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Epicenter Location Capability of a Small Aperture Array

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ABSTRACT

The epicenter estimation capability of a small aperture array is investigated by examining the backazimuth anomalies of eighty-eight local earthquakes in the vicinity of the Pinyon Flat of southern California. The backazimuth anomalies of the entire data set are estimated by comparing observed backazimuths with reliable reference backazimuths directly computed from the known locations as reported by the Anza and Caltech seismic networks. Further, the observed backazimuths are computed by using a beamforming technique to analyze arrivals of the first P-waves recorded at a small dense array with 25 stations within an aperture of about 3 km. A plot of the backazimuth anomalies with the reference backazimuths shows that the first order backazimuth anomalies are strongly dependent on the backazimuths in a sine-like function. This result generally agrees with the theoretical calculation from a simple crustal model with an interface dipping twenty-five degrees to the northeast and, consequently, indicates that the epicenter location capability of a small aperture array may be improved with the correction of anomalous backazimuths based on the crustal model with a dipping interface.

(Key words: Epicenter location, Small aperture array, Backazimuth anomaly and Dipping interface)

1. INTRODUCTION

Locating earthquakes is one of the most fundamental works leading to insight into the characteristics of plate tectonics and subsurface structures within the earth. For example, seismicity maps, which are constructed from earthquake locations, not only directly enable us to delineate the configurations of plate boundaries and subduction zones but also help us to define the types of active faults and volcanoes near the Earth's surface. Besides this, any further interpretations in many seismological studies or advanced engineering applications could not successfully be accomplished without the proper knowledge of earthquake locations.

To locate earthquakes, many different types of seismic arrays have been designed to record useful seismograms on the Earth's surface. One popular type of seismic array is

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with the deployment of a number of seismic stations on a local or regional area, covering a radius ranging from around tens to hundreds of kilometers. Although these traditional seismic networks are very powerful in locating earthquakes in many interesting areas on Earth, they can not be deployed in other more particular areas, such as on an isolated island or across a sensitive territorial boundary. As an alternative, however, a small aperture seismic array or a single station may well be used in such areas. Along with overcoming such geographic or political limits, a small aperture seismic array or a single station is easier to set up than a traditional seismic network. Therefore, it is worthwhile investigating the epicenter location capability of a small aperture array or a single three-component station.

It is well known that the epicenters of distant earthquakes can be located theoretically by determining their distance and backazimuth from a single three-component station or a small array. However, the uncertainty of epicenters is primarily a factor of the backazimuth errors. For well-recorded earthquakes, the distance is relatively easy to calculate from the time difference between different phases of arriving seismic waves, such as S-P. On the other hand, the backazimuth, the azimuthal direction from the station to the source, is more difficult to determine accurately due to the heterogeneities of the subsurface earth structure through which the rays pass.

For teleseismic events, backazimuth anomalies are primarily associated with the accumulative effect of lateral velocity variations in the crust and/or the mantle (Niazi, 1966; Hearty *et al.*, 1977; Briden *et al.*, 1982; Walck and Minster, 1982; Ram and Yadav, 1984; Granet, 1986 and Dainty and Battis, 1989). In the early seventies, many investigators (e.g., Weichert, 1972; Davies and Sheppard, 1972; Powell, 1975; Kanasewich *et al.*, 1972, 1973; and Sengupta and Julian, 1974) preferred the exposition that the deep mantle lateral velocity variations were responsible for P-wave backazimuth anomalies because the primary raypath of teleseismic events is through the deep mantle. In contrast, other studies have shown that deep mantle lateral velocity variations were not responsible for such backazimuth anomalies. For example, several investigators (Engdahl and Felix, 1971; Wright, 1973; Okal and Kuster, 1975; Berteussen, 1976; Vermeulen and Doornbos, 1977) found that backazimuth anomalies were independent of phase type but rather were dependent on subarray location. They concluded that these anomalies were generated by the structures in the crust or upper mantle beneath the receiver stations. In addition to that, Walck and Minster (1982) proposed a simple model of upper mantle lateral velocity variations to interpret the backazimuth anomalies in southern California. Another study by Steck and Prothero (1993) reported that the backazimuth anomalies were most likely contaminated by strong velocity variations in the subcaldera crust between the depths of 6 and 35 km. In short, many previous studies suggested that backazimuth anomalies were strongly associated with crustal structures beneath a single seismic station or a seismic array.

The present study was undertaken in order to investigate the epicenter location capability of a small aperture array by means of a detailed examination of backazimuth anomalies which are probably caused by inhomogeneous structures beneath the array. The data used in this study are the arrivals of the first P-wave of eighty-eight local earthquakes recorded at a small dense array in the Pinyon Flat of southern California. This array consists of 25 three-component broadband instruments, including a center station (A0) and four concentric (A, B, C and D) rings, within an aperture of about 3 km. Such an array is very useful for studying the detailed characteristics of wave propagation across the array and for obtaining signal enhancement which takes advantage of the differences in the characteristics of wave propagation between signals and noises. In the beginning of this paper, the performance of a beamforming technique is evaluated. Then the backazimuth anomalies of the entire data set are obtained by subtracting the observed results with the reference backazimuths that are independently calculated from the known earthquake locations reported by the Anza and Caltech seismic networks. Finally, the characteristics of the backazimuth anomalies are investigated so as to provide an understanding of the effects of subsurface structures beneath the array and to improve the capability of epicenter location from a small aperture array.

2. DATA AND THE ARRAY

The data base contains eighty-eight local events recorded at a small dense seismic array in the vicinity of Pinyon Flat in southern California during the period between January and April 1991. Hypocenters of all these events were reported by the Anza and Caltech seismic networks (Figure 1), and their uncertainties are generally believed to be less than a few kilometers (~2 km) due to the dense station coverage of the networks. As a rule, these earthquakes are most often located along two major fault zones in the southern California area: the San Andreas fault and the San Jacinto fault zones. As shown in Figure 1, the distribution of these earthquakes covers almost all of the azimuth directions of the small aperture seismic array at the Pinyon Flat.

