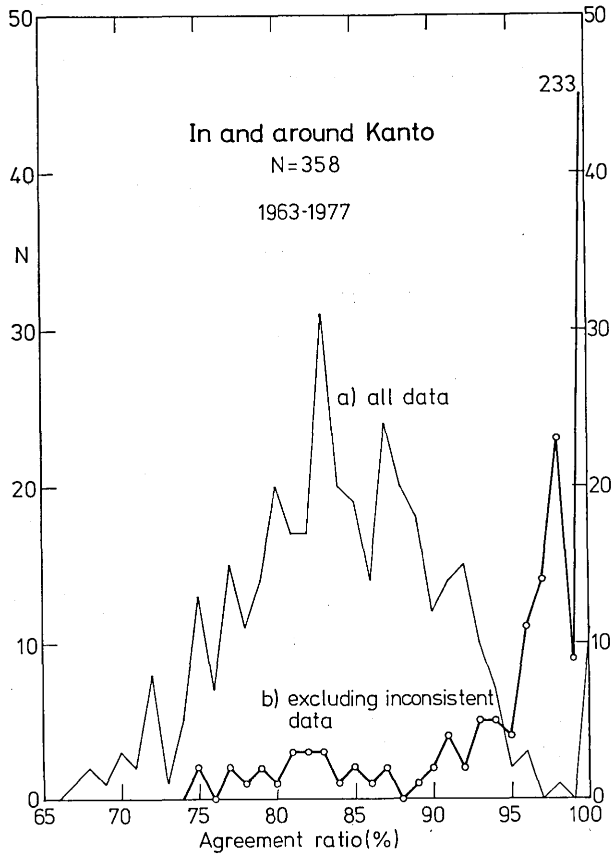

Fig. 4. Frequency of P-scores of 358 earthquakes which occurred in and around the Kanto region during 15 years from 1963 to 1977, (a) for all data of first motion collected from the JMA and ISC bulletins, where the fault-plane solutions are determined by the previous method, and (b) for the winnowed first motion data by the new method described in the text.

"+" and "−" denote compressional and dilatational first motion, respectively.

For each earthquake comparisons of observed first motion data with theoretical ones were made for 6156 $(=36\times9\times19)$ trials of the axes of maximum pressure and tension (P and T). For each trial ratios of number of consistent first motion data to the total ones are recorded, and plausible fault-plane solutions with the ratio greater than a certain level was stored. In the above comparisons the reliability of each station for only plausible solutions is also recorded. Referring to Fig. 1 a level of 75% is adopted as the lowest score of the plausible solutions.

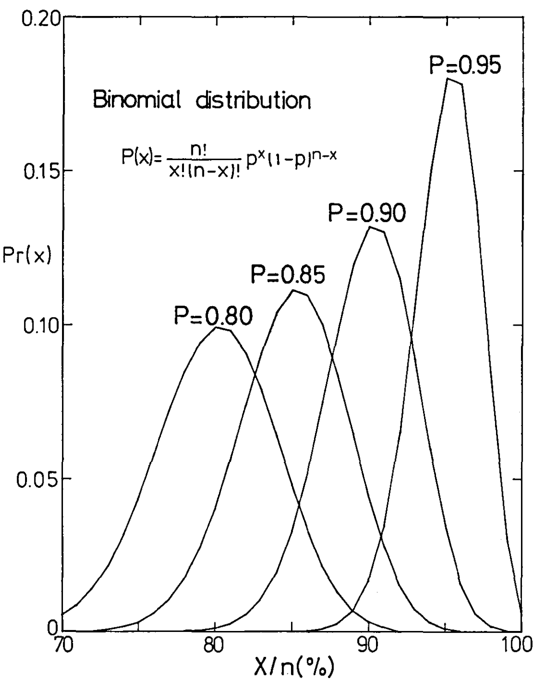

Fig. 5. Probabilities of the binomial distribution for several values of trial probability, p. Number of trials (abscissa) are normalized to the ratios in %.

Fig. 4 shows the frequency distribution of the scores (in %) of the first motion data agreeing to the fault-plane solutions for 358 earthquakes which occurred in and around the Kanto region during the period from 1963 to 1977. A thin line (a) in the figure shows the best fit solutions in the first run for all data collected. Most of the fault-plane solutions satisfy only 75 to 95% of collected first motion data. Scores near 100% are seen in these cases of small numbers of first motion data as few as 10.

It is meaningless to represent the confidence regions of the fault-plane solutions in cases with such low scores. Fig. 5 represents the binomial distributions for various values of the trial probability, p. Compared with the observed frequency of the scores, the actual value of the trial probability or the portion of consistent first motion data seems to be 80 to 90%. This means that the probability of consistent first motion data is about 80 to 90%, which is nearly equal to that found by HODGSON and ADAMS (1958) and STEVENS and HODGSON (1968). In the analysis of focal mechanisms, apparently incorrect first motion data are sometimes observed on the focal sphere, as for instance opposite directions from the