The Pinyon Flat seismic array was originally installed by the Kirghizia Seismic Array Committee of the Incorporated Research Institutes for Seismology (IRIS) Eurasian Seismic Studies Program for the study of the problems related to wave propagation and source

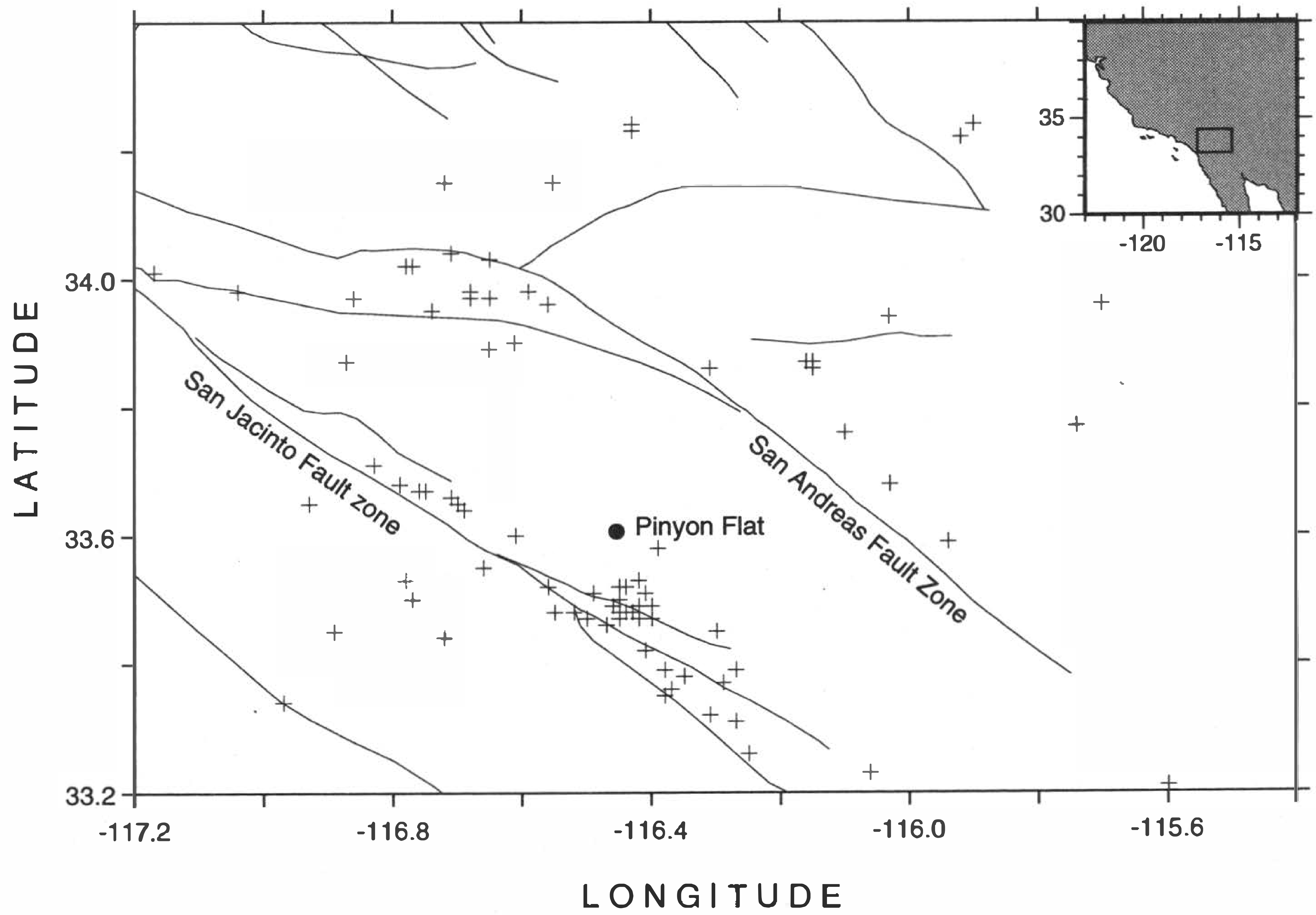

Fig. 1. Locations of the Pinyon Flat seismic array (marked by a black dot) and eighty-eight local earthquakes (marked by plus signs) reported by the Anza and Caltech seismic networks in southern California during the period between January and April, 1991.

property. The array is about 12 km northeast of the San Jacinto fault zone and about 25 km southwest of the San Andreas fault zone. The general array area has little topographic relief for several kilometers within the array even though it is in a portion of the Penninsular Ranges between the two major fault zones and has a thin weathered layer overlying a rigid basement (Fletcher *et al.*, 1990).

The array spatial distribution, similar to the NORRES array (Mykkeltveit *et al.*, 1983), was designed to be a small dense array with an aperture of about 3 km (Figure 2). This array, instead of using short-period vertical instruments in the NORRES array, consists of 25 three-component broadband seismic stations. Geometrically, it includes a center station (A0) and four concentric (A, B, C and D) rings with the radii of 150, 320, 735 and 1480 meters. The station numbers from A- to D-rings are 3, 5, 7 and 9, respectively with the center station close to the Pinon Flat Observatory (PFO), one of the most popular geophysical observation sites in southern California.

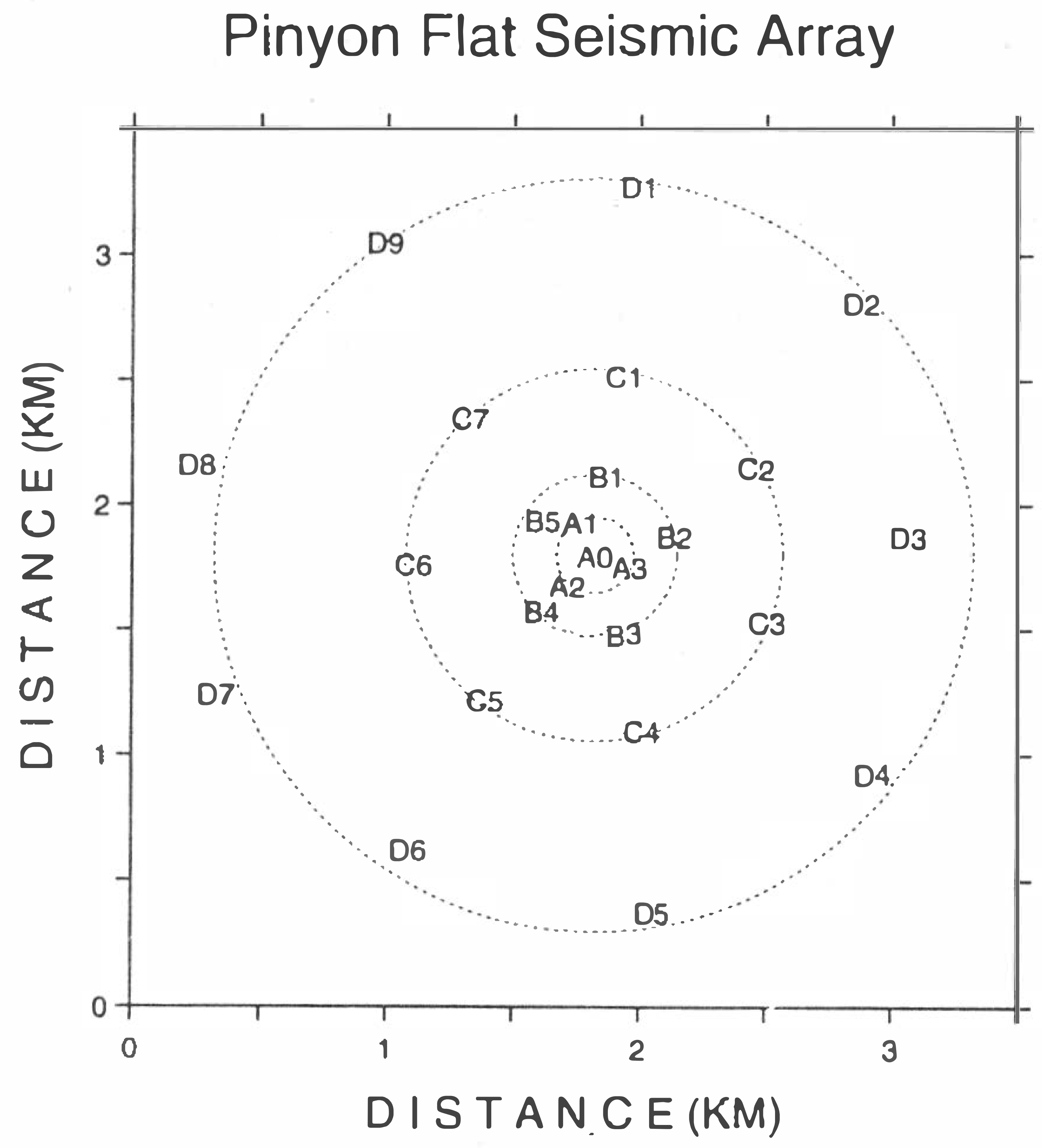

Fig. 2. Pattern of the 25 stations in the Pinyon Flat seismic array. The rings of A, B, C and D are indicated by four co-center dashed circles with the radii of 150, 320, 735 and 1480 meters, respectively.

The selection of the Pinyon Flat seismic array to examine the detailed characteristics of backazimuth anomalies was first initiated for the following reasons. First, such an array is useful for obtaining reliable backazimuths of incoming phases due to its effectiveness in noise suppression and spatial sampling characteristics. Second, if the medium beneath this array can be assumed to be homogeneous, the variation in the backazimuth across this array may be neglected because of the sufficiently small aperture compared with epicentral distance. In contrast, the backazimuth across a large aperture array can be quite different, geometrically. Finally, since seismograms recorded at the array are stored at a sampling rate of 100 points per second, they provide a high precision of 0.01 sec for the accurate picking of the arrival time of the first P-wave.

The analysis of backazimuths from the first P-waves of local earthquakes is based on the following reasons. First, backazimuths computed from local earthquakes are usually better than those from teleseismic events even though teleseismic events have been popularly analyzed during the past few decades. Since teleseisms travel nearly vertically through the crust, the travel time differences across the array are small. As a result, small amounts of noise can introduce significant errors when backazimuth angles are being determined. Second, the first P-waves of local earthquakes usually provide more accurate information than any other phases since they are the least ambiguous in the entire seismogram. For example, arrivals of the first P-waves of a representative earthquake recorded in the entire array can be accurately read in Figure 3. Third, many local earthquakes associated with the active San Jacinto and San Andreas fault zones can not only be easily collected during a short period of time but can also provide a better spatial distribution of the incident rays evenly covering all azimuth directions (Figure 1).

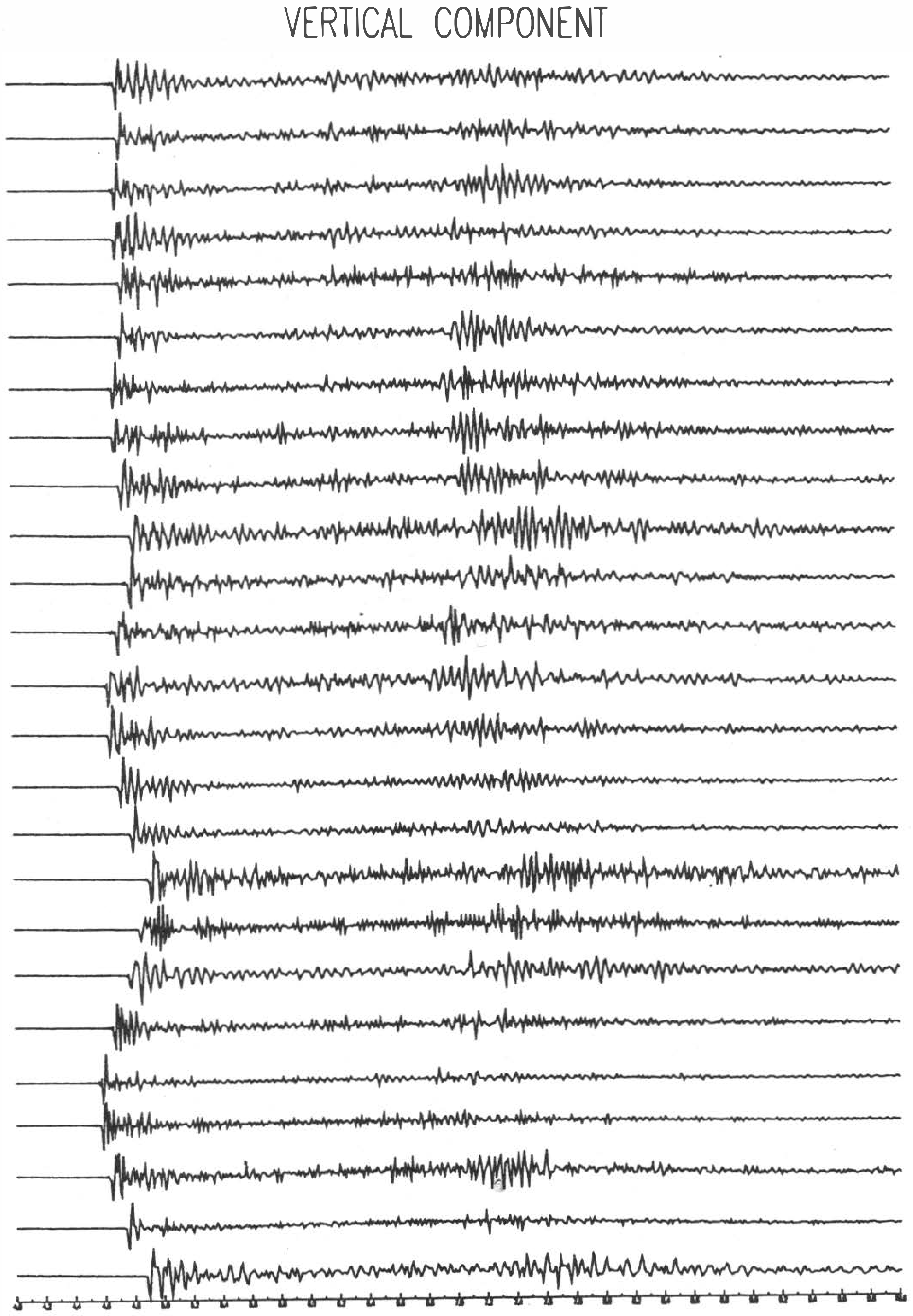

Fig. 3. Vertical component seismograms of a representative earthquake recorded at the Pinyon Flat seismic array.