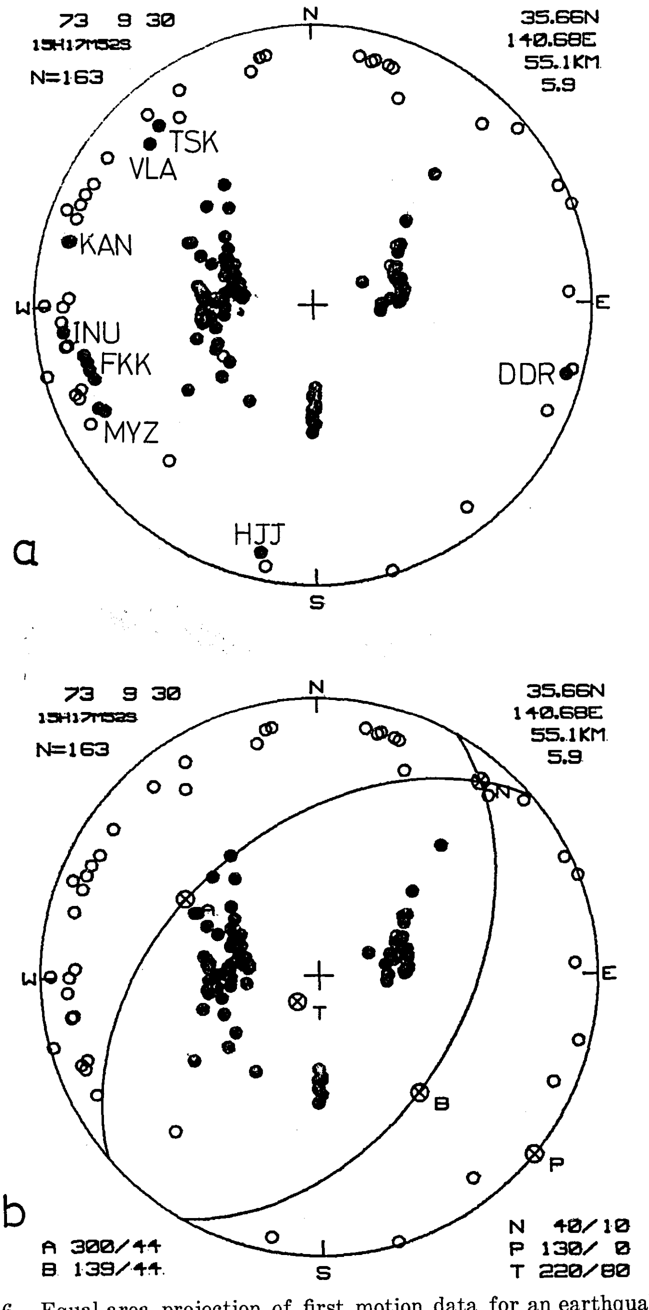

Fig. 6. Equal-area projection of first motion data for an earthquake which occurred near Choshi, Central Japan, on September 30, 1973, (35.66°N, 140.68°E, h=55.1 km, M=5.9). (a) All first motion data collected (n=199), where some stations, TSK, VLA, KAN, DDR, show apparently opposite directions from the dajacent ones, (b) Winnowed first motion data (n=163) with 35 stations discarded by the method described in the text.

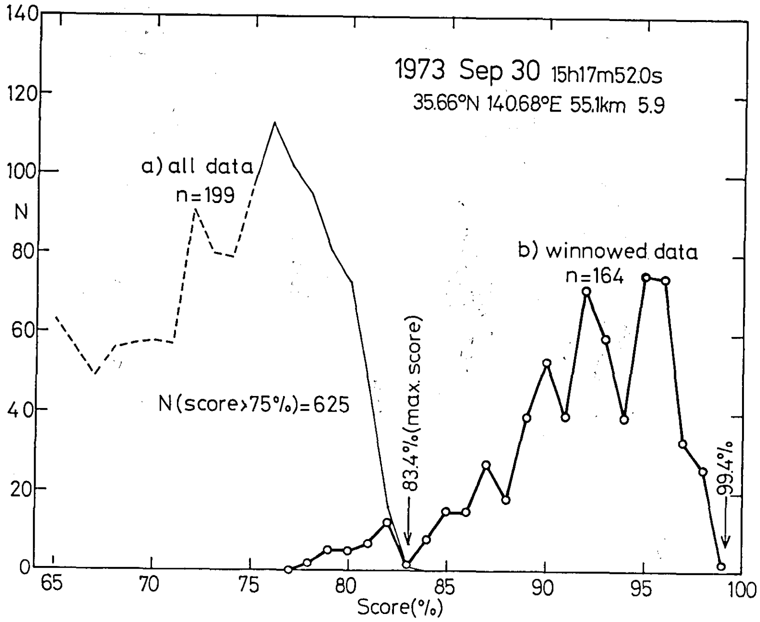

Fig. 7. Improvement of P-scores of an earthquake which occurred near Choshi, Central Japan, on September 30, 1973. The thin line shows P-scores for all data collected (n=199). The thick line indicates P-scores for the winnowed data (n=163).

adjacent stations even though they are located in the common areas of the same first motion direction.

Fig. 6a represents the equal-area projection of the P-wave first motion on the focal hemisphere for an earthquake which occurred near Choshi, Chiba Prefecture, Central Japan, on September 30, 1973 (h=55.1 km, M=5.9). Different directions of the first motion from adjacent ones are observed for some stations (TSK, DDR, HJJ, INU, *etc*). In the previous graphical method these stations are discarded arbitrarily from one trial to another.

A thin line (a) in Fig. 7 indicates the frequency distribution of scores for the all data collected (n=199). The maximum score reaches only 83.4%. Six hundreds and twenty-five tentative solutions satisfy the given first motion data with scores of 75% or greater. The station TSK (Tsukuba of the Dodaira seismograph network of the Earthquake Research Institute) reports the compressional first motion (+) for this earthquake, but this is inconsistent to 458 out of 625 probable solutions. For this earthquake 35 stations report inconsistent first motion data for more than a half of the probable solutions having scores of 75% or greater. The lower part of Fig. 6 shows the equal-area projection of the first motion

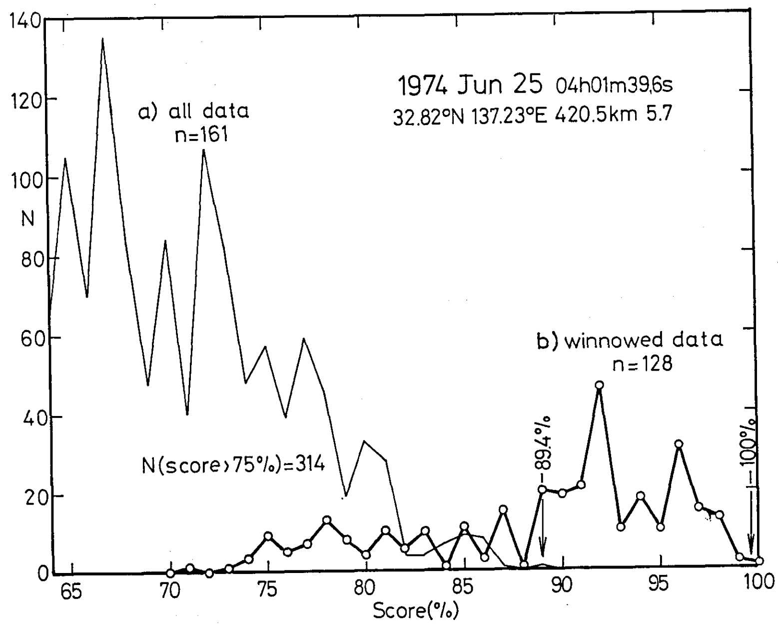

Fig. 8. Improvement of the P-scores for a deep-focus earthquake which occurred far south off Honshu, on June 25, 1974 (32.82°N, 137.23°E, h=420.5 km, m=5.7)

data after discarding 35 stations and one of the fault-plane solutions (P, T, N, A and B axes), together with the nodal planes.