3. BACKAZIMUTH ESTIMATION

A beamforming technique (Green *et al.*, 1966) is employed in this study to analyze the seismic data recorded at the Pinyon Flat seismic array of southern California in that it is one of the simplest yet most effective methods for determining the backazimuth to the epicenters. Its basic principle is to fit the observed arrivals of a particular phase passing through a seismic array by a plane wave. The unknown parameters, including both the backazimuth and apparent velocity of the particular phase, is simultaneously determined through a least-squares inversion by providing a set of observed arrivals at the array.

Although observations from a number of stations greater than three are theoretically enough to solve both the backazimuth and apparent velocity with this technique, the accuracy of the estimated results is strongly dependent on how many observations are obtained within the array. In other words, backazimuths computed from various sub-array stations might be quite different. Figure 4a gives a plot of the backazimuths computed from numerous possible station configurations within the D-ring. To illustrate, there are 84 solutions computed from 3 arbitrarilly chosen stations within the D-ring. The results of all of the configurations from three to eight stations clearly show that the dispersion of the computed backazimuths narrows as the number of stations increases even though they all center around 190 degrees. The greatest difference among these observations could reach about twenty degrees when three stations are arbitrarily selected from the D-ring, but deviations progressively converge to only about four degrees when eight stations are selected.

Numerical results from a simple statistical calculation show more clearly that the range of one standard deviation of the computed backazimuths gradually decreases from twelve degrees for three stations to only three degrees for eight stations (Figure 4b). The backazimuth computed from nine stations is very close to the mean values obtained from other station configurations within the D-ring. In short, the phenomenon of stable convergence implies that the backazimuth computed from nine stations of the D-ring already provide acceptable results. Furthermore, the backazimuth estimated from all 25 stations of the entire array is 190 degrees with a standard error of 0.2 degrees. This is also very close to the value obtained from D-ring or the mean values obtained from other sub-D-rings. All these features strongly indicate that the observed backazimuth computed from twenty-five stations of the entire array is quite accurate and reliable. Consequently, in the next section, this technique is employed to estimate the backazimuth of each event of the entire data set based on arrivals recorded in the array.

4. RESULTS AND DISCUSSIONS

For each event, the backazimuth anomaly of the first P-waves was obtained by subtracting from an observed backazimuth by a reference backazimuth that is directly obtained from the known location reported by the Anza and Caltech seismic networks in southern California. The reference backazimuth is usually quite reliable because the uncertainty of the epicenter has often been said to be less than a few kilometers ($\sim$2 km) due to the dense station coverage of the networks. Meanwhile, the observed backazimuth computed by using a beamforming technique can also be accepted since the arrivals of the first P-wave can be accurately read from the seismograms recorded at the 25 stations of the Pinyon Flat seismic array (Figure 3).

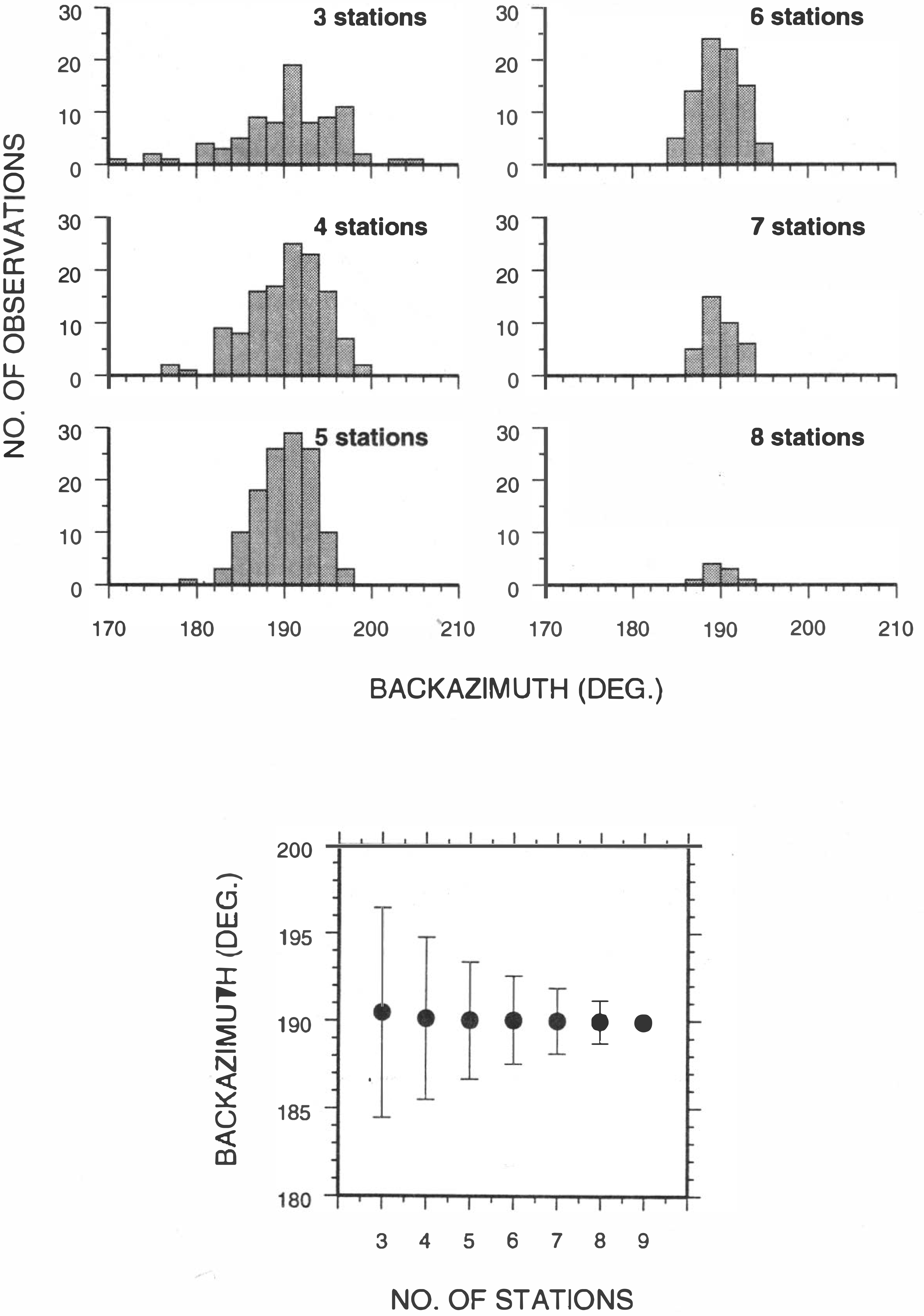

Fig. 4. An example of backazimuths computed from different station configurations. (a) Histograms of observed backazimuths from 3 to 8 arbitrarilly chosen stations. (b) Their mean values (marked by black dots) and ranges of one standard deviation (marked by bars).

Figure 5 plots the comparison of the calculated backazimuths and the corresponding reference backazimuths of eighty-eight local events. In general, the variation of the backazimuth anomalies is mostly limited to within a range of about twenty degrees even though the greatest anomaly could reach about twenty-eight degrees. Furthermore, a simple statistical tabulation demonstrates that the most frequently observed backazimuth anomalies are concentrated between five and six degrees (Figure 6). More than half of the observed backazimuth anomalies are greater than five degrees.

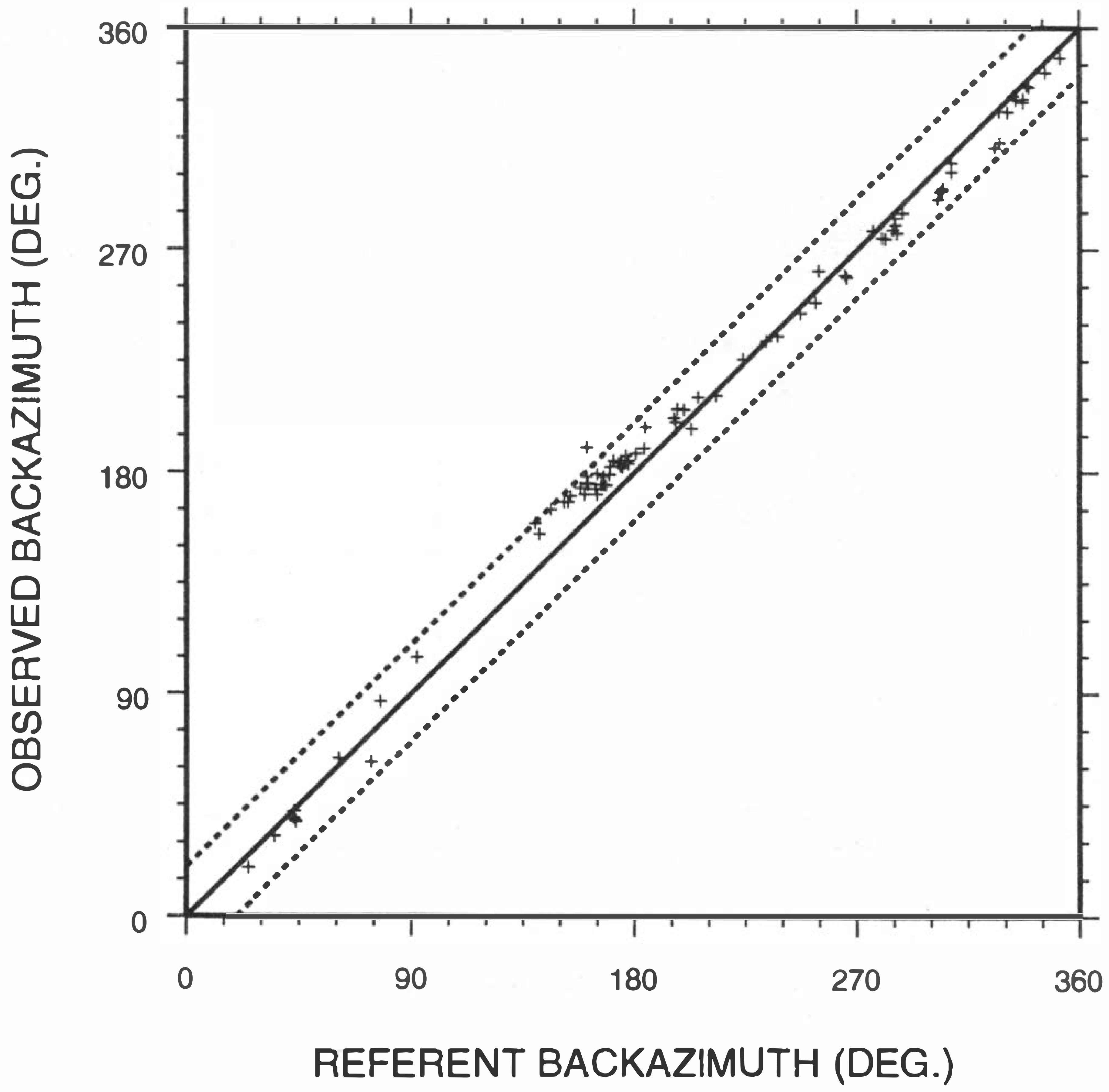

Fig. 5. Relationship between the observed and reference backazimuths. The solid line delineates the same value between both backazimuths, and the dashed lines limit a range of twenty degrees variation.