The thick line (b) in Fig. 7 shows the frequency distribution of scores for the winnowed first motion data. The maximum score reaches 99.4 %. Fig. 8 represents the case of a deep-focus earthquake occurring far south off Honshu on June 25, 1974. The difference of the scores between the peak and maximum is greater than in Fig. 7.

Discarding inconsistent first motion data should be done carefully (POPE, 1972). For the first motion data collected from the seismological bulletins, high scores could not be expected in the previous methods. Inconsistent data may lead to mistakes in studies of the earthquake mechanism, and such data should be carefully discarded in such an objective method as mentioned above.

The new numerical method described in this chapter is summarized as follows.

(1) expected first motion for a full set of 6156 tentative fault-plane solutions and scores by comparing with observed first motion data,
(2) plausible fault-plane solutions with scores of 75% or greater are recorded,

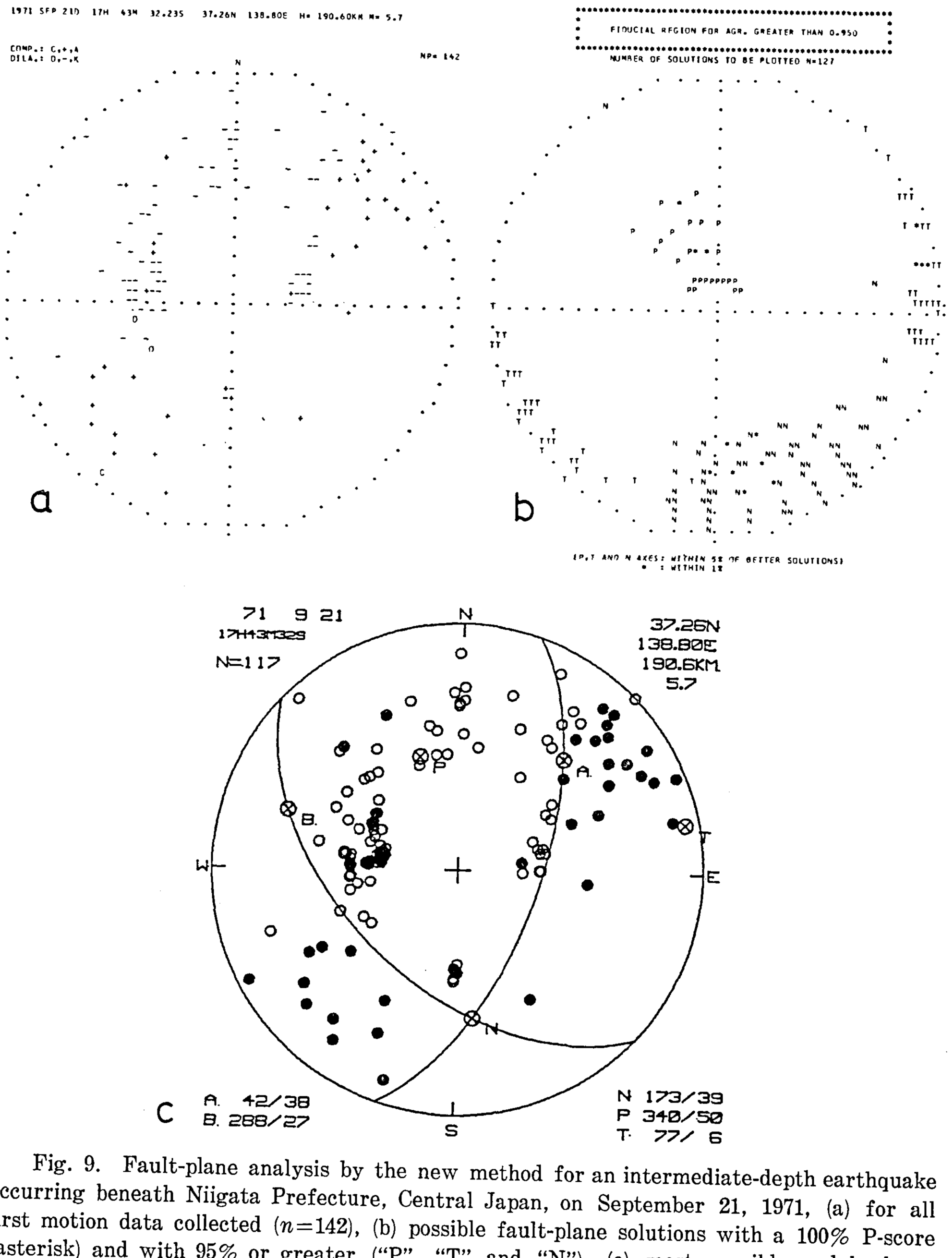

Fig. 9. Fault-plane analysis by the new method for an intermediate-depth earthquake occurring beneath Niigata Prefecture, Central Japan, on September 21, 1971, (a) for all first motion data collected (n=142), (b) possible fault-plane solutions with a 100% P-score (asterisk) and with 95% or greater ("P", "T" and "N"), (c) most possible nodal planes determined after discarding 25 data.

(3) station reliability is estimated by rate of consistent first motion data for plausible solutions,

(4) stations with less reliability, where observed first motion data dis-

agree with more than a half of the plausible solutions, are discarded,
(5) re-counting scores of the remaining first motion data for the plausible solutions,
(6) list the fault-plane solutions with the maximum scores of 100%, otherwise 95% or greater,
(7) lastly, locating numerically pole axes of nodal planes.

Computer times from dozens of seconds to a couple of minutes are required for data sets of first motion with the number from dozens to hundreds. If the calculation of take-off angles for each earthquake is replaced by reading the tables of take-off angles, computer time will be greatly reduced.

4. Some notes in fault-plane determination by the new method

The new method described in the present paper has been applied to 358 earthquakes of magnitude 5.5 or greater, which occurred during 15 years from 1963 to 1977 within a area in and near the Kanto region, bounded by latitude 31°N and 39°N and longitude 137°E and 145°E. Epicenters and focal depths are redetermined by correcting the observed travel-times using the mean Pn residuals at each station. First motion data were collected from the seismological bulletins of the JMA and the ISC. The number of observed first motion data ranges from 6 to 267.