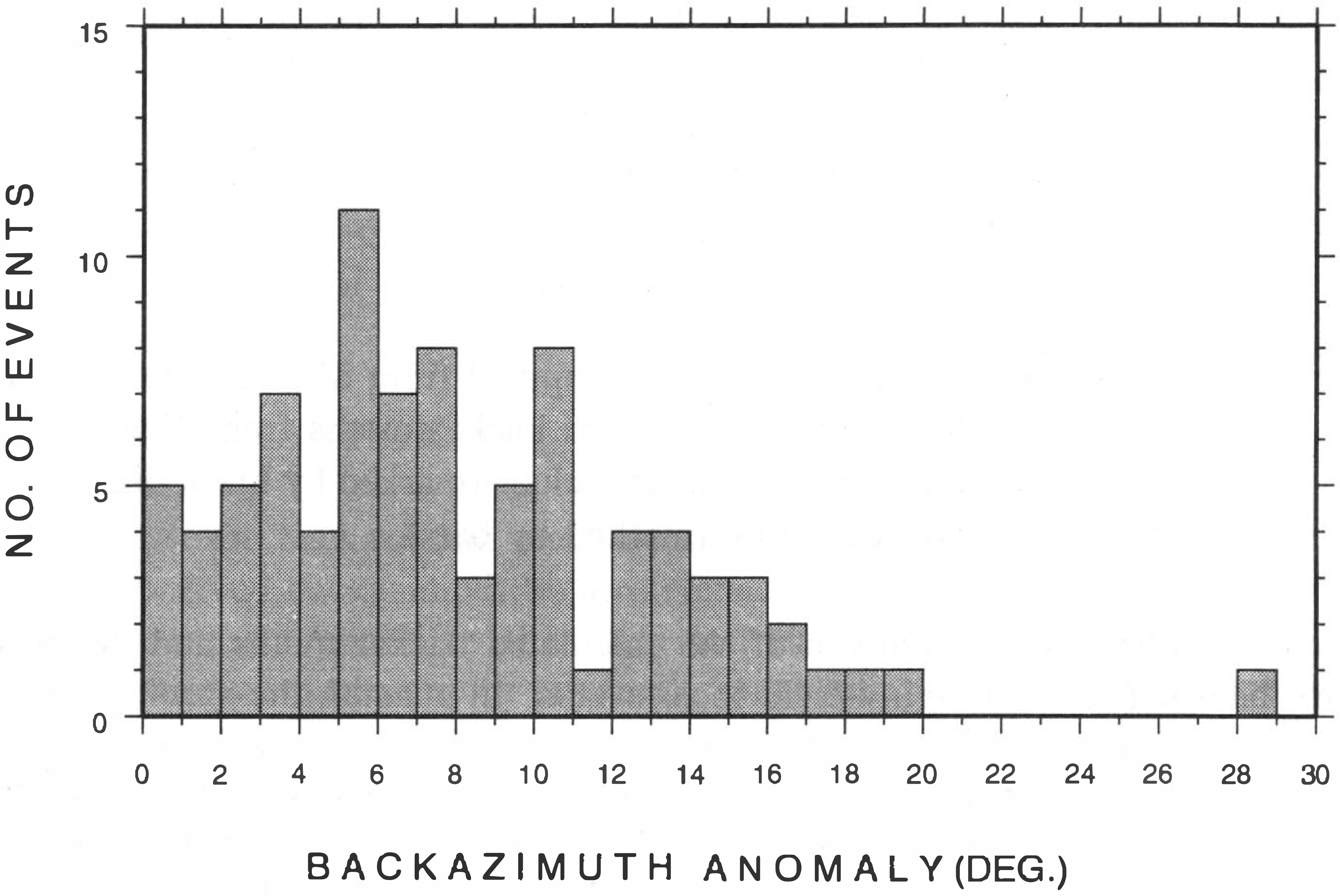

Fig. 6. Histogram of backazimuth anomalies.

Significant backazimuth anomalies that may cause remarkable errors in epicenter location may be attributed to four possible factors, including (1) uncertainties in the reference earthquake locations, (2) observed errors at a station or an array, (3) computed errors from estimated techniques, and (4) propagation effects due to the lateral velocity variation of subsurface structures. First, major backazimuth anomalies obviously can not come from the epicenter errors because the Anza and Caltech seismic networks provide excellent constraints on the event locations (less than 2 km). For instance, there is only about 3 degree backazimuth errors if an event at 20 km away is considered with a 1-km mislocation. Second, it is concluded that strong backazimuth anomalies can be from neither the computed errors because they are far greater than the standard errors obtained from the beamforming technique that have been discussed in the previous section, nor can they be from the observed errors due to the high precision sampling rate recording from a dense broadband array. Accordingly, the only one remaining viable factor to explain the significant backazimuth anomalies is the effect of the subsurface structures through which the rays passed.

To better understand the characteristics of these strong backazimuth anomalies, they have been plotted as a function of reference backazimuths (Figure 7). It is worth noting that the backazimuth anomalies not only vary cinsistently with the backazimuths, but also present systematic biases. In general, positive anomalies are found in the backazimuth directions from 45 to 225 degrees, while negative anomalies appear in the opposite directions. The strongest anomalies are detected in around the southeast direction where the observed backazimuths are about ten to twenty degrees greater than the expected angles. On the other hand, the observed backazimuths are about ten degrees less than the expected angles around the northwest direction. Meanwhile, there are almost no significant differences in either the northeast or southwest directions. In summary, a simple sine-like function seems good enough to describe the first-order variation of backazimuth anomalies as a function of the backazimuth. These results strongly indicate that the ray paths have systematically been bent as they have laterally crossed the study area, and the magnitudes of such bending has been strongly dependent on the direction of the incoming waves.

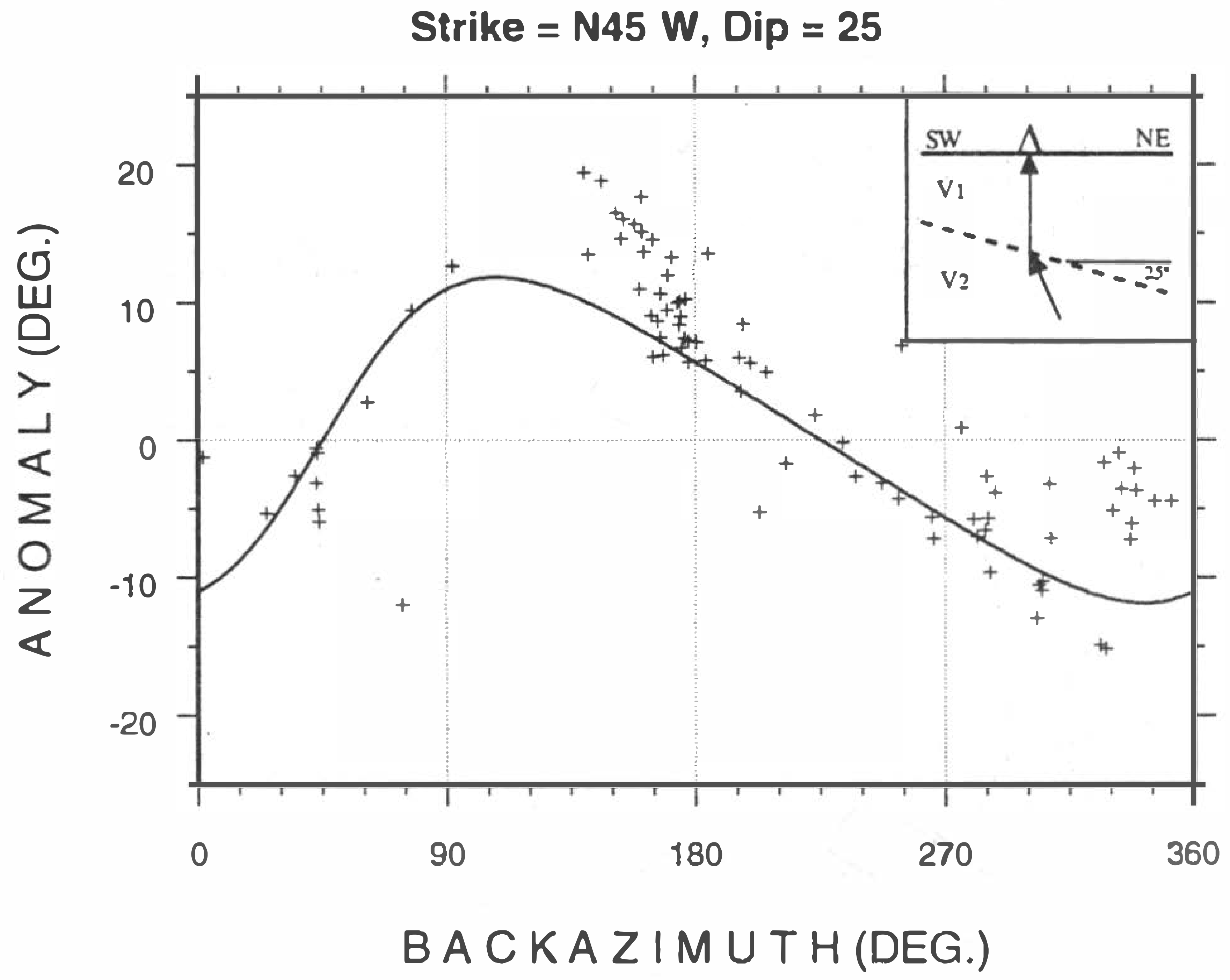

Fig. 7. A comparison between the observed (plus sign) and theoretical (solid-line) backazimuth anomalies. The theoretical backazimuth anomalies are constructed from a simple model with an interface dipping twenty-five degrees to the NE (the upper right corner of the Figure).

A simple model to explain the observed strong backazimuth anomalies above is a crustal model with dipping interfaces beneath the array. A theoretical curve of backazimuth anomalies is computed based on a typical model of an interface dipping twenty-five degrees to the northeast (Figure 7). The velocities of the upper and lower layers in the crustal model are assumed to be 5.6 km/s and 6.8 km/s, respectively. The theoretical result shows that anomalies vary with backazimuths, depending on the incident azimuth of the P-waves. To illustrate, the theoretical backazimuth anomalies are very strong when the incident waves are approximately along the strike of the dipping interface. Conversely, there are almost no anomalies when the incoming waves are along the dip direction of the dipping interface. In general, the theoretical results are quite consistent with the main (or first-order) pattern of the observed anomalies. Some distinct inconsistences in the backazimuths ranging from 145° and 180° are probably caused by the effect of epicenter errors at short epicentral distances.

The preceding discussion of the comparison between observed and theoretical backazimuths indicates that the capability of epicenter location of the Pinyon Flat seismic array can be improved when a simple crustal model with a dipping interface is assumed. More accurate epicenters can be obtained with the first order of systematic backazimuth anomalies that are constructed from the model removed. A comparison of the epicenter errors is shown in Figure 8. Epicenter errors directly estimated from the array reveals that they peak prominently at 1.25-1.5 km (Figure 8a). It should be noted that the epicenter errors of some events are greater than 10 km. On the other hand, the largest peak of epicenter errors obtained after backazimuth corrections is found at 0.25-0.5 km (Figure 8b). There is only one event whose epicenter error is greater than 10 km. In summary, the number of large epicenter errors significantly decreases thereby limiting the errors of about half of the events to within 2 km.