In the first run for all the first motion data collected from the bulletin, there are only 17 earthquakes whose fault-plane solutions can be determined with scores of 95% or greater. For the winnowed first motion data, however, the fault-plane solutions of 294 earthquakes (8% of 358 earthquakes) could be determined with scores over 95%. The frequency distribution of the scores for these winnowed data are shown by a thick line (b) in Fig, 4. Fault-plane solutions with scores of 100% have been obtained even for cases of 100 and more of first motion data.

Fig. 9 shows an example of an intermediate-depth earthquake which occurred below Niigata Prefecture, Central Japan, on September 21, 1971, whose fault-plane solution can be uniquely determined by discarding 25 stations from 117 first motion data (Fig. 9a). Small variations of the axes of maximum pressure and null vector are noticeable (Fig. 9b). Fault-plane solutions satisfying more than 95% of the first motion data are represented by the letter "P", "T" and "N", respectively. Solutions with a 100% score are represented by asterisks, "*". Fig. 9c shows the equal-area projection of the first motion data and most plausible nodal planes, which are located at the middle of the confidence regions. Fig. 10 shows an example of uniquely determined solutions with a lower score of 96.9%

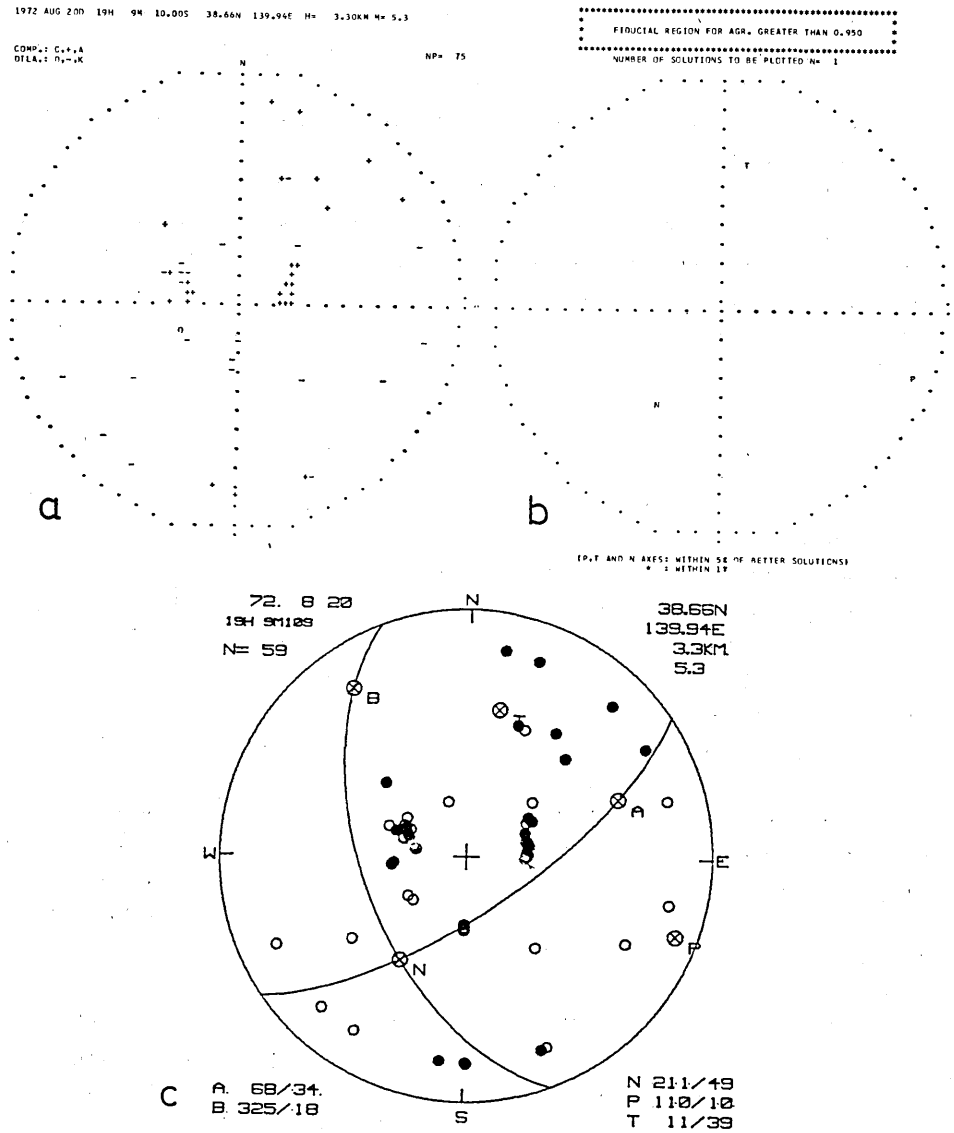

Fig. 10. A uniquely determined fault-plane solution with a maximum score of 96.6% with 16 data discarded for a very shallow earthquake which occurred beneath Yamagata Prefecture, Central Japan, on August 20, 1972. (a) first motion data collected (n=75), (b) axes of maximum pressure and tension and null vector, (c) nodal planes of the most possible solutions.

for a very shallow earthquake which occurred below Yamagata Prefecture, Northeast Japan, on August 20, 1972 (38.66°N, 139.94°E, h=3.3km, M=5.3).

Even for the winnowed first motion data, there are some cases where

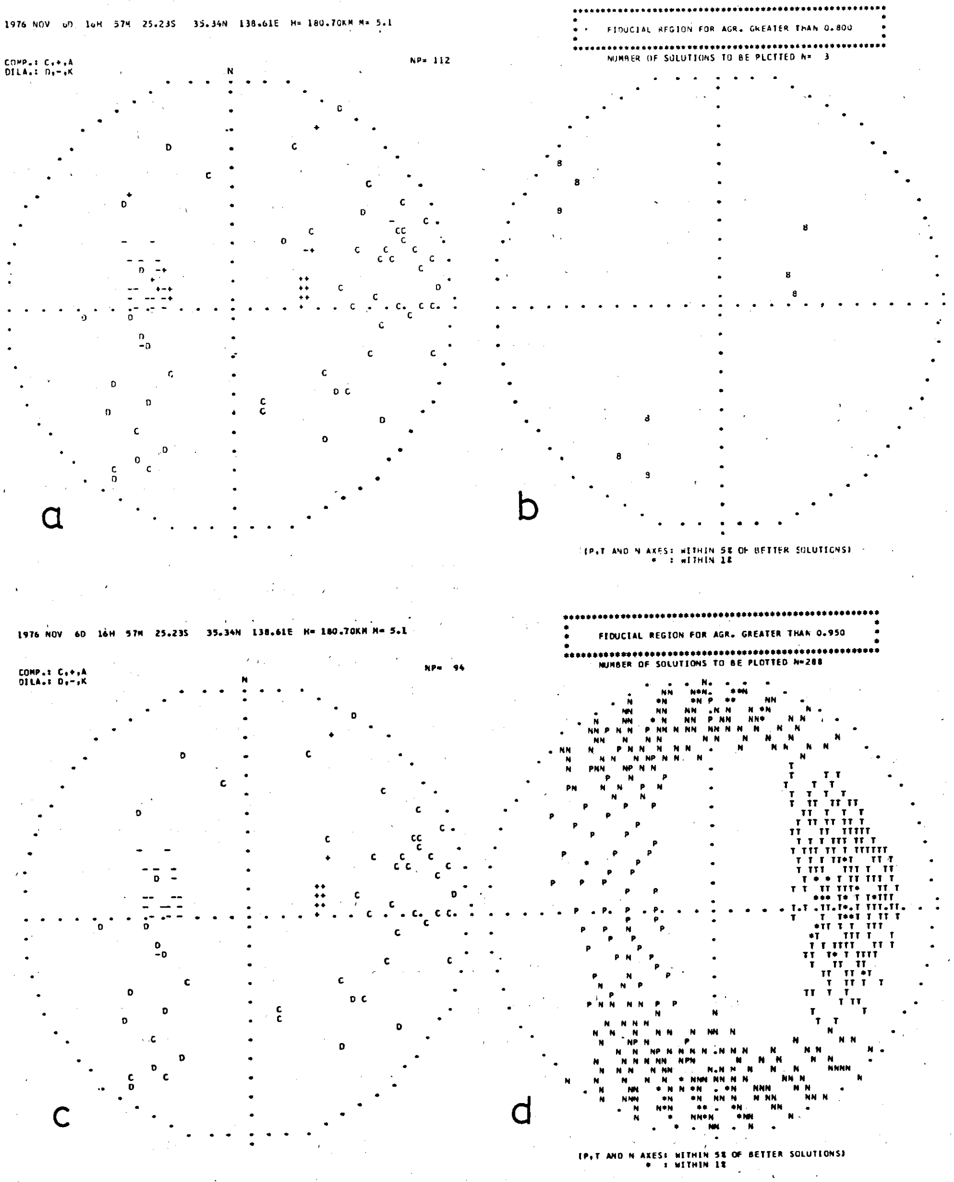

Fig. 11. Preliminary omission of inconsistent first motion data for an intermediate-depth earthquake which occurred beneath Shizuoka Prefecture, Central Japan, on November 6, 1976, (a) all the first motion data collected (n=112), (b) axes of the P, T and N determined with a high score of 83.9% for all data, (c) first motion data with 18 data omitted preliminarily, (d) possible fault-plane solutions with scores over 95%.

scores over 95% could not be obtained. Fig. 11 shows an example of an intermediate-depth earthquake which occurred below Shizuoka Prefecture, Central Japan, on November 6, 1976. There are some first motion data which are apparently opposite to the adjacent ones among the all data collected (n=112). The maximum score reaches 83.9%, and their axes of maximum pressure and tension and the null vector are shown by "8" in Fig. 11b. Scores over 75% were obtained for only 72 trials of fault-plane solutions. After discarding 18 from 112 first motion data (Fig. 11c), 34 probable solutions with scores of 100% are obtained (shown by asterisks in Fig. 11b). Solutions shown in Fig. 11b correspond to the best fit solutions in the previous method. Significant differences are noticeable between the fault-plane solutions obtained by the previous methods and by the new method of winnowing the first motion data.

There have been experienced with some cases, where scores over 95% can not be obtained even by the new method. According to information about ratios of inconsistent first motion data to possible solutions, it may be possible to obtain useful solutions by discarding the less consistent data.

Fig. 12 shows an example of "multiple solutions", or equally possible fault-plane solutions, for a shallow earthquake which occurred off Ibaraki Prefecture, Central Japan, on March 17, 1973 (36.96°N, 141.72°E, h=29.8km, M=5.3). These multiple solutions are separable into two groups for each pressure axis (P, T and N) as seen in the figure. More information about earthquake mechanism is needed to select a final solution, such as the S-wave polarization angles, and body and surface waveforms. Three of the multiple fault-plane solutions are shown in Fig. 13 for an earthquake which occurred near Choshi, Central Japan on March 3, 1974 (35.58° N, 140.74° E, h=49.0km, M=6.1). The variation is small for the axes of maximum tension (T), but the other axes are greatly variable.

Fig. 14 shows a case of too many possible solutions for an earthquaks. This earthquake occurred east off Hachijojima Island, south of Honshu, on October 28, 1968, with abundant first motion data. After discarding 13 first motion data, 98 possible fault-plane solutions with 100% scores, and 361 solutions with scores over 95% were obtained. The pressure axes (P, T and N) show a very wide variation on the focal sphere. Even the 100%-score fault-plane solutions cannot be regarded as final. Fig. 15 shows a case with a relatively small number of first motion data (n=10) for a deep-focus earthquake which occurred far south off Honshu on January 23, 1968. For this earthquake, 333 possible fault-plane solutions with a 100% score are obtained after winnowing two first-motion data.