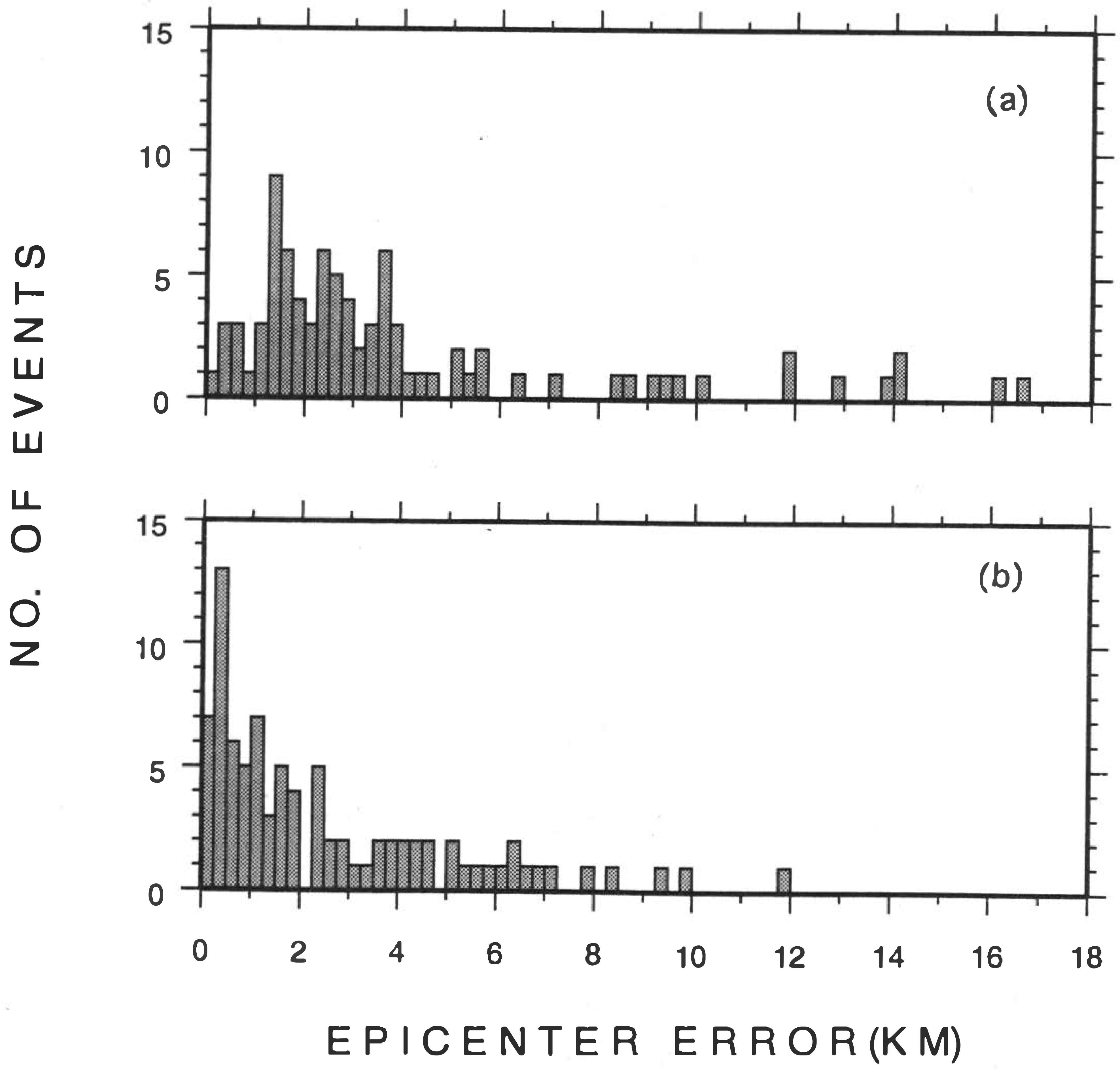

Fig. 8. Histograms of epicenter errors estimated (a) directly from the observed backazimuths, and (b) after some corrections from a dipping model.

5. CONCLUSIONS

The capability of locating earthquakes from a small aperture array is shown to be strongly associated with our understanding of subsurface structures because the observed backazimuths used to determine the source direction may be biased due to the heterogeneous structures beneath the array. In this study, it is shown that the capability of epicenter location from the Pinyon Flat seismic array of southern California can be significantly improved by using a simple dipping interface model to correct the observed backazimuths. Specifically, a model with an interface dipping of 25 degrees to the northeast is proposed so that the first order systematic anomalies are removed. As such, the number of large epicenter errors significantly decreases resulting in errors of many events being limited to within 2 km. In addition, the performance of the beamforming technique is shown to be very stable in estimating the backazimuths from the seismograms generated by local earthquakes and recorded at a dense small array. The examination of the backazimuth from a representative event has been presented as an example to show that the result estimated from 9 stations of the D-ring is almost same as that from all 25 stations of the entire array.

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REFERENCES

Berteussen, K. A., 1976: The origin of slowness and azimuth anomalies at large arrays. *Bull. Seism. Soc. Am.*, **66**, 719-751.

Briden, J. C., R. F. Mereu, and D. N. Whitcombe, 1982: A teleseismic study of the West African craton margin in Senegal: P-wave slowness and azimuth anomalies. *Geophys. J. R. Astr. Soc.*, **71**, 793-808.

Dainty, A. M., and J. C. Battis, 1989: Variation of apparent azimuth of arrivals at a small aperture array in New England (abstract). *EOS Trans. AGU*, **70**, p.400.

Davies, D., and R. M. Sheppard, 1972: Lateral heterogeneity in the earth's mantle. *Nature*, **239**, 318-323.

Engdahl, E. R., and C. P. Felix, 1971: Nature of travel-time anomalies at LASA. *J. Geophys. Res.*, **76**, 2706-2715.

Fletcher, J. B., T. Fumal, H. Liu, and R. Porcella, 1990: Near-surface velocities and attenuation at two bore-holes near Anza, CA from logging data. *Bull. Seismol. Soc. Am.*, **80**, 807-831.

Granet, M., 1986: A teleseismic study of the Upper Rhinegraben area: array mislocation diagram and 3-D velocity inversion. *J. Geophys. Res.*, **59**, 119-128.

Green, P. E., E. J. Kelley, and M. J. Levin, 1966: A comparison of array processing methods. *Geophys. J. R. Astr. Soc.*, **11**, 67-84.

Hearty, D. J., R. F. Mereu, and C. Wright, 1977: Lateral variations in upper crustal structure below the La Malbaie area from slowness, azimuth, and traveltime measurements of teleseisms. *Can. J. Earth Sci.*, **14**, 2284-2293.

Kanasewich, E. R., R. M. Ellis, C. H. Chapman, and P. R. Gutowski, 1972: Teleseismic array evidence of inhomogeneities in the lower mantle and the origin of the Hawaiian Islands. *Nature*, **239**, p.99.

Kanasewich, E. R., R. M. Ellis, C. H. Chapman, and P. R. Gutowski, 1973: Seismic array evidence of a core boundary source for the Hawaiian linear volcanic chain. *J. Geophys. Res.*, **78**, 1361-1371.

Myhheltveit, S., K. Astrbol, D. J. Doornbos, and E. S. Husebye, 1983: Seismic array configuration optimization. *Bull. Seism. Soc. Am.*, **73**, 173-186.

Niazi, M., 1966: Corrections to apparent azimuths and traveltime gradients for a dipping Mohorovicic discontinuity. *Bull. Seism. Soc. Am.*, **56**, 491-509.

Okal, E., and G. Kuster, 1975: A teleseismic array study in French Polynesia. Implications for distant and local structure. *Geophys. Res. Lett.*, **2**, 5-8.

Powell, C., 1975: Evidence for mantle heterogeneity from two large seismic arrays. *Nature*, **254**, 40-42.

Ram, A., and L. Yadav, 1984: Structural corrections for slowness and azimuth of seismic signals arriving at the Gauribidanur array. *Bull. Seim. Soc. Am.*, **74**, 97-105.

Sengupta, M. K., and B. R. Julian, 1974: Mantle velocity and its regional variation. *EOS Trans. AGU*, **55**, p.350.

Steck, L. K., and W. A. Prothero, Jr., 1993: Observations of direct P-wave slowness and azimuth anomalies for teleseisms recorded in Long Valley Caldera, California. *Bull. Seism. Soc. Am.*, **83**, 1391-1419.

Vermeulen, J. M., and D. J. Doornbos, 1977: Mantle heterogeneity and mislocation patterns for seismic networks. *J. Geophys. Res.*, **43**, 545-559.

Walck, M. C., and J. B. Mister, 1982: Relative array analysis of upper mantle lateral velocity variations in southern California. *J. Geophys. Res.*, bf 87, 1754-1772.

Weichert, D. H., 1972: Anomalous azimuths of P: evidence of lateral variations in the deep mantle. *Earth Planet. Sci. Lett.*, **17**, 181-188.

Wright, C., 1973: Observations of multiple core reflections of the PnKP and SnKP type and regional variations at the core of the mantle. *Earth Planet. Sci. Lett.*, **19**, 453-460.