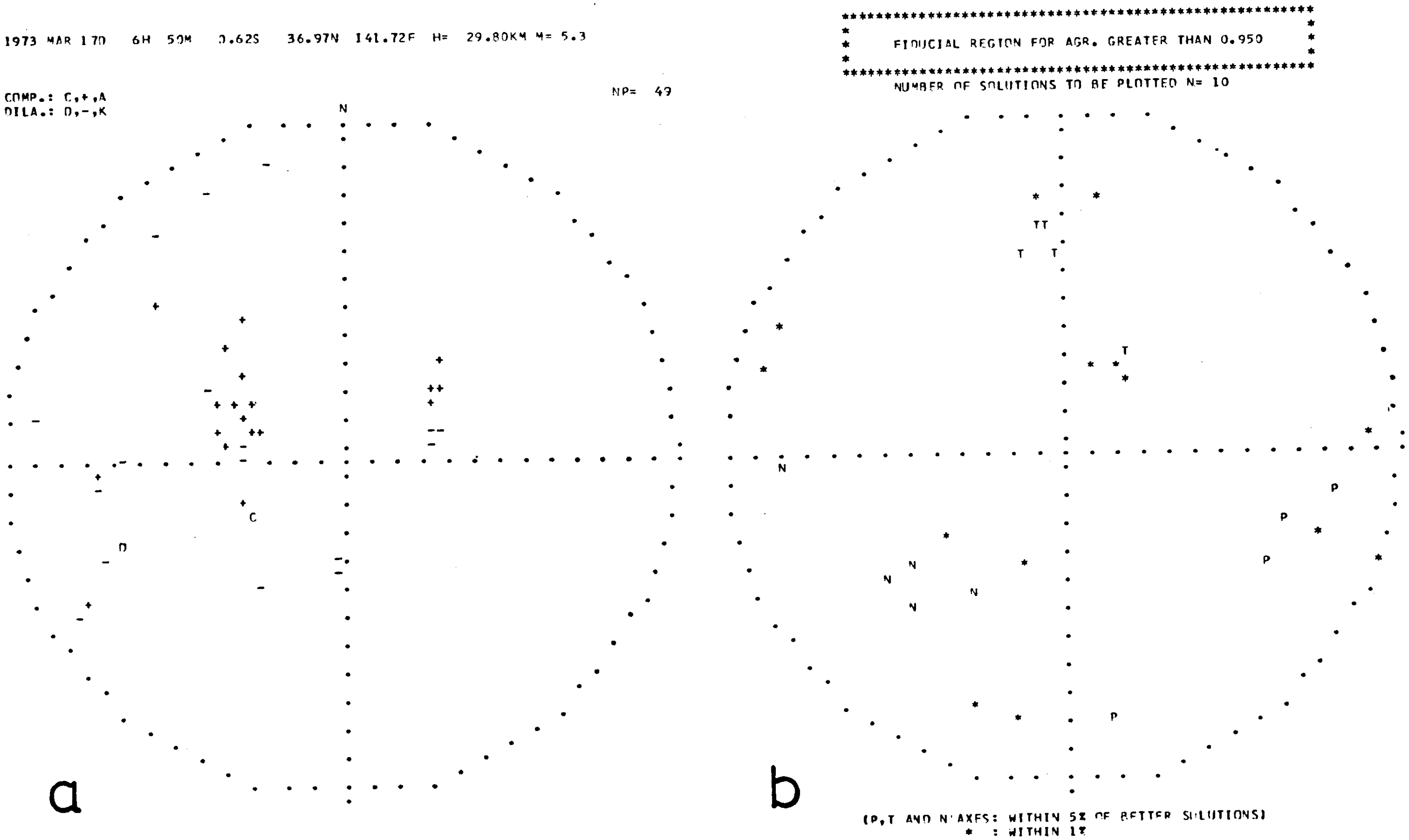

Fig. 12. Multiple solutions for a shallow earthquake which occurred off Ibaraki Prefecture, Central Japan, on March 17, 1973 (36.97°N, 141.72°E, h=29.8 km, M=5.3). (a) first motion data collected (N=49), (b) two groups of possible fault-plane solutions.

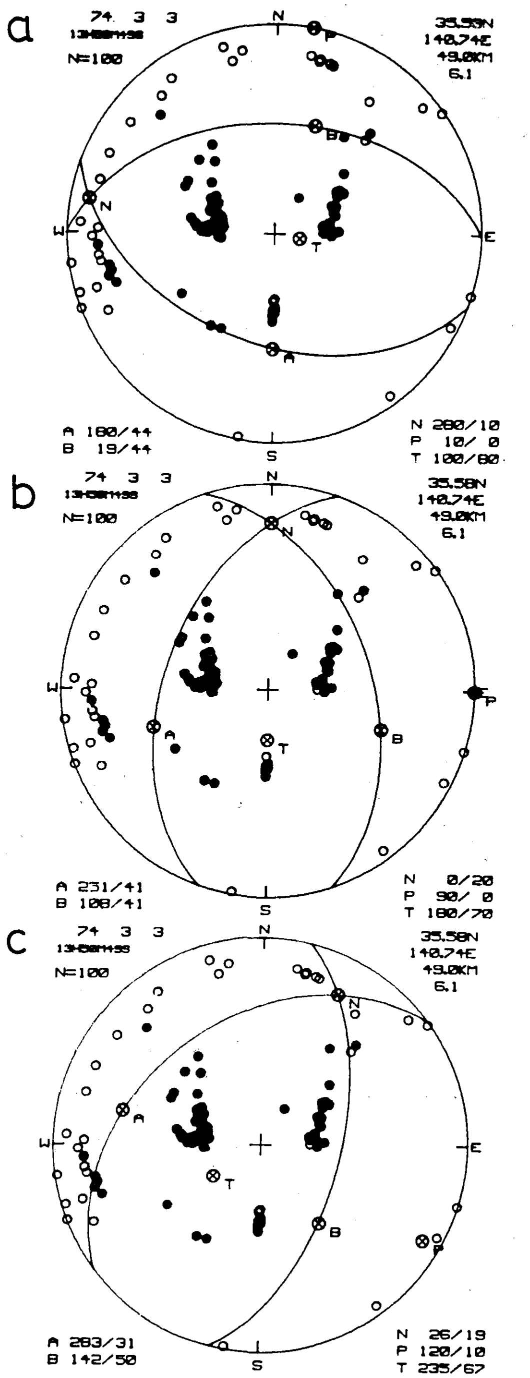

Fig. 13. Multiple solutions for an earthquake which occurred near Choshi, Central Japan, on March 3, 1974 (35.58°N, 140.74°E, h=49.0 km, M=6.1).

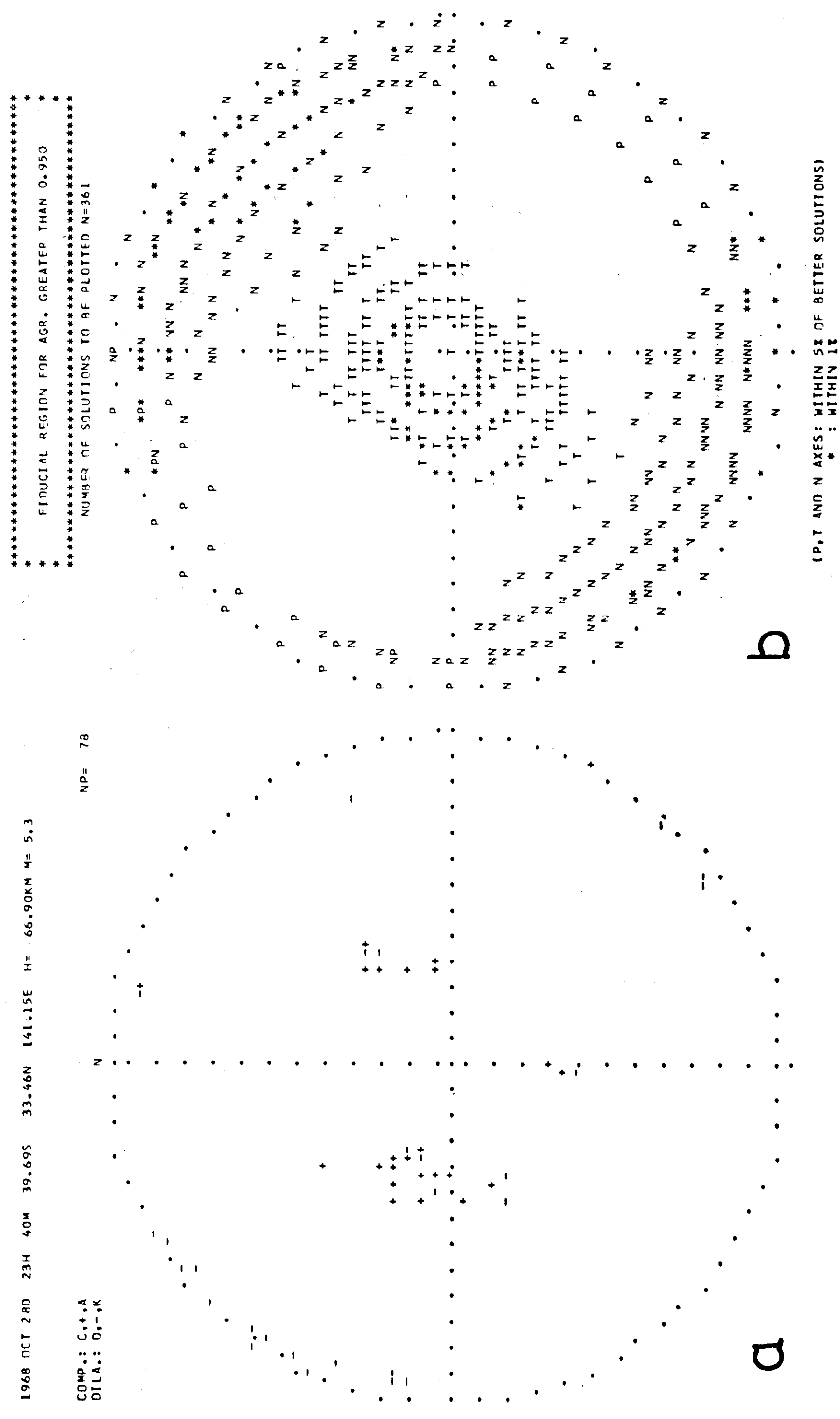

Fig. 14. Too many possible solutions for an earthquake which occurred east off Hachijojima Island, south of Honshu, on October 28, 1968.

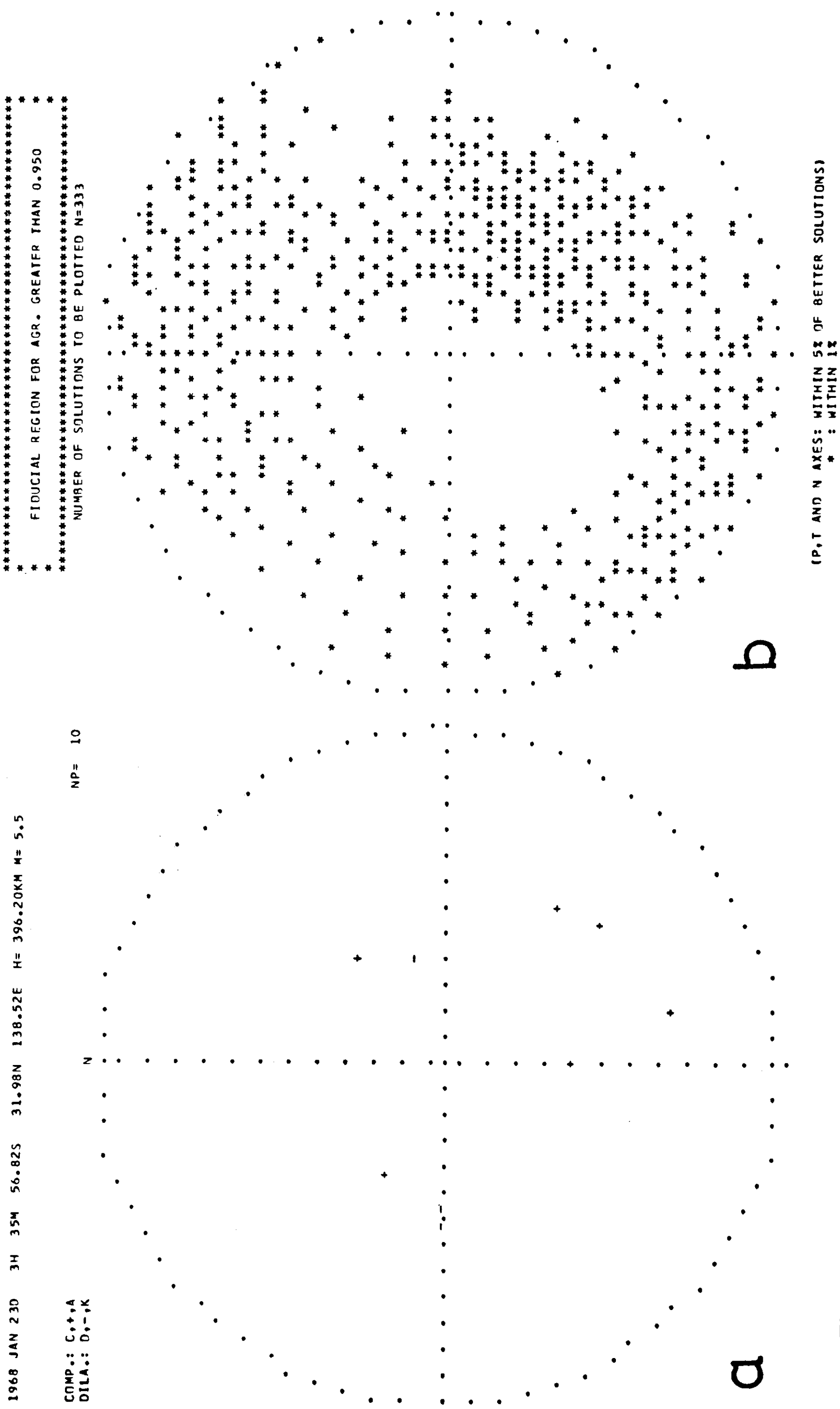

Fig. 15. Too many possible solutions for a few number of first motion data (n=10) observed for a deep-focus earthquake, which occurred far south off Honshu on January 23, 1968 (31.98°N, 138.52°E, h=396.2 km, M=5.5).

5. Discussion

Fault-plane solutions for P-wave first motion determined by the previous graphical methods are influenced by the coverage of the first motion data with respect to azimuth and take-off angle on the focal sphere. Graphical solutions are arbitrary or willful (MAKI *et al.*, 1980), and equally probable solutions have been missed in the graphical method. Such a lack of objectivity may be reduced to some extent by comparing the first motion data with systematically varied tentative fault-plane solutions (MAKI, 1968, 1969).

Incorrect first motion data is found for many earthquakes, especially in data collected from seismological bulletins. Inconsistent data amount to 20% of the total even for the best fit solutions. For such low-quality first motion data, high confidences to fault-plane solutions cannot be obtained. Inconsistent first motion data can be apparently identified because of opposite directions to the adjacent ones, although they are in common areas of the same first motion directions. Significannt differences were observed between the best fit solutions by the previous methods and those obtained by omitting such incorrect first motion data.

Errors in the fault-plane solutions have been estimated in the computer method by rotatable angles when allowing two addional data to become wrong (KNOPOFF, 1961b; KASAHARA, 1963; RITSEMA, 1964; WICKENS and HODGSON, 1976; HORIUCHI *et al.*, 1972). In this method, existences of inconsistent first motion data may sometimes severely influence fault-plane solutions.

The recent computer method developed by DILLINGER *et al.* (1971, 1972) makes it possible to estimate the useful error terms of the fault-plane solutions, or confidence regions with a 95% scores. However, such a high agreement of 95% or greater cannot be obtained for the first motion data collected from seismological bulletins (HODGSON and ADAMS, 1958; STEVENS and HODGSON, 1968). Omittable first motion data are apt to appear at the same stations. The "station bias" method has been adopted in early computer methods. But dozens of stations have begun to report first motion data in recent years, then such station biases cannot be estimated for all stations.

Equally possible solutions are smetimes separable into several groups with significant differences. Final solutions should be determined by combining such other information as S-wave polarization angles, radiation patterns of body and surface waves (UDIAS and BAUMANN, 1969; CHANDRA, 1971; KEILIS-BOROK *et al.*, 1972; STAUDER and BOLLINGER, 1965).

A more accurate determination of the epicentral location and focal depths are required for applying a numerical method. Especially for shallow earthquakes the focal depth and take-off angles at sources should be estimated for the local crustal and upper mantle structure.

6. Conclusion

A new numerical method for determining fault-plane solutions from P-wave first motion data has been introduced. This method consists of winnowing automatically first motion data and estimating possible regions of alternative solutions, or confidence regions. The lack of objectivity seen in the previous graphical methods could be eliminated by assigning tentative solutions in equal intervals of azimuth and take-off angle on the focal sphere. Winnowing is accomplished by discarding first motion data which are in false directions to the plausible solutions with scores of 75% or greater. Apparently incorrect first motion data, which have the opposite direction from the adjacent ones, even though located in the common areas of the same first motions, can be discarded in this way.

The new numerical method was applied to 358 earthquakes which occurred in and around the Kanto region during 15 years from 1963 to 1977. These earthquakes have been relocated by correcting the observed travel times using the mean Pn residuals at each station, and thus epicentral location and focal depth are more accurately determined than in previous studies. Take-off angles are estimated by taking account the local crustal structure.

Best fit solutions in the previous methods satisfy the given first motion data for only scores from 75% to 95%, and scores of 95% or greater were observed for only 17 earthquakes. By winnowing the first motion data as described above, the scores of 95% or greater can be obtained for 294 earthquakes (84%).

Confidence regions of the fault-plane solutions were sometimes separable into several groups. Widely variable regions of equally possible solutions were also observed for other earthquakes. Significant differences in the fault-plane solutions were observed between the previous and the new method. Fault-plane solutions obtained in the previous methods seem to be influenced by the particular data of first motion.

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10. 地震メカニズムの数値解法

地震研究所 牧 正

P波初動データによる地震メカニズム解とその信頼域の数値的解析法が改良された．従来の方法，特に図式法では，特定の初動データがメカニズム解を左右する傾向がある．初動方向データの中で，周囲と比較して，明らかに誤まりと思われるものがみられる場合がある．又与えられた初動データを満足する他の解が存在する場合もある．

今回の数値解法では，与えられた初動データが客観的・自動的に判別され不良データが省かれる．又初動データの 95% 以上を満足する主圧力軸（P，T）の信頼域も得られる．

この数値解法は関東地方周辺の 358 個の地震に応用され，294 個の地震に対して解が得られた，残りの地震 (16%) では最良のメカニズム解に対する初動データのスコアは 95%以下である．これらの地震に対する観測点別のスコアにもとづいて，初動データを取捨選択して，メカニズム解を得ることができる．

従来の方法による“最良解”と今回の数値解には違いがみられることがある．又代用解がいくつかのグループに分れたり，広範囲に分布する場合もみられる．